GRANULAR MULTIPHASE CFD MODEL FOR FLUIDIZED BEDS: EFFECT OF DRAG MODEL

Bhargav M.M.S.R.S[1], Teja Reddy Vakamalla[2*], Narasimha Mangadoddy[3]

[1]*Department of Mechanical Engineering, Amrita Vishwa Vidyapeetham, Coimbatore, India – 641112*
[2]*Department of Chemical Engineering, Pandit Deendayal Petroleum University, Gandhinagar, India - 382007*
[3]*Department of Chemical Engineering, Indian Institute of Technology Hyderabad, Telangana, India – 502285*

*Email: teja.reddy@sot.pdpu.ac.in

Abstract – Gas-solid fluidized beds are widely used in many industrial operations. The study of flow hydrodynamics is very essential while designing a gas-solid fluidized bed reactor. In densely packed beds, interphase momentum transfer coefficient plays a vital role in characterizing the fluidized bed dynamic behaviour. In gas-solid flows, drag force is critical to model the interphase momentum transfer. The motivation of this paper is to study the effect of drag on the flow properties of bubbling and turbulent fluidized beds using Computational Fluid Dynamics (CFD). Eulerian two fluid model using Kinetic Theory of Granular Flow (KTGF) options coupled with suitable drag models such as Gidaspow, Syamlal O'Brien, Beetstra, Brucato, Simon, EMMS and Tenneti drag correlations are employed for this purpose. CFD predicted results are validated against experiments in terms of bubble diameter, axial, radial variation of solids volume fraction and bed expansion ratio. In case of bubbling fluidization with central gas jet; Brucato, Beetstra and Simon drag models are closely predicted the experimental solids volume fraction and bubble diameter. For turbulent fluidization; Brucato and EMMS drag models are predicting close void fraction values against experimental measurements. Critical assessment of suitable drag model has been made in detailed manner.

INTRODUCTION

In a fluidized bed, the pressurized air is injected through a packed bed of particles. The particles reach a minimum fluidization condition, when the drag force balances the weight, thus the solid bed starting to behave like fluid. This phenomenon is commonly known as fluidization. Based on superficial gas velocity, different flow regimes of fluidization occur. They are fixed bed, bubbling, slug, turbulent and pneumatic transport. Because of its main advantages such as uniform particle mixing, uniform temperature gradients and continuous operating system, the fluidized bed reactors are widely used in drying, coating and granulation. The usage of fluidization can also be seen in catalytic cracking of petroleum industry, combustion, gasification, various metallurgical and chemical processes. The study of flow hydrodynamics is very essential while designing a gas-solid fluidized bed reactor. Gas-solid flows are very dynamic in nature and hence it is a challenging task to measure the flow hydrodynamics accurately. Over the years, a number of experimental and computational studies have been undertaken to understand the qualitative and quantitative flow dynamic behaviour of the fluidized beds (Gidaspow, 1994; Gidaspow, et al., 1983; Li, et al., 1994; Liu, et al., 2003; Syamlal, et al., 1994).

Experiments being cumbersome and expensive, CFD is already proved as a promising tool for predicting the appropriate flow dynamics (Beetstra, 2005; Gujjula, et al., 2015; Hong, et al., 2012; Passalacqua, et al., 2009; Taghipour, et al., 2005). Eulerian-Eulerian and Eulerian-Lagrangian multiphase models are commonly used multiphase models for numerical predictions. In Eulerian-Lagrangian multiphase model, the continuous phase is modeled using Eulerian frame of reference and discrete particles are modeled using Lagrangian frame of reference. In Eulerian-Eulerian multiphase model, both the continuous and discrete particle phases are modeled in Eulerian frame of reference. Because of its limitation of the total number of particles used in the discrete particle model simulation, several researchers have worked using two fluid model, where the gas and solid flows are statistically averaged and described as an interpenetrating continua. The solid phase properties are described using kinetic theory of granular flow (Gidaspow, 1994). Conditional averaging is applied to arrive at two fluid equations from instantaneous local equations. Due to averaging, mass and momentum equations contain extra terms that account for interphase momentum transfer and turbulent velocity fluctuations. Interphase momentum transfer is modelled using drag force. Drag force is the primary coupling force between the gas phase and the solid phase. Hence Drag force is an important factor which characterizes the interaction between the phases. Several correlations are developed to quantify drag coefficient and identifying the appropriate drag model is crucial for accurate flow dynamics of a given fluidization process. A brief literature review on the drag model effect by different researchers is provided below.

