A Numerical Investigation of an Industrial Scale Gas-Solids CFB

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Abstract This paper investigates the ability of a two-fluid hydrodynamic model to accurately predict pressure drop in an industrial scale circulating fluidized bed (CFB). Experimental data generated at the National Energy Technology Laboratory (NETL) is used to validate the numerical model. Two dimensional simulations of the riser section of the CFB were performed over a range of solids circulation rates and riser gas velocities. Riser inventory is shown to be the appropriate quantity for determining when steady-state conditions have been reached and field variables should be time-averaged. This investigation also shows inconsistencies in the prediction of riser inventories when using different high order limiters.

1 Introduction

Over sixty years have passed since circulating fluidized beds (CFB's) appeared on the scene as a new technology in gas-solids systems. Since then industry has increasingly relied upon CFB's to satisfy both economic and operational goals in such industrial areas as power generation, mineral and chemical processes. Despite their growth in popularity different designs, scale-up, and new applications are slow to emerge due primarily to the lack of understanding of the complex hydrodynamic interactions between the gas and solids phases. The general approach in designing new CFB's is usually based on a collection of empirical correlations and/or scaling laws. However, it is still difficult to integrate this information into a comprehensive model and when large changes in scale or operating parameters occur the usage of such an approach is questionable.

Two-fluid hydrodynamic models are slowly gaining acceptance as an alternative method in understanding the complex interactions between the gas and solids

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phases in a CFB and aid in the design and scale-up. The idea of describing gas-solids systems with a two-fluid hydrodynamic model have existed since the early 60's (Davidson, 1961; Jackson, 1963; Anderson and Jackson, 1967). The resulting equations set forth by these researchers are very difficult to solve, and numerical solutions capable of predicting some of the complex interactions between the phases such as clusters and core-annular structure came much later (for example, Tsuo and Gidaspow, 1990; Gidaspow et al., 1992; O'Brien and Syamlal, 1993).

Today there are numerous numerical investigations of CFB's on a small (experimental) scale, but investigations on an industrial scale are rarely found in the literature. Industrial scale investigations are usually limited to obtaining only a few seconds of data and using low order discretization techniques (first order upwinding) to speed up convergence rates. Unfortunately, this type of approach generally gives unsatisfactory results. In this investigation we used long run times in order for the solids inventory in the riser to reach a steady-state condition. This investigation shows that higher order methods should be used because first order upwinding (FOU) is too diffusive to accurately predict the complex interactions between the phases. The second order Superbee limiter and a recently published upwind-biased four point fourth order interpolation method (FPFOI) (Song et al., 1999) are compared using a deferred correction approach. Recently, Guenther and Syamlal, (2001) have shown that large CPU times and stability concerns, usually associated with using high order methods in dense gas-solids flows, can be significantly reduced by using deferred correction. This investigation also shows that the Superbee limiter consistently over-predicted the solids riser inventory compared to the FPFOI results.

2 Mathematical Model

Two-fluid hydrodynamic models, also referred to as Eulerian-Eulerian models, treat the fluid and solids as two continuous and fully interpenetrating phases. This approach results in mass, momentum, and energy balance equations for both the gas and solids phases. For isothermal conditions, the continuity and momentum balance equations (gas phase $m = g$, solids phase $m = s$) are given below.

Continuity

$$\frac{\partial}{\partial t}(\varepsilon_m \rho_m) + \nabla \cdot (\varepsilon_m \rho_m \vec{v}_m) = 0 \tag{1}$$

Momentum

$$\frac{\partial}{\partial t}(\varepsilon_m \rho_m \vec{v}_m) + \nabla \cdot (\varepsilon_m \rho_m \vec{v}_m \vec{v}_m) = \nabla \cdot \bar{\bar{S}}_m + \sum_{l=1}^{M} \vec{I}_{ml} + \vec{f}_m \tag{2}$$

Expressions for the gas-solids drag $\vec{I}_{ml}$ and gas-solids stress terms $\overline{\overline{S}}_m$ are needed to close the system. Deatils about the constitutive models can be found in Syamlal et al. (1993), Syamlal (1998), and Guenther and Syamlal (2001).

3 Numerical Procedure

The governing set of partial differential equations (1)-(2) are solved using a finite volume technique. The MFIX code developed at the National Energy Technology Center was used for the numerical study (see www.mfix.org for details). The numerical procedure, the second-order spatial discretization method and deferred correction approach are described in Syamlal (1998) and Guenther and Syamlal (2001). For the present study we also included an upwind-biased four point fourth order interpolation method (FPFOI) (Song et al. 1999) in MFIX. This method was used to discretize the convection terms in the continuity and momentum equations using the limiter ULTIMATE (Leonard, 1991) to prevent unphysical numerical oscillations. A purpose of this study has been to compare the performance of FPFOI and Superbee methods for simulating circulating fluidized beds.

