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Hydrodynamics of an FCC riser using energy minimization multiscale drag model

Milinkumar T. Shah, Ranjeet P. Utikar, Moses O. Tade, Vishnu K. Pareek*

Department of Chemical Engineering, Curtin University, GPO Box U1987, Perth, Western Australia 6845, Australia

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ABSTRACT

In this study, a structured-based drag was derived using the energy minimization multiscale (EMMS) model, and used to carry out computational fluid dynamics (CFD) simulations for low and high solid flux fluid catalytic cracking (FCC) risers. The results were compared with those using the Gidaspow drag model, as well as experimental data and previous simulation results. Initially, the EMMS model was solved for two flow conditions and the correlations for the drag coefficients were derived, which were then used to simulate 2D domain of the risers. The time-averaged axial and radial profiles of voidages and pressured drop were compared with the experimental data. The comparison showed that only EMMS model was able to capture the axial heterogeneity with the dense bottom and dilute top sections. The radial profiles using both drag models showed only qualitative agreement with the experimental data. The results using the EMMS and Gidaspow drag model showed a reasonable agreement near the wall and the centre, respectively. Thus, it was concluded that the EMMS model was able to predict both axial and radial heterogeneity for both flow conditions, but only qualitatively; however, further improvements are required to achieve quantitative agreement with the experimental data.

1. Introduction

Fluid catalytic cracking (FCC) is one of the important unit operations in a refinery and it converts heavy hydrocarbons into lighter products. In the FCC, the conversion reactions take place in a riser where the hot catalyst comes in contact with the heavy vacuum gas oil. The hot catalyst vaporises the liquid feed and cracking reaction occurs as the oil vapor and catalyst flow concurrently in the riser. The gas–solid flow in the riser dictates its performance, and is characterized by fast fluidization of Geldart A particles. In the last decade, continuum models based on computational fluid dynamics (CFD) have been extensively applied to understand the hydrodynamics of the riser flow [1–5]. These studies have emphasized the need of accurately modelling the interactions between the gas and solid phases. Generally, the interactions are described using an interphase drag force, and as a result several gas–solid drag models have been proposed in the literature for different flow conditions [6–10]. In the recent years, multiscale approaches such as the sub grid scale (SGS) and the energy minimization multiscale (EMMS) models, which derive a structure-based drag, have gained popularity over the conventional drag models. The EMMS model [8] calculates the drag using the global flow parameters such as the solid mass flux and superficial gas velocities. Because of its relative simplicity and computational feasibility, there has been a growing research interest in applying the EMMS model for simulating the hydrodynamics of riser. Thus, it is important to evaluate the EMMS model over a wide range of operating conditions. This paper reports a comparison between the numerical predictions using the EMMS and Gidapow drag models.

Several hydrodynamics studies using the EMMS model have been published in the literature. Yang et al. [11] simulated a low flux FCC riser with a drag correlation derived using an EMMS model, the hydrodynamic predictions from which were compared with that using the Gidaspow drag model. The authors concluded that the EMMS gave more consistent results for the axial and radial heterogeneity than Gidaspow's drag model. Wang et al. [12] made further advancements in the EMMS model by introducing multiple acceleration terms for individual phases. The solution of this extended the EMMS model resulted in a huge matrix of drag coefficients (known as an EMMS/matrix) for different local solid flux and gas velocities. Naren et al. [13] critically evaluated the formulation of EMMS model. Their study revealed that it is not possible to obtain minima under all flow conditions as postulated by the EMMS model. Qi et al. [14] applied the EMMS approach to modify the drag correlation of Syamlal–O'Brien [10], which the authors then used to simulate the flow of a riser, and concluded that the results using the modified drag model gave better agreement with the experimental data. Jiradilok et al. [3] and later Chalermsinsuwan et al. [15] used the drag formulation for the low flux flow to simulate the flow in high solid flux risers. This was a major drawback in these two studies because the solution of the EMMS

* Corresponding author. Tel.: +61 08 9266 4687; fax: +61 08 9266 2681.
E-mail address: v.pareek@curtin.edu.au (V.K. Pareek).