Table 1: Literature Review

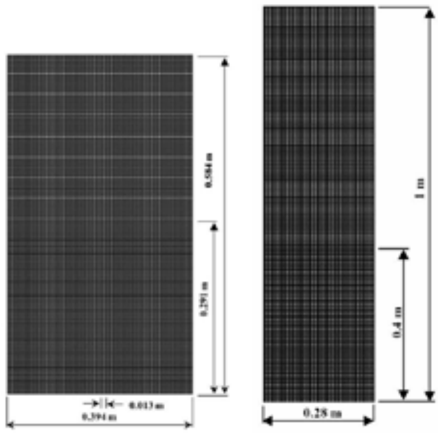
Authors	CFD model and Fluidization type	Remarks
Yang et al., (2003)	Eulerian-Eulerian, k-ε, EMMS and Wen-Yu. Circulating fluidized bed	Better volume fraction predictions were associated with EMMS over Wen and Yu/Ergun drag models compared to experimental results.
Taghipour et al., (2005)	Eulerian-Eulerian, k-ε, Gidaspow, Syamlal-O'Brien and Wen and Yu. Turbulent fluidization	Reasonable prediction of experimental pressure drop across the bed, instantaneous and time averaged solid concentration by all the drag models.
Lundberg et al., (2008)	Eulerian-Eulerian, k-ε, Gidaspow, Syamlal-O 'Brien, Hill-Koch-Ladd, Richardson Zaki and RUC. Bubbling fluidization	RUC and Hill-Koch-Ladd models predicted the highest drag. RUC, Hill-Koch-Ladd and Gidaspow well predicted the experimental results.
Shah et al., (2011)	Eulerian-Eulerian, k-ε, EMMS and Gidaspow. Turbulent fluidization	EMMS predictions were deviated well at the height where low to high solid concentration transition occurred. Gidaspow and EMMS well predicted the qualitative behaviour.
Benzarti et al., (2012)	Eulerian-Eulerian, Laminar model, Gidaspow, Syamlal-O'Brien and EMMS. Bubbling fluidization	Syamlal and Gidaspow drag models over predicted the drag force and estimated a greater bed expansion compared to that of EMMS model.
Shah et al., (2015)	Eulerian-Eulerian, Laminar model, Ergun/ Wen and Yu, Space averaged, Macroscopic and EMMS. Circulating fluidized bed	Sub grid models predicted better volume fractions compared to Ergun/Wen-Yu. Downward and upward velocities were predicted qualitatively. A correction was formulated for drag force for coarse meshes.
Armellini et al., (2015)	Eulerian-Eulerian, k-ω, Gidaspow, Syamlal-O'Brien, EMMS and Four zone model, Circulating fluidized bed	EMMS and four zone model predicted well in highest solid concentration region. Correction for drag models based on clustering was emphasized.
Bakshi et al., (2015)	Eulerian-Eulerian, k-ω, Gidaspow and Syamlal-O'Brien. bubbling fluidization	Effect of specularity coefficient in the range 0.01 and 0.3 is investigated. Gidaspow drag model predicted well in homogeneous system while Syamlal-O'Brien determined well for higher gas velocities.
Askaripour et al., (2015)	Eulerian-Eulerian, k-ω, Gidaspow, Syamlal-O 'Brien, Hill-Koch-Ladd and Wen- Yu. Bubbling fluidization	Wen-Yu made better predictions of experimental results when compared to Gidaspow and Syamlal-O'Brien.

