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Numerical comparison of two modes of gas-solid riser operation: Fluid catalytic cracking vs CFB combustor

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ABSTRACT

Two modes of gas-solid riser operation, i.e., fluid catalytic cracking (FCC) and circulating fluidized bed combustor (CFBC), have been recognized in literature; particularly in the understanding of choking phenomena. This work compares these two modes of operation through computational fluid dynamics (CFD) simulation. In CFD simulations, the different operations are represented by fixing appropriate boundary conditions: solids flux or solids inventory. It is found that the FCC and CFBC modes generally have the same dependence of solids flux on the mean solids volume fraction or solids inventory. However, during the choking transition, the FCC mode of operation needs more time to reach a steady state; thus the FCC system may have insufficient time to respond to valve adjustments or flow state change, leading to the choking. The difference between FCC and CFBC systems is more pronounced for the systems with longer risers. A more detailed investigation of these two modes of riser operation may require a three-dimensional full loop simulation with dynamic valve adjustment.

Introduction

Circulating fluidized beds (CFBs) have been widely applied in industrial processes, such as alumina calcination, fluidized bed combustion and gasification, fluid catalytic cracking (FCC), and chemical looping (Grace, Avidan, & Knowlton, 1997; Kang, 2014; Kwauk, 1994; Reh, 1996; Squires, Kwauk, & Avidan, 1985; Werther, 2005; Werther & Hartge, 2014; Zhu, 2005). Key parameters of CFBs include material properties (such as particle diameter, d_p, and density, ρ_s) and operating conditions (such as superficial gas velocity, U_g, and solids flux, G_s). The modes of operation (Reh, 1996) and geometric factors (Grace, 1996) are also important factors in the performance of a CFB, though they are rarely discussed in literature. Generally, two modes of operation can be distinguished in CFBs (Reh, 1996): one has been developed from refinery technology where catalyst particles are fluidized and circulated with a "controlled recycle" (such as in a FCC reactor); the other has been developed from processes involving internal combustion where solid particles are circulated with an "undelayed recycle" (such as in a CFB combustor or alumina calciner). Normally, the solids flux in FCC reactors is controlled using mechanical valves (such as a butterfly valve or a flashboard valve), whereas the solids flux in a CFB combustor (CFBC) can be adjusted by using non-mechanical, gas-aerated valves (such as a U-valve, L-valve, or siphon), through which the pressure drop balance is established and adjusted between the downcomer and riser. We distinguish these two modes of operation in terms of solids-flow control: controlled recycle and undelayed recycle, by referring to their typical reactors (FCC and CFBC), respectively in the following discussions.

Solids-flow control is closely related to the "choking" phenomenon. Classical choking was initially introduced as a flow instability, characterized by an abrupt rise in pressure drop per unit length of pipe and apparent collapse to a slugging state, when decreasing the superficial gas velocity under a constant solids flux (Zenz, 1949). Later the term "choking" was employed in the context of the "fast fluidization" of CFB and related to the clustering of particles (Bi & Grace, 1995; Bi, Grace, & Zhu, 1993; Du & Fan, 2004; Du, Warsito, & Fan, 2004; Karri & Knowlton, 1991; Li & Kwauk, 1994; Takeuchi, Hirama, Chiba, Biswas, & Leung, 1986; Yang, 2004; Yerushalmi, Turner, & Squires, 1976; Yousfi & Gau, 1974; Zhang

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& Zhang, 2015). Instead of changing gas flow rate, Bai, Issangya, and Grace (1998) proposed a method for determination of choking velocity by manipulating the mechanical valve for solids flux. In their experiment with FCC particles, the mechanical valve was initially closed and the gas flowed through the empty riser at a preset flow rate. Gradually opening the valve led to an increase of solids flux and pressure drop in the riser, and eventually resulted in a sharp increase of pressure drop at the riser bottom, where heterogeneous clusters were formed in place of uniform dilute suspension, corresponding to the accumulative choking. Beyond this point, further opening of the valve had no influence on the solids flux because it had reached the saturation carrying capacity. They also indicated that a quick valve opening could result in bed collapse if the system had insufficient time to follow the change of flow pattern. Based on experiments with FCC particles, Li and Kwauk (1994) and Li, Wen, Ge, Cui, and Ren (1998) indicated that the S-shaped, axial voidage profile in the riser corresponds to the accumulative choking phenomenon in CFB, which can be characterized by the co-existence of dilute top and dense bottom regions, whereas the solids flux is equal to the saturation carrying capacity (K^*). Once the choking is established, the opening of the valve has no influence on the solids flux. If the opening of the valve is decreased (or increased), the input solids flow rate temporarily becomes smaller (or bigger) than K^*; however, the solid output rate remains at K^*, depleting the solids in the riser. So, the voidage of the dilute region at the top of the riser remains constant; the dilute region extends toward the bottom (or top) of the bed, and the new position of the inflection point of sigmoid profile will be lower (or higher).

In pneumatic conveying systems or FCC reactors, the solids flux is expected to be fixed by using a mechanical valve (controlled recycle). When a thin and long riser is used in such systems, the size of meso-scale clusters inside the riser may be comparable to the tube diameter, causing slugging and classical choking during flow regime transition from dilute to dense transport (Bi et al., 1993; Zenz, 1949). However, when a CFBC system with a non-mechanical siphon and a large cross-sectional furnace is encountered, the solids flow rate cannot be fixed directly. Instead, the solids flow can be adjusted by changing the solids inventory and thus the pressure drop balance around the whole loop. Thereby a smooth transition from the dilute flow to the S-shaped, dilute-dense coexisting flow and finally all-dense flow can be achieved and easily adjusted without apparent flow instability (undelayed recycle) (Reh, 1996). So we can see that the different operation modes (i.e., FCC or CFBC mode, corresponding to fixed solids flux or solids inventory respectively) can result in quite different flow behavior and transition.

