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Investigation on hydrodynamics of gas fluidized bed with bubble size distribution using Energy Minimization Multi Scale (EMMS) mixture model

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ABSTRACT

Modeling of fluidized beds with special focus on mesoscale structures has become prominent area of research in recent years. These efforts have focused on incorporating the effects of bubbles and clusters on the bed hydrodynamics. To account for the effects of these mesoscale bubbles on hydrodynamics of gas fluidized beds, appropriate sub-grid models are required. Energy Minimization Multiscale Modeling (EMMS) is one of the promising approaches available to this end. Present work focuses on development of an EMMS modeling approach where a bubble size distribution has been considered. In this work, bubble based EMMS mixture model developed earlier by same team has been modified. To consider the distribution, user defined values of minimum ($d_{b,min}$) and maximum diameter ($d_{b,max}$) are specified. As a first test case, a uniform bubble size distribution was followed. Due to the distribution, drag force was considered to comprise of contribution from each size group. The mathematical form of the objective function describing the energy for suspension and transport has not been altered. The heterogeneity index (H_d) from this new drag modification is used for simulation of turbulent fluidized beds with particles from Group A and B. It is shown in present work that this current EMMS model is capable of capturing major hydrodynamic features of fluidized beds.

Keywords: EMMS; CFD; turbulent bed; fluidization; multiphase.

INTRODUCTION

Recent years have witnessed significant growth in modeling and simulation of fluidization with specific focus on resolution of mesoscale structures [1, 2]. Depending upon the operating conditions, these mesoscale structures appear either as gas bubbles or particle clusters [3]. Gas bubbles rising through a suspension of solid particles has been a subject of intensive research. Several experimental and modeling efforts have been put to resolve these gas voids or bubbles [4-8].

Accurate modeling and CFD simulations of bubbling fluidized beds has been a challenge [8-10]. Gas–solid flows, such as in bubbling fluidized beds, show a range of spatial-temporal structures, which results in heterogeneity. Accurate modeling of these mesoscale bubbles is key to predicting accurate hydrodynamics of bubbling and turbulent fluidized beds. Energy minimization multiscale (EMMS) modeling has proved to be a promising approach in recent years for modeling of these mesoscale bubbles [11]. This and other related works have incorporated solid particle clusters for prediction of hydrodynamics in high velocity fluidized beds such as risers. In order to model the effects of gas bubbles on the hydrodynamics of bubbling fluidized beds, the original cluster based EMMS model was extended to bubbling regime [12]. In a recent attempt, an EMMS model was developed to account for gas bubbles for high velocity fluidization generally called turbulent fluidization [13, 14]. It was shown in these works that the model was able to capture the hydrodynamics of the so called turbulent fluidized beds of both Group A and B particles reasonably well. One limitation of most of these bubble-based models is that suitable empirical or theoretical closures for estimation of bubble diameter and the energy required for suspension and transport have to be supplied. These bubble-based models have used a typical correlation for predicting the bubble diameter. In a recent effort towards improving the EMMS model, a new stability condition was proposed [15]. To account for the particle size distribution, an EMMS model for binary gas-solid flows in a riser has been proposed in recent past [16]. In reality, in bubbling and turbulent fluidized beds, wide range of bubble diameters exist. Although progress has been made, still work needs to be done to account for the coexistence of a range of bubble diameters for specific operating conditions. The novelty of current work is to address the effects of bubble size distribution with reference to the drag force in fluidized bed hydrodynamics. In the next section, the general framework followed for development of present EMMS mixture model is presented. Then the output of this EMMS mixture model is applied to simulate the hydrodynamics of turbulent fluidized beds. This is the first time that turbulent fluidized beds have been simulated with inclusion of bubble based EMMS model accounting for size distribution of gas bubbles. Results are compared to available experimental data. The paper concludes with emphasis on future work.