SCOPE OF WORK

From the literature it is observed that, Most of the CFD studies are conducted with conventional and homogeneous drag models such as Gidaspow (1994) and Syamlal O'Brein et al., (1994). However in fluidization process, the system is heterogeneous and there is formation of clusters which results in drag reduction. Hence it is essential to study drag models that account for the heterogeneity of the flow. In the recent years, several new drag models have been formulated based on the Lattice Boltzmann methods, the heterogeneous structures (by considering clustering phenomena) and the superficial fluid turbulence. A comprehensive comparison of the above mentioned heterogeneous drag models are made in the current study. The heterogeneous drag models considered for the present study other than Gidaspow (1994) and Syamlal et al., (1994) drag models are: Beetstra (2005), Simon et al., (2015), Tenneti et al., (2011), EMMS (Hong et al., 2012) and Brucato et al., (1998). These drag models are engaged for bubbling fluidization with central gas jet and turbulent fluidization conditions. The motivation of the present work is to characterize the hydrodynamics and evaluate the effect of different drag models on the fluidization behaviour. The numerical predictions are validated against the experimental results of Gidaspow et al., (1983) for bubbling fluidization with central gas jet and Taghipour et al., (2005) for freely bubbling/turbulent fluidization. The ultimate aim of this work is to determine an appropriate drag model for a flow specific regime.

METHODOLOGY

The methodology used here is similar to (Gujjula, et al., 2015). Eulerian-Eulerian multiphase model coupled with laminar and k-ε turbulence model along with seven different drag models (Gidaspow (1994) and Syamlal et al., (1994), Beetstra (2005), Simon et al., (2015), Tenneti et al., (2011), EMMS (Hong et al., 2012) and Brucato et al., (1998)) are utilized for this purpose. The 2D meshes used for bubbling fluidized bed with central gas jet (31k) and uniformly fed turbulent fluidized bed (30k) along with dimensions are displayed in Fig. 1 after the through grid dependence test. Pressure outlet boundary condition is specified at the top. No slip boundary condition is used at the walls for the gas phase. Partial slip condition is specified for the solids at the wall. Pressure and velocity are coupled by Phase Coupled SIMPLE scheme. All the drag models are implemented in Fluent through User Defined Functions (UDF). A maximum of 20 iterations per time step is used and the residual is specified to be 0.0001 for the convergence criteria. From the literature, it is found that the specularity coefficient has significant influence on the flow field. Hence, specularity coefficient is employed based on (Passalacqua, et al., 2009) and (Taghipour, et al., 2005) for bubbling with central jet and freely bubbling fluidization respectively. The parameters used for the CFD simulations of both the fluidized beds are provided in Table 2. The simulations are performed with ANSYS's Fluent 14.5.



(a) (b)

Fig. 1 Meshes used for (a) bubbling fluidized bed with central gas jet and (b) uniformly fed turbulent fluidized bed.

Table 2: Parameters used for the CFD simulation studies

Variable	Bubbling fluidized bed	Turbulent fluidized bed
Superficial gas jet velocity, m s^{-1}	3.55	0.38, 0.46
Particle diameter, μm	500	275
Particle density, kg m^{-3}	2610	2500
Angle of internal friction, °	28	28°
Time step, second	10^{-5}	10^{-3}
Simulation time, seconds	1	55
Restitution Coefficient	0.9	0.9
Specularity coefficient	0.6	0.6
Coefficient of lift	0.25	0.25
Turbulence model	Laminar	k-ε

