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Validation of filtered two-fluid models for gas–particle flows against experimental data from bubbling fluidized bed

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ABSTRACT

Predictions of simulations based on filtered Two-Fluid Models (TFMs) with constitutive relations for filtered fluid–particle drag coefficient and filtered stresses proposed by Igci and Sundaresan [Ind. Eng. Chem. Res. 50 (2011) 13190–13201] and Milioli et al. [AIChE J. 59 (2013) 3265–3275] were compared against experimental data from a bubbling fluidized bed challenge problem put forward by the National Energy Technology Laboratory and Particulate Solids Research Inc. It is found that the most important correction to filtered models is a modification to the drag, and filtered stresses play a secondary role at best. As expected, coarse grid simulations using the kinetic-theory based TFM over-predicted the gas–particle drag force, yielding unphysical bed expansion. The filtered fluid–particle drag model proposed by Igci and Sundaresan that classifies the inhomogeneity in sub-filter scale flow structures using filter size and filtered particle volume fraction as markers also predicted unphysical bed expansion. Refined filtered drag models proposed by Milioli et al. based on filtered fluid–particle slip velocity as an additional marker led to good agreement with experimental data on bed expansion and the time-averaged gas pressure gradient. It was also observed that inadequate grid resolution in the region between gas distributor and the adjacent cylindrical wall of the test unit could lead to spurious asymmetric gas–particle flow predictions. With the inclusion of adequate inflation layer elements in that region, flow predictions became nearly symmetric with little to no effect on bed expansion predictions. However, it dramatically and qualitatively altered the details of gas–particle structures in the bed.

1. Introduction

Gas–particle flows in commercial-scale fluidized beds are characterized by heterogeneous structures ranging from microscale to macroscale. Resolving them in simulations using the kinetic-theory based Two-Fluid Model (TFM) [1,2] is usually expensive due to the requirement of fine grid resolution of the order of a few particle diameters. Based on practical considerations for computing resources and simulation turnaround time, it is often desirable to employ relatively coarse grids in simulations. However, coarse grid simulations using the kinetic-theory based TFM do not account for the effects of microscale structures on macroscopic behavior, and typically over-predict fluid–particle drag force and under-predict particle phase stresses [3–6]. A natural approach is to use filtered TFMs [7–17] where the effects of microscale structures are modeled and macroscale structures are resolved in simulations, with the focus being on probing macroscale gas–particle flow features that are of principal interest in commercial-scale devices.

Filtered TFMs with constitutive relations for filtered fluid–particle drag coefficient and filtered stresses are beginning to appear in the literature [7–17]. Several research groups [8–17] have performed highly resolved simulations of gas–particle flows using the kinetic-theory based TFM and extracted filtered results using filtered particle volume fraction and filter size as markers that classify the inhomogeneity of sub-filter scale flow structures. Based on such approach, Igci and Sundaresan [10] proposed constitutive relations for filtered drag coefficient, particle phase pressure, and shear viscosity. In recent studies [14–17], filtered fluid–particle slip velocity has been identified as an important additional marker for filtered drag coefficient. In addition to these markers, Milioli et al. [17] examined several possible markers and then proposed refined constitutive models, expressing the filtered drag coefficient in terms of filtered particle volume fraction, filter size and filtered slip velocity, and the meso-scale pressure and viscosity of both phases in terms of filtered particle volume fraction, filter size and filtered scalar shear rates.

The objective of the present study is to compare the predictions of simulations based on filtered TFMs with constitutive relations proposed

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by Igci and Sundaresan [10] and Milioli et al. [17] against experimental data from a bubbling fluidized bed challenge problem designed for model validation purposes. This challenge problem, put forth by the National Energy Technology Laboratory (NETL), Morgantown, WV and Particulate Solids Research Inc. (PSRI), Chicago, IL, is particularly attractive for validation of filtered TFMs as adequately-resolved kinetic-theory based TFM simulations of the pilot-scale test unit employed in these experiments would be prohibitively expensive. A schematic of the test unit used to gather experimental data is shown in Fig. 1. It includes a 0.91 m diameter and 7.09 m height fluidized bed section, primary and secondary cyclones and two different types of gas distributors — ring or pipe manifold sparger. Further information on the challenge problem including geometry of the test system, its dimensions, operating conditions and instrumentations can easily be accessed on the NETL website [18].

Table 1
Physical properties of gas and particles.