EMMS MIXTURE MODEL BASED ON BUBBLE DESCRIPTION

Detailed formulation of EMMS mixture model has been presented in our previous efforts [13,14]. We, therefore, will not present the model equations to avoid repetition. Figure 1 presents general algorithm for calculation of the drag modification using the current EMMS scheme. For any EMMS formulation based on bubble description, an input of bubble diameter is required. Almost all of the past bubble based EMMS efforts have used correlation derived by [17] for calculation of equilibrium mesoscale structure diameter. However, here we consider that instead of a single bubble diameter, a range of sizes coexist. This range can be divided into several classes varying from minimum ($d_{b,min}$) to maximum ($d_{b,max}$). Mesoscale drag is calculated for each of the classes and a cumulative effect is used to calculated interphase slip velocity. Rest of the procedure of calculation of drag reduction and other operating parameters is essentially the same.

The maximum bubble diameter still remains to be specified. It is accepted that in gas-solid flows, Geldart Group A and B type particles exhibit type I and type II transitions from bubbling to turbulent regimes, respectively [18]. The maximum stable bubble diameter for type I is generally $0.7D_t$. However, for type II this value is greater than $0.7D_t$. In order to keep the process simple, a value of $0.7D_t$ was used for both Geldart groups in present work. Another significant factor that will have effect on the hydrodynamics is how the bubbles sizes are distributed in the bed. It has been mentioned in literature that bubble size distribution at any given height can be described by different choices of distribution functions [19]. However, for present work it has been assumed that all these bubbles are uniformly distributed. Therefore, all the classes will contribute equally to the drag force.