RESULTS AND DISCUSSION

BUBBLING FLUIDIZED BED WITH CENTRAL GAS JET

A gas jet is introduced through the small orifice with a superficial velocity of 3.55 m/s. While the remaining bottom portion is fed with a minimum fluidization velocity of 0.28 m/s. The qualitative prediction of complete phenomenon of the gas bubble for a total time of one second by Beetstra drag model is qualitatively shown in Fig.2. The gas injected through the packed bed results in the formation of a bubble as shown in the Fig. 2 (at 0.1 seconds). The gas bubble size increases and apparently detaches from the orifice inlet at 0.2 seconds. Once the bubble is detached, it starts to rise through the bed of solids. An expansion in the bubble size diameter can be observed while moving upward. The maximum bubble size can be equivalent to the column diameter (can be seen at 0.7 seconds). The bubble rises till the maximum bed height position and then deforms. Following the larger bubble several small bubbles are formed because of local turbulence. Formation of small bubbles can be observed since from 0.3 seconds.

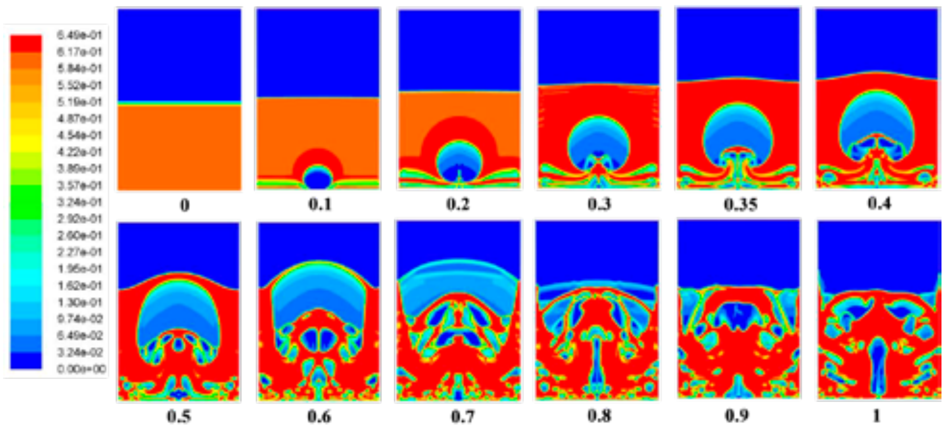


Fig.2: Evolution of bubble with time (seconds) by central gas jet in bubbling fluidized bed predicted by Beetstra drag model.

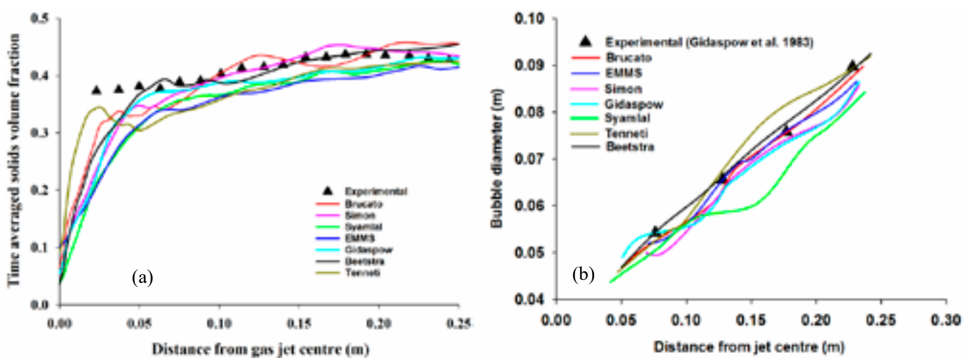


Fig. 3: CFD predicted (a) time averaged solids volume fraction (b) bubble diameter along the axial direction from jet centre in bubbling fluidized bed.