Similar operation-dependent differences can also be found in numerical simulations. With the rapid development of computational fluid dynamics (CFD) in recent decades, increasing efforts have been put into simulating the flow behavior in gas–solid risers. Most of these simulations have been conducted on simplified two- or three-dimensional (2D or 3D) geometries (Agrawal, Loezos, Syamlal, & Sundaresan, 2001; Benyahia, 2012; Benyahia, Gonzalez Ortiz, & Paz Paredes, 2003; Dong, Wang, & Li, 2008; Hong, Shi, Wang, & Li, 2013; Hong, Wang, Zhou, Wang, & Li, 2012; Igci, Andrews, Sundaresan, Pannala, & O'Brien, 2008; Li, Dietiker, & Shadle, 2014; Li, Song, Benyahia, Wang, & Li, 2012; Tsuji, Tanaka, & Yonemura, 1998; Yang, Wang, Ge, & Li, 2003). In particular, the superficial gas velocity and solids flux are normally specified in simulations as the given conditions, whereas the pressure drop or the solids volume fraction ε_s in the riser is predicted (Gidaspow, Jung, & Singh, 2004; Neri & Gidaspow, 2000; Nieuwland, van Sint Annaland, Kuipers, & Van Swaaij, 1996; Tsuo & Gidaspow, 1990). However, as discussed above (Bai et al., 1998; Li & Kwauk, 1994; Li et al., 1998), the solids flux may remain constant for a range of pressure drops or solids inventories in the riser during the accumulative choking. Multiple values of pressure drop may correspond to a single value of solids flux, so it is questionable as to which pressure drop can be predicted by specifying only the superficial gas velocity and solids flux. Accordingly, some researchers have performed 2D simulations of the riser by specifying the superficial gas velocity and solids inventory in the riser so that the solids flux can be predicted by recycling the entrained solids from the outlet to the side inlet without any delay (Hong et al., 2013; Lu, Wang, & Li, 2009; Wang & Li, 2007; Yang et al., 2003). 3D, full-loop simulations of the CFB systems were performed by specifying the superficial gas velocity and solids inventory in the whole loop (Li et al., 2014; Lu et al., 2013; Zhang, Lu, Wang, & Li, 2008, 2010) and recently a 3D, full-loop simulation with online adjustment of the mechanical valve (Liu, Zhao, Wang, & Li, 2015). The two modes of numerical simulation, the specification of solids flux and solids inventory, explore the differences found between the two modes of CFB operations: FCC with controlled recycle and CFBC with undelayed recycle, respectively.

In our previous simulations, we have shown that energy minimization multi-scale (EMMS) based drag models can be applied to predict the choking phenomenon. For example, Wang, Lu, and Li (2007) performed a two fluid model (TFM) simulation with EMMS drag (Yang et al., 2003) over the 2D geometry of the riser. The choking and non-choking flow regime transitions in an air-FCC system were predicted under different operating conditions and the results were in reasonable agreement with experimental data. Furthermore, Wang, Lu, Dong, and Li (2008) and Wang, Lu, Zhang, Shi, and Li (2010) showed the difference between the intrinsic and apparent flow regimes by performing TFM simulation of choking in CFB systems with different riser heights, in which the EMMS/matrix drag (Lu et al., 2009; Wang & Li, 2007) and 2D geometry of a riser were used. The choking phenomenon was found to heavily depend on the riser height, disappearing in a short riser because of the strong effect of the developing region near the inlet/outlet zones. Zhang et al. (2008) captured the choking phenomenon with a 3D, full-loop simulation of the whole CFB, where the TFM with EMMS/matrix drag was used. The choking transition was found to be less pronounced than that reported by Wang et al. (2007) possibly because of the effects of geometric factors such as the inlet and outlet configurations. Li, Song, Wang, and Li (2013) predicted the choking phenomenon with multiphase, particle in cell (MP-PIC) simulation of the same riser used in Wang et al. (2007) and the EMMS/matrix drag was used. It should be emphasized that in all of these efforts the solids inventory was specified in the simulation, thus the CFBC operation with undelayed recycle was implied.

Recognizing that these two modes of operation are closely related to the two major branches of practice in CFB technology (Kwauk, 1994; Reh, 1996; Squires et al., 1985), and that they are also related to the differing theories of choking (Bi et al., 1993; Yang, 2004), it is useful to compare these two modes of operation in numerical simulations. Indeed, it is easier to precisely control the parameters in CFD simulations than in real experiments, and such numerical comparison can be expected to facilitate convergence of the different understandings of CFB technology and the relevant flow instabilities. This work performs and compares two CFD simulations of a CFB riser by specifying the solids flux and solids inventory alternatively. Based on this numerical comparison, the difference between FCC and CFBC operations and the choking phenomenon will also be discussed.

Simulation

The riser part of the CFB facility used in the experiments of Li and Kwauk (1994) was selected for the simulations. The riser (10.5 m in height and 0.09-m I.D.) was simplified into a 2D geometry, as shown in Fig. 1, to save computational time. Gambit® 2.4 (Fluent, USA) was used to generate the grids, each cell was 1.5 mm × 23.3 mm.