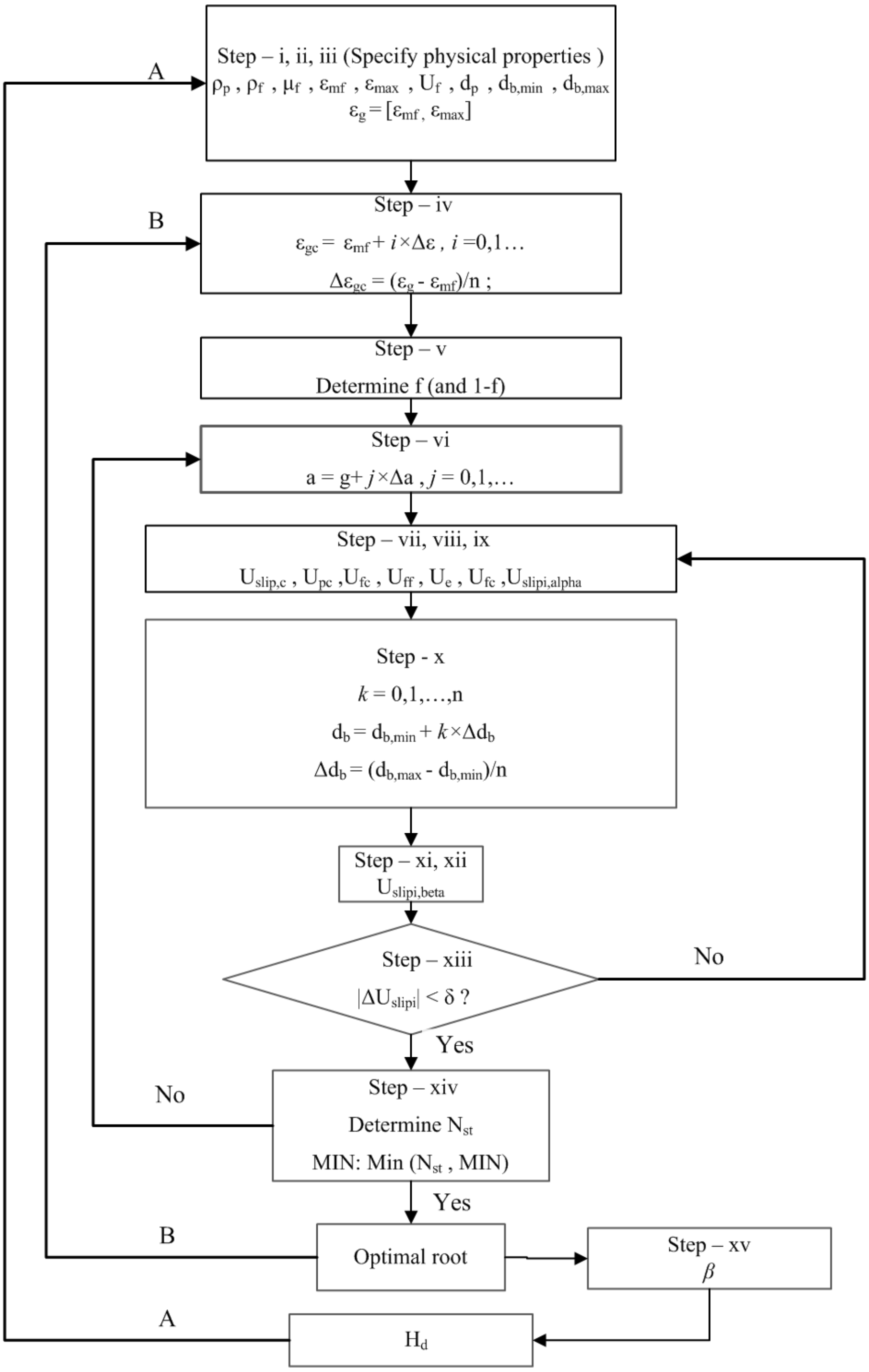

Figure 1. Stepwise scheme for calculation of drag modification with EMMS mixture model

CFD SIMULATION OF TURBULENT FLUIDIZED BEDS

Having obtained the drag correction by incorporating the mesoscale structure, we now perform the CFD simulation of turbulent fluidized beds using the modified drag. The fluidized beds used in current work are the ones presented in our previous work. The reader is informed that the grid independence of these two beds was carried out in our previous work [14]. The simulation settings for Group A system in Table 1 were obtained from the work of [20]. The source of experimental data for system particles from Group B is Gao et al. from Zhejiang University (China) [21]. It was, therefore, assumed here that grid had negligible role to play in the final profiles. Table 1 presents the operating and geometric details of these two beds.