Fig. 3 (a) displays the validation of CFD predicted mean (time averaged) solids fraction results by different drag model based formulations against experimental measurements (Gidaspow et al., 1983). It can be observed that Beetstra, Brucato and Simon drag model are closely predicting the experimental solids volume fraction along the axial positions. Beetstra and Tenneti drag formulations which are developed from the Lattice Boltzmann

Methods (LBM) studies utilized only single relaxation collision operator. This introduces a viscosity dependent error in the boundary placement. Since, Simon drag model employs a two relaxation time lattice Boltzmann code, which accounts for the viscosity dependent boundary placement. This might be a reason for Simon drag model giving reliable results in case of bubbling fluidized with a central jet. On the other hand, Brucato drag model is developed based on experiments performed using solid-liquid flows in turbulent regime. Hence Brucato is able to well predict the homogeneous gas-solid flows in even in the laminar region. Fig. 3 (b) shows the validation of the bubble diameter with axial height. The bubble diameter predicted by Tenneti drag model is higher compared to the experimental measurements after the 0.15 m axial position. Very close bubble diameter is predicted by Beetstra drag model. Brucato, Simon, EMMS and Gidaspow drag models are closely predicting the bubble diameter while Syamlal is completely under predicting the experimental bubble diameter. An average error of less than 10% is observed with Brucato, Simon and EMMS drag models when compared with experimental measurements.

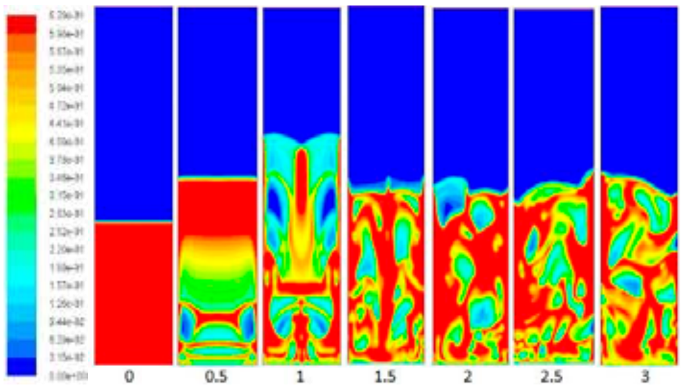


Fig.4: variation of CFD predicted solids volume fraction profiles at different time in turbulent fluidized bed *(U* = 0.38 m/s, drag function: Brucato).

FREELY BUBBLING/TURBULENT FLUIDIZED BED

In this case, superficial gas velocity of 0.38 m/s is uniformly fed through the rectangular column. This results in the spontaneous formation of tiny bubbles at the bottom of the bed. The bubbles rise and coalesce resulting in formation of larger bubbles. Due to larger diameter, bubbles rise faster resulting in increased bed height. The larger bubbles finally break at the free surface of the bed. In this way, continuous formation, coalition and breakage of bubbles occur. The contours of solids volume faction for the first three seconds of the fluidization by Brucato drag model is displayed in Fig. 4. In this case of freely bubbling fluidization, the hydrodynamics is characterized by heterogeneity which can be clearly observed from the same figure. Fig. 5 (a) shows the CFD predicted time averaged solid fraction contours by different drag models compared against the experimental measurements. The time averaging is done for 20 seconds from 5 to 25 seconds. The quantitative comparison of CFD predicted void fractions by different drag models against experimental data (Taghipour et al., 2005) is displayed in Fig. 5 (b). From the experimental results, it can be observed that the radial solids volume fraction data shows asymmetry. Brucato, EMMS and Syamlal O'Brein drag models closely predicted the experimental data over the remaining drag models. Since Brucato drag model is developed based on the fluid turbulence, this model is expected to produce accurate predictions in the turbulent fluidization zone. While EMMS drag model takes into account of the heterogeneity and hence gives reasonable predictions. Further, the simulations are continued with Brucato, EMMS and Syamlal O'Brein drag models with an inlet velocity of 0.46 m/s. Corresponding results are displayed in Fig 5 (c). At this velocity, Brucato drag model predicts the mean void fraction very closely against experimental data. EMMS and Syamlal O'Brein drag models are completely over predicted the data. This graph reaffirms that Brucato drag model well predicts the experimental data in the turbulence dominated freely bubbling fluidization.