		Case 1, 2 and 3	Case 4
d	Particle Sauter mean diameter	78.66×10^{-6} m	68.1×10^{-6} m
ρ_s	Particle density	1489 kg/m^3	1489 kg/m^3
ρ_g	Gas density	1.3 kg/m^3	1.3 kg/m^3
μ_g	Gas viscosity	1.8×10^{-5} kg/m s	1.8×10^{-5} kg/m s
e_p	Coefficient of restitution	0.9	0.9
v_t	Terminal settling velocity	0.23 m/s	0.18 m/s
v_t^2/g	Characteristic length	0.0054 m	0.0033 m
v_t/g	Characteristic time	0.0234 s	0.0183 s
$\rho_s v_t^2$	Characteristic stress	78.77 kg/m s^2	48.24 kg/m s^2
$\rho_s v_t$	Characteristic mass flux	342.5 kg/m^{2}s	268 kg/m^2 s

In the NETL–PSRI experiments, fluid catalytic cracking particles with different levels of fines content (3% or 12%) were fluidized using ambient air. The physical properties of air and particles are given in Table 1. Experiments were conducted at four different conditions (listed in Table 2), probing the effects of bed depth (cases 1 and 2) and fines content (cases 3 and 4) on fluidization. It was reported in the Circulating Fluid Bed X conference [19] that defluidized regions or gas bypassing could be observed visually in cases 1 and 3 corresponding to deep bed and lower fines content, respectively. Experimental data were provided in the form of: (a) time-averaged gas pressure gradient profile, (b) mean and standard deviation of differential pressure – across the entire bed as well as across 0.61 m section at mid-point elevation of 2.62 m – at four different equally spaced azimuthal locations, and (c) the lateral bubble void fraction profiles (only for cases 1 and 4).

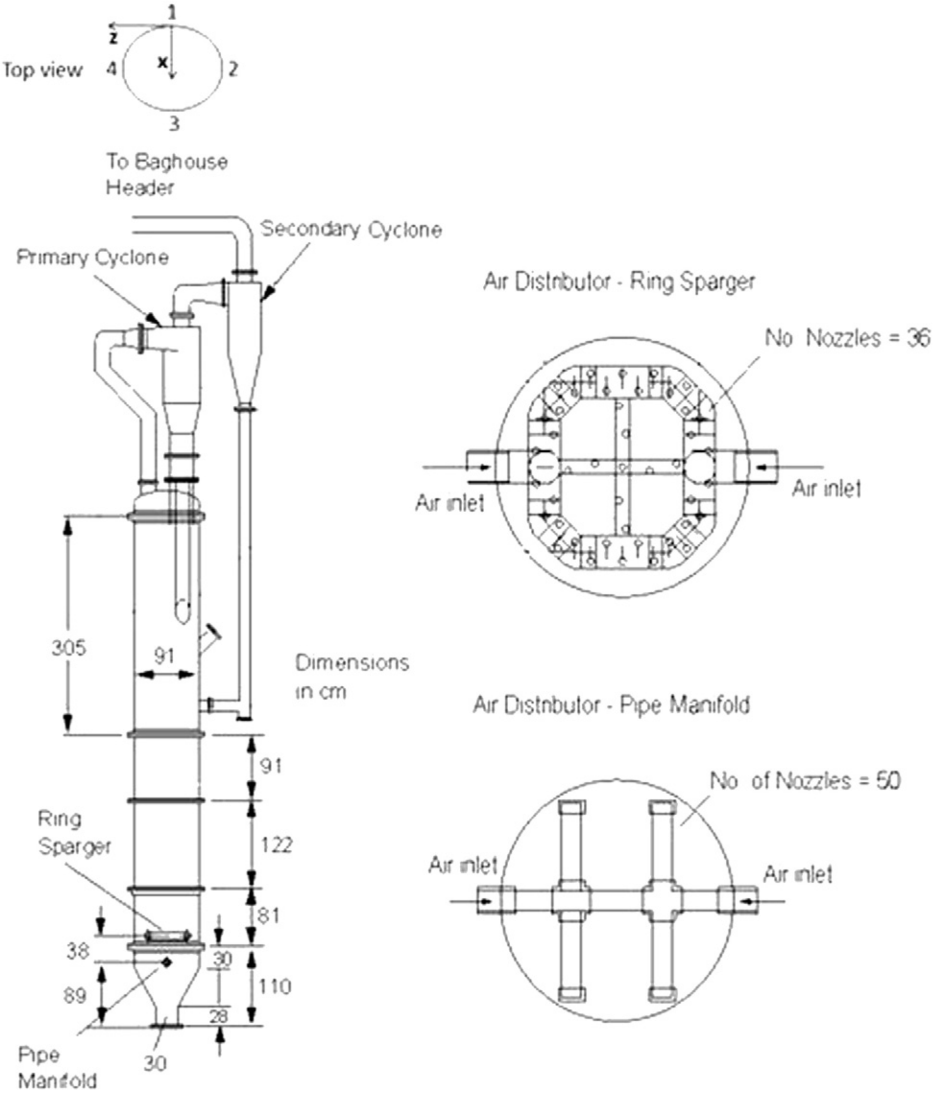

Fig. 1. Schematic drawing of the PSRI test unit. Two different types of gas distributors – Ring Sparger and Pipe Manifold – used in experiments are also shown. Top view shows the four azimuthal locations where the differential pressures were measured. The physical properties of gas and particles are given in Table 1. The experimental flow conditions are summarized in Table 2.