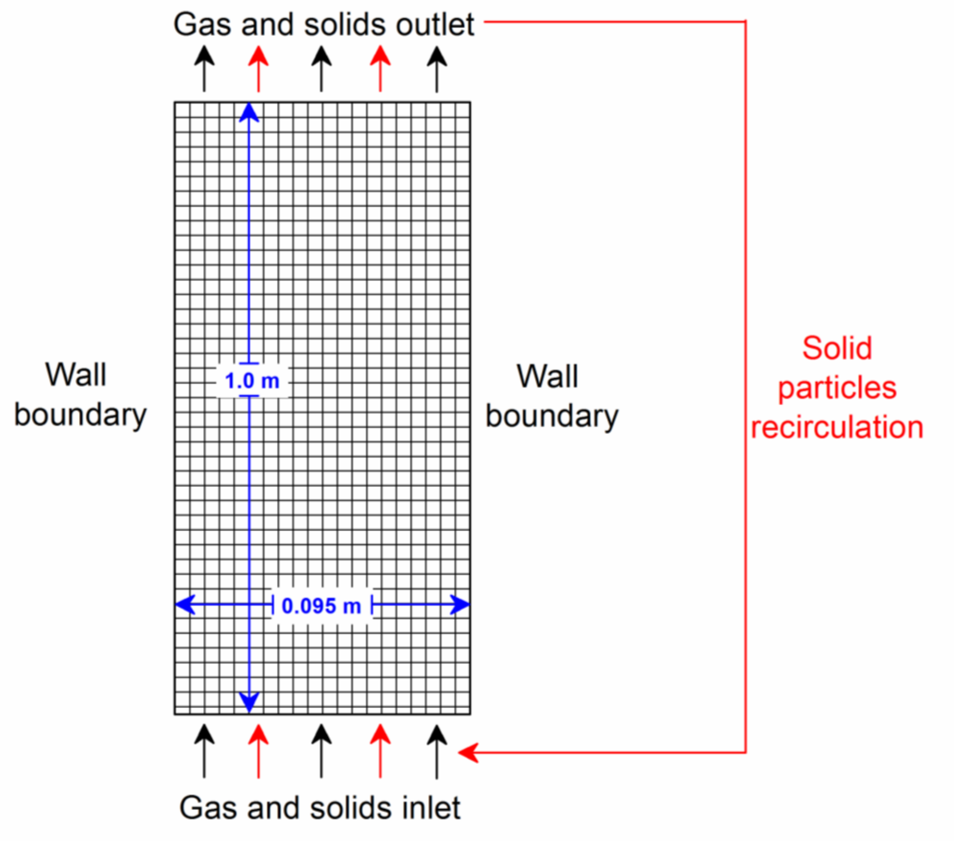

Figure 2 Geometry and boundary conditions used for Group B system [14].

It is to be noted that the 2D bed for Group A 0.5 m × 4 m and for Group B is 0.095 × 1 m. Schematic drawing of this setup is presented in Figure 2. This figure is for the Group B system. Group A setup is similar except the dimensions are changed according to Table 1 is for both the simulation inlets were prescribe as "velocity inlets" while outlets were designated as "pressure outlets". Furthermore, the viscous model used in current work is laminar. All simulations were carried out using the finite volume scheme available in ANSYS Fluent®. The mesh used was composed of two dimensional rectangular cells.

RESULTS AND DISCUSSION

Figure 3 shows the grid independence performed for the simulation of fluidized bed comprising of Group-A particles. Three different grid sizes were tested with the current model. The results were compared with the experimental data in terms of bed density i.e. ($(1-\varepsilon_g)\rho_g + \varepsilon_g\rho_g$). It is clear that the two fine grids i.e. 100 × 194 and 200 × 420 produce similar results. For further comparisons, a grid of 100 × 194 is considered.

Figure 4 (a) shows the instantaneous solids fraction in the column for the case of EMMS model (Model E). The pockets of gas bubbles are clearly visible. It is also clear that they vary in size. Figure 4 (b) shows the axial solid concentration profile for homogeneous drag model i.e. Model G (i.e. Gidaspow) and present model i.e. Model E. It is clearly seen that the Model G has not been able to capture the characteristic dense bottom dilute top zone of the bed. On the other hand, the predictions of Model E are in good agreement with experiments due to effective drag modification. The incorporation of bubble size distribution in present effort has improved the simulation accuracy in the bottom dense of the bed. Furthermore, it can be seen in Figure 4 that for Group A fluidized bed, the EMMS model is capable of predicting the bed density in good agreement with experimental data in the bottom and top regions. A deviation of about 10% exists. However, in the transition region, the difference between the simulation and experiment is around is around 30%. One of the major reason of this deviation of the simulation results from experimental is that the drag model in this work is based on bubbles rising through a dense suspension. The top dilute model can be better modeled by including the cluster description of mesoscale structures. It will be very interesting if a switching between bubble based and cluster-based model is developed and incorporated to include both the effects of bubbles as well as clusters. This will be particularly helpful in accurate simulation of intermediate region. Figure 4 (c) shows the time averaged solids concentration in the bed for the case of Model E. The dense region along the wall of the bed is clear indication of core-annular type structure which is a characteristic of typical high velocity fluidization regime.

Table 1. Parameters for CFD simulation

Parameter	Group A Particles	Group B Particles
Bed diameter	0.5 m	0.095 m
Bed height	4 m	1 m
Gas density	1.225 kg/m^3	
Gas viscosity	1.789x10^{-5} kg/(m.s)	
Particle diameter	60 µm	139 µm
Particle density	2400 kg/m^3	2400 kg/m^3
Initial bed height	1 m	0.204 m
Inlet gas velocity	0.5 m/s	1.25 m/s
Grid density	100 × 194	40 × 250
Maximum packing limit	0.63	
Restitution coefficient	0.5	0.9, 0.5
Inlet boundary condition	Velocity inlet	
Outlet boundary condition	Atmospheric pressure	
Wall boundary condition for gas phase	No slip	
Wall boundary condition for solid phase	Partial slip (specularity coefficient = 10^{-4})	
Time step	5 × 10^{-4} s	
Convergence criterion	10^{-3}	