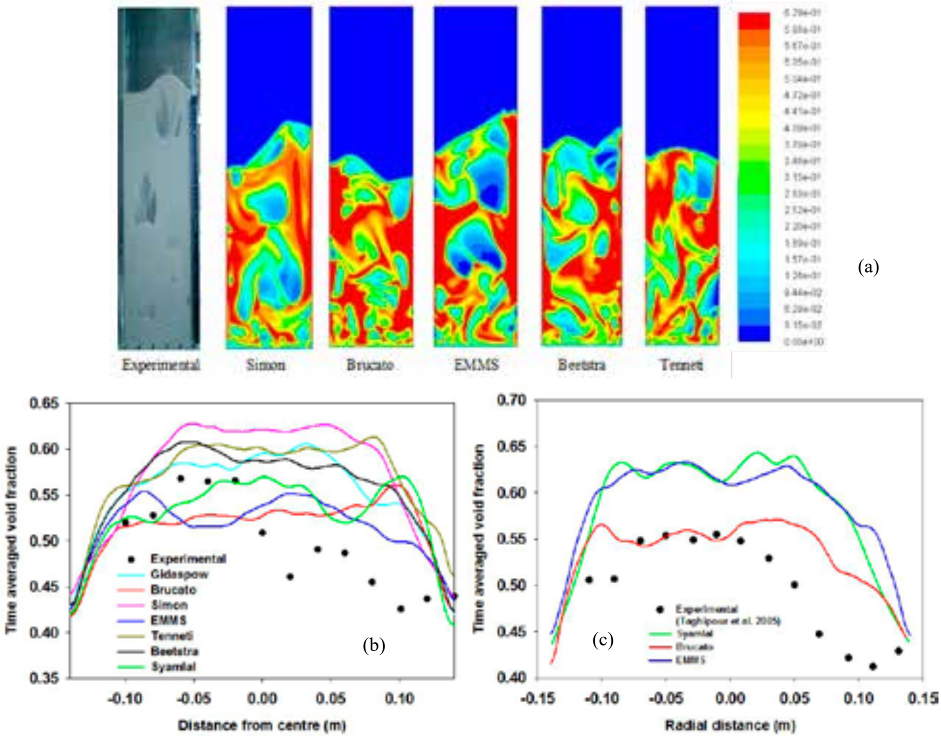


Fig.5: Comparison of CFD predicted (a) mean solids volume fraction contours and (b) time averaged mean void fractions along the radial direction at an axial height of 0.2 m, velocity of 0.38 m/s in a uniformly fed freely bubbling fluidized bed for different drag models.

CONCLUSION

In this work, simulations are performed with Eulerian-Eulerian multiphase model coupled with laminar and k-ε turbulence models. Interphase momentum transfer coefficient being modeled with seven different drag models (Gidaspow, Syamlal O'Brein, Beetstra, Brucato, Simon, Tenneti and EMMS) in two different fluidization regimes (Bubbling and turbulent). The numerically predicted mean solids volume fraction, bubble diameter and mean void fraction are validated against Gidaspow et al., (1983) experimental data in case of bubbling fluidization with central jet and Taghipour et al., (2005) experimental data in case of turbulent/freely bubbling fluidization. Beetstra and EMMS drag models which are based on the heterogeneity (clustering phenomena) is closely predicting the mean solids volume fraction and bubble diameter in bubbling fluidization. Whereas, Brucato drag model showing superiority over the remaining drag model predictions in the turbulent fluidization. Since the Brucato drag model developed from the fluid turbulence this can be expected. In all cases, the conventional Gidaspow and Syamlal O'Brein drag model predictions are deviated from the experimental measurements.

REFERENCES

Armellini, V., Marco D. C., Helver C. A., Jose L. G., Milton M., Waldir P. M. 2015. Effect of different gas-solid drag models in a high-flux circulating fluidized bed riser. Chemical Engineering Transactions 43, 1627-1632.

Askaripour, H., & Molaei Dehkordi, A. 2015. Simulation of 3D freely bubbling gas–solid fluidized beds using various drag models: TFM approach. Chemical Engineering Research and Design 100, 377-390.