4 Experimental and Numerical Results

The riser portion of the experimental set-up has an inside diameter of 12 inches and is 56.4 feet high. The main fluidizing gas, air, was fed through a perforated plate at the base of the riser. Solids entered the riser via a 10 inch diameter loopseal 16 inches above the plate and exit through a 8 inch diameter blind-tee configuration 52.4 feet above the plate. To minimize static charge buildup, the riser consisted mostly of carbon steel segments. It was equipped with 23 differential pressure transmitters connected in series to measure incremental pressure drops along the bed. The solids phase consisted of 1000 μm cork particles with a density of 190 kg/m^3.

The MFIX simulations were conducted using two-dimensional Cartesian coordinates. (A 2D axisymmetric simulation would appear to be the natural choice for approximating the cylindrical riser section. However, unphysical clusters form at the centerline in such simulations. Hence, we chose a 2D Cartesian grid in this preliminary investigation to compare high order limiters.) The computational grid consisted of 30 cells in the x-direction and 860 cells in the y-direction and no-slip boundary conditions were used for both phases. Initially, the riser was void of any solids corresponding to the experimental conditions at start-up. The voidage and solids velocity at the side inlet and gas velocity at the base of the riser were held constant during each simulation. Also, additional air (move air) was specified

with the solids to account for the fluidizing air used in the loopseal and at the base of the standpipe during operation. Each simulation was run until 10-15 seconds of data at steady-state conditions was collected. In this investigation steady-state was determined when the total solids inventory in the riser did not show any large fluctuations over time. This criteria for steady-state required longer run times than using solids circulation rate as a criteria. In fact, solids circulation rates reached steady-state conditions well before the solids inventory in the riser did and should not be used to determine steady-state conditions. Typically, simulations required 80-120 seconds of data to be collected using only the final 10-15 seconds in our analysis. Simulations were conducted on high-end dual processor PC's and run times were generally on the order of three-four weeks.

Experimental operating conditions and the pressure drops over a 15 m section of the riser are summarized in Table 1. Experimental data are time averaged over 5 minutes of steady-state operating conditions.

RUN	V_g (m/s)	G_s (kg/s)	ΔP_{Exp} (Pa)	$\Delta P_{FPFOI}(Pa)$
CK2	2.3	0.2035	744	730
CK4	3.2	0.4259	2046	1888
CK7	3.2	0.5655	2618	2412
CK16	4.3	0.7758	2370	2335
CK17	4.3	1.0966	3121	2894

Table 1: Experimental operating conditions and riser pressure drops.

Pressure drops predicted by MFIX using FPFOI are given in last column. Excellent agreement of the incremental pressure drop between intermediate pressure taps was also predicted by FPFOI. Figure 1 gives the pressure drop per unit length ($\Delta P/\Delta L$) along the length of the riser for run CK7. The other runs showed similar quantitative agreement with experiment.

Using CK7 Figure 2 compares the predicted average voidage with the voidage calculated from the equation $\Delta P/\Delta L = (1-\varepsilon_g)\rho_s\vec{g}$. The predicted voidage is time averaged and spatially averaged across the width of the riser. In the upper regions of the riser the voidage calculated from the equation differs from the actual voidage. Similar differences were observed for the other runs also. Until further simulations are completed, it is believed that the discrepancy in the numerical results between the predicted and calculated voidages is due to the two-dimensionality of the simulation and the no-slip boundary conditions. In the numerical simulations a large percentage of the solids are carried beyond the exit and are recirculated back down along the wall opposite of the exit. This pattern is certainly physical for a blind-tee configuration, but without an additional degree of freedom afforded by a third dimension the numerical effect is greatly exaggerated. Because of the solids no-slip

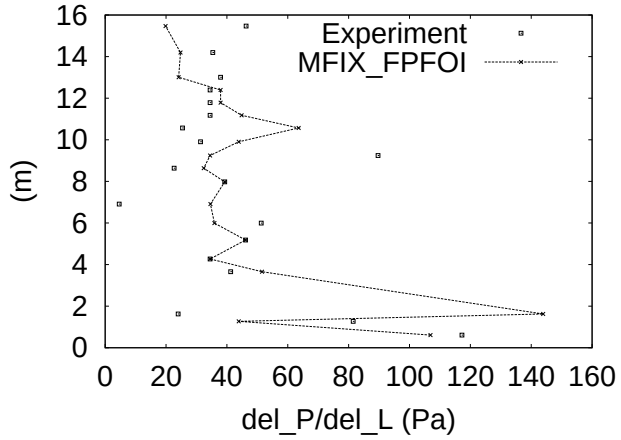

Figure 1: Incremental Pressure Drop For RUN CK7.