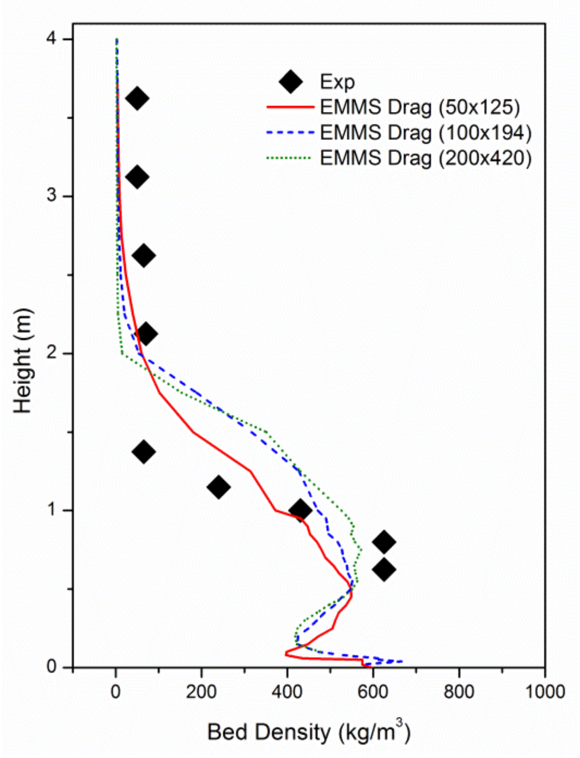

Figure 3 Predictions of bed density for different grid sizes for turbulent fluidized bed of Group A particles [14].

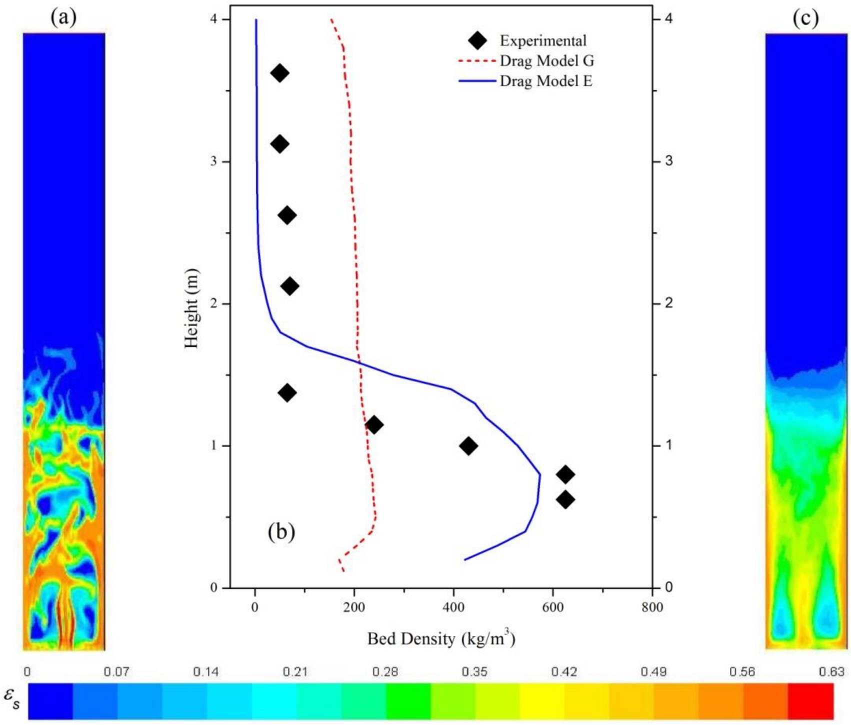

Figure 4. Results of CFD simulation for system with particles from Group-A

Figure 5 shows the grid independence test for turbulent fluidized bed with Group-B particles. The prediction of axial voidage profile as a function of grid number shows that the very coarse grid of 20 × 200 predicts the experimental data much different than the other three grids. Based on these predictions, the grid with 40 × 250 number was chosen for detailed comparison of further results.