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Nomenclature

a	average acceleration of particles for a control volume, $m\,s^{-2}$
C_{D0}	standard drag coefficient of a particle
C_{Dc}	drag coefficient of a particle in the cluster phase
C_{Df}	drag coefficient of a particle in the dilute phase
C_{Di}	drag coefficient of a particle in the interface between the cluster and dilute phases
d_p	solid diameter, m
e_{ss}	coefficient of restitution
f	cluster fraction
Fr	empirical material constant, $kg\,m^2\,s^{-2}$
F_c	drag force acting on a single particle in the cluster phase
F_f	drag force acting on a single particle in the dilute phase
F_i	drag force acting on a single cluster
g	gravitational acceleration, $m\,s^{-2}$
$g_{o,ss}$	radial distribution function
I	unit stress tensor
I_{2D}	second invariant of the deviatoric stress tensor
m_c	number of particles per unit volume in the cluster phase
m_f	number of particles per unit volume in the dilute phase
m_i	number of clusters per unit volume
n	empirical material constant in frictional pressure model
p	empirical material constant in frictional pressure model
p	pressure, $kg\,m^{-1}\,s^{-2}$
P_s	solids pressure, $kg\,m^{-1}\,s^{-2}$
P_f	frictional pressure, $kg\,m^{-1}\,s^{-2}$
u	velocity, $m\,s^{-1}$
U_p	superficial particle velocity, $m\,s^{-1}$
U_g	superficial gas velocity, $m\,s^{-1}$
U_f	superficial gas velocity in the cluster phase, $m\,s^{-1}$
U_c	superficial gas velocity in the dilute phase, $m\,s^{-1}$
U_{pc}	superficial particle velocity in the cluster phase, $m\,s^{-1}$
U_{pf}	superficial particle velocity in the dilute phase, $m\,s^{-1}$
U_{sc}	slip velocity in the cluster phase, $m\,s^{-1}$
U_{sf}	slip velocity in the dilute phase, $m\,s^{-1}$
U_{si}	slip velocity at the interface, $m\,s^{-1}$

Greek letters

ε	volume fraction
ε_c	voidage of the cluster phase
ε_f	voidage of the dilute phase
ε_{mf}	minimum fluidizing voidage
ε_{max}	maximum voidage
β	drag coefficient, $kg\,m^3\,s^{-1}$
β_0	standard drag coefficient, $kg\,m^3\,s^{-1}$
ρ	density, $kg\,m^{-3}$
τ	stress tensor, $kg\,m^{-1}\,s^{-2}$
μ_g	gas viscosity, $kg\,m^{-1}\,s^{-1}$
μ_s	solid viscosity, $kg\,m^{-1}\,s^{-1}$
λ_s	solid bulk viscosity, $kg\,m^{-1}\,s^{-1}$
Θ_s	granular temperature, $m^2\,s^{-2}$
ϕ	angle of internal friction
ω	correction factor

Subscripts

Col	collisional
c	cluster phase
f	dilute phase
fri	frictional
g	gas phase
i	interface between the cluster and dilute phase
kin	kinetic
max	maximum
min	minimum
s	solid phase

Abbreviation

CFD	computational fluid dynamics
EMMS	energy minimization multiscale modelling
FCC	fluid catalytic cracking
KTGF	kinetic theory of granular flows
QUICK	quadratic upstream interpolation for convective kinetics
SIMPLE	semi-implicit method for pressure-linked equations

model depends on the flow parameters, and the drag calculated for a particular flow system cannot be used in another flow system [13].

Although there have been several studies on the EMMS model over the past several years, it is clear from the preceding discussion that most of the previous studies on the EMMS model considered either low solid flux flows or used the drag derived from the low solid flux flows. A rigorous evaluation is, therefore, necessary before these models can be adopted for industrial scale simulations. In this study, we have used the EMMS and Gidaspow models for conducting 2D CFD simulations for both low and high solid flux FCC risers. The simulation predictions for the axial and radial profiles of voidages using both drag models were compared with experimental data. The performance and applicability of the drag models has also been evaluated for predicting the hydrodynamics of low and high solid flux conditions.

2. Gas–solid flow model

The gas–solid flow models can be broadly classified in two categories, namely Eulerian–Eulerian (EE) and Eulerian–Langrangian (EL), approaches. In most of the simulation studies on risers, the EE approach has been used because it is more suitable for large scale equipment having high solid inventories [16]. In this approach, both phases are treated as an interpenetrating continuum, and the ensemble averaging of local instantaneous mass, momentum and energy balances for the each phase are used in formulating the governing equations. However, due to the continuum assumption, the stress tensor for the solid phase is not explicitly defined. Therefore, the stress tensor for the solid phase is derived by making an analogy between the particle motions with the motion of gas molecules in kinetic theory of gases [9,17–19]. This stress tensor then requires additional closure for several other properties such as the granular viscosity, solid pressure, frictional viscosity and frictional pressure. The governing equations along with the constitutive equations used in the EE model are summarised in Table 1.The momentum exchange between the gas and solid phases is accounted for using an interphase exchange coefficient which has a profound effect on the predictions of the EE model. The available drag models can be briefly classified into two categories; (i) the conventional drag models and (ii) the structure-bases drag models. The conventional drag models such as those of Gidaspow [9]