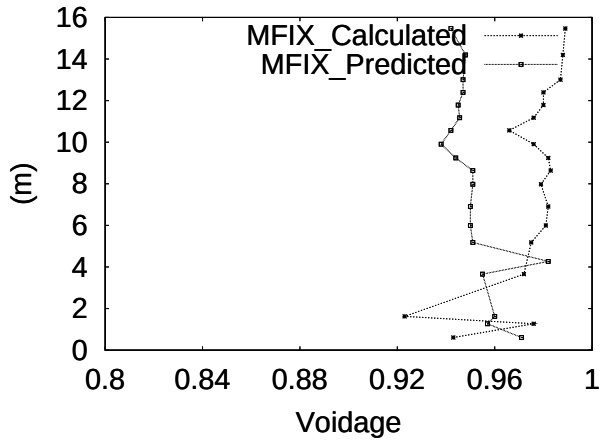

Figure 2: Axial Voidage Profiles For Run CK7.

boundary conditions no work is required by the gas to suspend or accelerate the solids in the cells adjacent to the wall. However, in the numerical prediction of the axial voidage these solids are accounted for. Grid refinement done on smaller scale problems has shown the discrepancies in Figure 2 and observed in the other runs can be minimized. Unfortunately, this approach would result in prohibitively large CPU times for simulations on an industrial scale.

We also compared the FPFOI results with the results of the Superbee limiter. Superbee consistently over predicted the riser inventory and in many cases remained in a bed-filling regime throughout the simulation. Figure 3 compares the total riser inventory for run CK2 between Superbee and FPFOI. Similar discrepancies were observed for runs CK4 and CK7 and Superbee was not used in runs CK16 and CK17. This considerable difference is surprising, and it appears that Superbee predicts a regime change. The results of this study show that the overall pressure

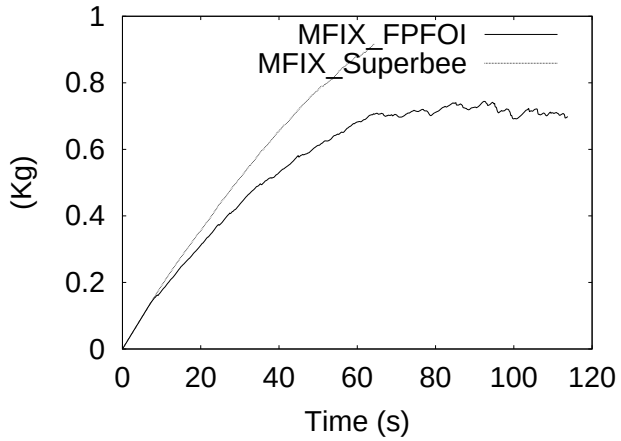

Figure 3: Total Riser Inventory For Run CK2.

drop can be matched and, surprisingly, exceeded as in the case of Superbee. In the simulations previously reported in the literature, the calculated pressure drop is usually less than the experimental value, and to match the experimental data, parameters such as the solids viscosity or the drag are adjusted (see for example, O'Brien and Syamlal 1993). The studies previously reported in the literature are for smaller (100 μm) diameter particles, and the usage of a sufficiently small grid for industrial-scale CFB's is prohibitively expensive. This difficulty has lead to the need for developing subgrid scale models (Agrawal et al. 2001) that will allow the use of coarse grids. For the 1000 μm diameter particles used in this study, it appears that a grid resolution of about ten times the particle-diameter is sufficient to calculate pressure drop values that match experimental data, without adjusting any physical parameters.

5 Conclusion

Using riser inventory to determine steady-state, pressure drops predicted by MFIX using FPFOI showed excellent agreement with experimental data. Results also indicate that no-slip boundary conditions for the solids phase should be replaced with a more physical condition (partial-slip). This investigation has also shown the results of two higher-order methods (Superbee and FPFOI) differ considerably, with Superbee consistently over predicting the riser inventory and pressure drop. Current work is underway to determine the overall effect high order limiters have in gas-solids calculations.

6 Nomenclature

G_s(kg/s)	Solids Circulation Rate
$\vec{f}_m$(kg/m^{2}s^2	Body Force
$\vec{I}_{ml}$(kg/m^{2}s^2)	Gas-Solids Drag
ΔP(Pa)	Differential Pressure Drop
$\bar{\bar{S}}_m$ (Pa)	Stress Tensor
V_g(m/s)	Riser Gas Velocity
$\vec{v}_m$(m/s)	Velocity Vector
ε_m	Voidage

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