Figure 6 (a) presents the axial profile of gas void fraction for system having particles from Group-B. The comparison of both homogeneous drag model (Model G i.e. Gidaspow) and heterogeneous drag model (Model E) are compared with available experimental data [22]. For same grid resolution, Model G predicts dilute bed in the bottom zone and dense bed in the top zone as compared to Model E. Although Model E has qualitatively captured the dense bottom and dilute top profile in the bed, still relatively disparity between the model predictions and experiments exists. One of the possible reason for this difference between experiments and simulation can be that in the present EMMS model the size distribution of the bubbles has been considered to be uniform. This assumption may not be true in practical situations where sizes may not be uniformly distributed. Secondly, some minor changes are also expected to come in due to tuning of other simulation parameters. One such fact is a restitution coefficient which shows the ratio of particle velocities after and before the collision. Coefficient of restitution can have significant effect on bed hydrodynamics, especially in dense beds [23].

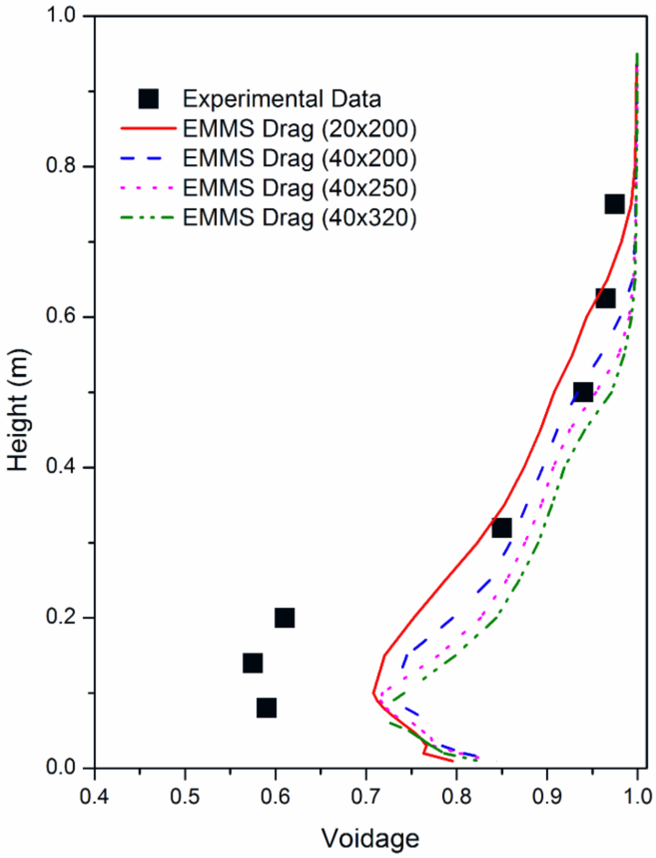

Figure 5 Predictions of bed voidage for different grid sizes for turbulent fluidized bed with Group B particles [14]

Figures 6 (b) and (c) present the radial profile of solids volume fraction (ε_s) at two different axial locations. It is clearly seen that results of Model G are not very close to the experimental data points. On the other hand, model predicts radial profile in good agreement with the experimental data. Figure 6 also shows results for Model E with two different values of restitution coefficient i.e. e_s. It can be observed that at both the restitution coefficients the middle region of the column i.e. up to 25% on either side of the centre line, predict similar results in good agreement with the experimental data. The difference between the experimental data and simulation results become significant in the near wall region i.e. between *r/R* values of ±(0.75-1.0). It is interesting to note that lowering the restitution coefficient from 0.9 to 0.5 brings the simulated profile in close agreement with the experimental data. One other reason for the disparity between the simulation and experiments is, as pointed previously, that the current EMMS model is based on bubbling phenomenon. It is known that particle clusters descend in the near wall region. It would, therefore, be realistic to develop an EMMS framework which incorporates both bubbling and clustering with suitable switching between the two mechanisms. Apart from this, it is also important to note that the modified drag correction is also a function of slip velocity between the fluid and solid particles [2]. In present work, the drag modification was considered only a function of voidage. However, for further quantitative comparisons, effect of slip velocity also needs to be included.