Bakshi, A., Altantzis, C., Bates, R. B., & Ghoniem, A. F. 2015. Eulerian–Eulerian simulation of dense solid–gas cylindrical fluidized beds: Impact of wall boundary condition and drag model on fluidization. Powder Technology 277, 47-62.

Beetstra, R. 2005. Drag force in random arrays of mono- and bidisperse spheres.

Benzarti, S., Mhiri, H., & Bournot, H. 2012. Drag models for simulation gas-solid flow in the bubbling fluidized bed of FCC particles. World Academy of Science, Engineering and Technology 61, 1138-1143.

Brucato, A., Grisafi, F., & Montante, G. 1998. Particle drag coefficients in turbulent fluids. Chemical Engineering Science 53, 20.

Gidaspow, D. 1994. Multiphase flow and fluidizationdization : Continuum and kinetic theory description. In: New York : Academic Press.

Gidaspow, D., Lin, C., & Seo, Y. C. 1983. Fluidization in two-dimensional beds with a jet. 1. Experimental porosity distributions. Industrial & Engineering Chemistry Fundamentals 22, 187-193.

Gujjula, R., & Mangadoddy, N. 2015. Hydrodynamic Study of Gas-Solid Internally Circulating Fluidized Bed Using Multi-Phase CFD Model. Particulate Science and Technology, null-null.

Hong, K., Wang, W., Zhou, Q., Wang, J., & Li, J. 2012. An EMMS-based multi-fluid model (EFM) for heterogeneous gas–solid riser flows: Part I. Formulation of structure-dependent conservation equations. Chemical Engineering Science 75, 376-389.

Li, J., & Kwauk, M. 1994. Particle-fluid two-phase flow energy-minimization multi-scale method, Metallurgical Industry Press, Beijin

Liu, J., Grace, J. R., & Bi, X. 2003. Novel multifunctional optical-fiber probe: I. Development and validation. AIChE Journal 49, 1405-1420.

Lundberg, J., & Halvorsen, B. M. 2008. A review of some existing drag models describing the interaction between phases in a bubbling fluidized bed. In 49th Scandinavian Conference on Modeling and Simulation. Oslo University College, Oslo, Norway.

Passalacqua, A., & Marmo, L. 2009. A critical comparison of frictional stress models applied to the simulation of bubbling fluidized beds. Chemical Engineering Science 64, 2795-2806.

Shah, M. T., Utikar, R. P., Tade, M. O., & Pareek, V. K. 2011. Hydrodynamics of an FCC riser using energy minimization multiscale drag model. Chemical Engineering Journal 168, 812-821.

Shah, S., Myöhänen, K., Kallio, S., & Hyppänen, T. 2015. CFD simulations of gas–solid flow in an industrial-scale circulating fluidized bed furnace using subgrid-scale drag models. Particuology 18, 66-75.

Simon, B., Mohanty, S., & Rüde, U. 2015. Drag correlation for dilute and moderately dense fluid-particle systems using the lattice Boltzmann method. International Journal of Multiphase Flow 68, 71-79.

Syamlal, M., & O'Brien, T. J. 1994. The derivation of a drag coefficient formula from velocity–voidage correlations. In. West Virginia: US Department of Energy, Office of Fossil Energy.

Taghipour, F., Ellis, N., & Wong, C. 2005. Experimental and computational study of gas–solid fluidized bed hydrodynamics. Chemical Engineering Science 60, 6857-6867.

Tenneti, S., Garg, R., & Subramaniam, S. 2011. Drag law for monodisperse gas–solid systems using particle-resolved direct numerical simulation of flow past fixed assemblies of spheres. International Journal of Multiphase Flow 37, 1072-1092.

Yang, N., Wang, W., Ge, W., & Li, J. 2003. CFD simulation of concurrent-up gas–solid flow in circulating fluidized beds with structure-dependent drag coefficient. Chemical Engineering Journal 96, 71–80.