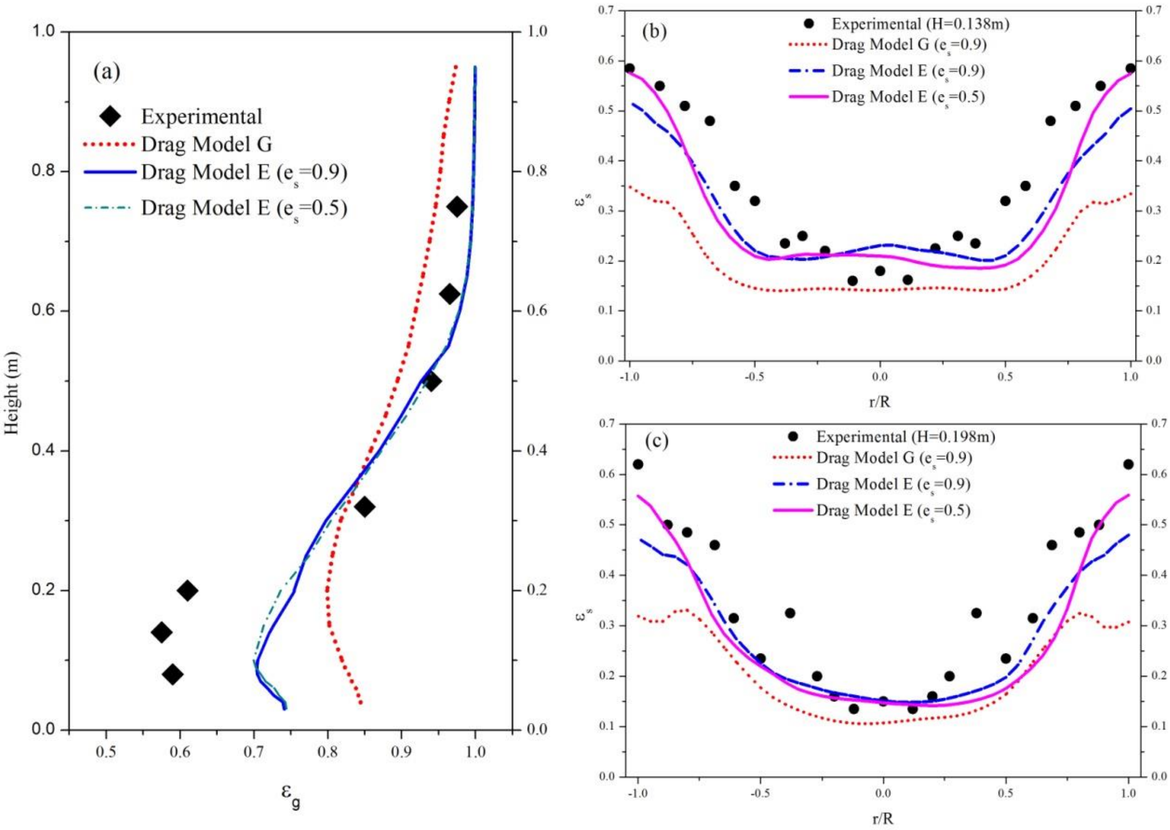

Figure 6. Axial and radial profiles of CFD simulation of Group-B turbulent fluidized bed

CONCLUSIONS

In the present paper, we presented further development of our EMMS model based on mixture description of the suspension and bubbles. Here, instead of an equivalent bubble diameter, a range of bubble diameters was considered to be present. Thus, for a given concentration the bed heterogeneity was supposed to be composed of different bubble sizes. It has been shown that using this methodology, qualitatively correct hydrodynamics of turbulent fluidized beds can be captured. It was the aim of present work to keep the process simple and focus on developing the method. Now that it has been shown that present model is capable of capturing major hydrodynamic features of fluidized beds, more work needs to be done to expand and validate the model with rigorous testing. In this context, effect of particle clusters also need to be incorporated. Effects of wall boundary conditions, particle-particle interaction also need to be assessed in detail. The drag modification needs to be extended with the inclusion of effect of slip velocity.

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