Three dimensional full-loop CFD simulation of hydrodynamics in a pilot-scale dual fluidized bed system for biomass gasification

Luo, Hao; Lin, Weigang; Song, Wenli; Li, Songgeng; Dam-Johansen, Kim; Wu, Hao

Published in:
Fuel Processing Technology

Link to article, DOI:
[10.1016/j.fuproc.2019.106146](https://doi.org/10.1016/j.fuproc.2019.106146)

Publication date:
2019

Document Version
Peer reviewed version

[Link back to DTU Orbit](#)

Citation (APA):
Luo, H., Lin, W., Song, W., Li, S., Dam-Johansen, K., & Wu, H. (2019). Three dimensional full-loop CFD simulation of hydrodynamics in a pilot-scale dual fluidized bed system for biomass gasification. *Fuel Processing Technology*, 195, [106146]. <https://doi.org/10.1016/j.fuproc.2019.106146>

General rights

Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal

If you believe that this document breaches copyright please contact us providing details, and we will remove access to the work immediately and investigate your claim.

Three dimensional full-loop CFD simulation of hydrodynamics in a pilot-scale dual fluidized bed system for biomass gasification

Hao Luo¹, Weigang Lin^{1,2}, Wenli Song^{2,3}, Songgeng Li^{2,3}, Kim Dam-Johansen¹, Hao Wu^{1*}

¹Department of Chemical and Biochemical Engineering, Technical University of Denmark, 2800 Kongens Lyngby, Denmark

²Sino-Danish College, University of Chinese Academy of Sciences, Beijing 100190, PR China.

³State Key Laboratory of Multi-Phase Complex Systems, Institute of Process Engineering, Chinese Academy of Sciences, Beijing 100190, PR China

Corresponding author: *haw@kt.dtu.dk

Abstract

A three-dimensional CFD model was developed to simulate the hydrodynamics in a pilot-scale dual fluidized bed system for biomass gasification. The system includes a fast fluidized bed (FFB) for char combustion, a cyclone separator, two loop-seals, and a bubbling fluidized bed (BFB) for biomass gasification. A comparison of a hybrid EMMS drag model (i.e. the EMMS/matrix drag model for FFB, and the EMMS/bubbling drag model for BFB) proposed in this paper and the Gidaspow drag model was carried out at air and steam gasification conditions. The solid circulation rate, solid inventory distribution, and the pressure distribution predicted by the hybrid EMMS drag model were in better agreement with experimental data. The effect of solid inventory on hydrodynamics was evaluated by using the hybrid EMMS drag model. The results indicate that the solid circulation rate and its fluctuation increased with increasing solid inventory. In the simulated system, the operating stability was reduced when the solid inventory was increased to 200 kg due to “choking” phenomenon.

Keywords: biomass gasification, dual fluidized bed, CFD simulations, EMMS, solid inventory

1 Introduction

Biomass is a renewable fuel, which is considered as an alternative to fossil fuels [1–4]. Gasification is a technology to convert biomass to syngas that can be used for production of electricity, chemicals and transportation fuels [2]. Fluidized bed [2,5,6] and fixed bed [7] are commonly applied in biomass gasification. Compared to a fixed bed, fluidized bed gasification has the advantages of high fuel flexibility [3], and more importantly, the realization of auto-thermal gasification by a dual fluidized bed system which can obtain high quality syngas without applying oxygen blown system [2].

In a dual fluidized bed system, biomass gasification, and char combustion occur in two separate fluidized beds, with the heat for biomass gasification provided by char combustion through recirculating particles. A dual fluidized bed system may consist of different types of fluidized beds. For example, a system with combustion in a fast fluidized bed (FFB) and gasification in a bubbling fluidized bed (BFB) is often applied [3,8,9]. However, the design and scale-up are challenging due to the complex hydrodynamics in the system [6,10].

Computational Fluid Dynamics (CFD) has been applied to study the hydrodynamics in a dual fluidized bed system [8–11]. The Eulerian-Eulerian (E-E) approach is commonly used [9,12–14], because it requires less computational resources than the Eulerian-Lagrangian (E-L) approach [15]. Nguyen et al.[9] validated a 2D E-E model by comparing with cold-state experiments in a pilot-scale dual fluidized bed gasification system. Their model was further used to study the solid circulation in the recycle loop and the effect of the loop-seal valve of the dual-fluidized bed system [12]. Yan et al. [13] developed a 3D model to simulate biomass steam gasification in a dual fluidized bed reactor. CFD modelling of other dual fluidized bed systems, e.g. chemical looping systems, has also been reported [16–20].

Most of the existing full-loop CFD models use a single drag model in simulating a system consisting of both a FFB and a BFB [8,9,12,13,21,22]. For example, the Gidaspow drag model has been used to simulate both FFB and BFB [23]. However, the model usually requires a small grid size (e.g. 20 times of particle size) [24], which is computational heavy for large-scale system, and it generally overestimates the momentum exchange between gas and solid phase for fast fluidization [24–26]. Compared to the Gidaspow drag model and other homogeneous drag models, the

heterogenous EMMS model drag models are less grid-dependent and thereby more favorable in simulating large-scale systems[24,27,28]. However, due to the different flow structure of a FFB and a BFB, different EMMS drag model, i.e. the EMMS/matrix model [29,30] for a FFB and the EMMS/bubbling model [27,31–33] for a BFB, are required in order to achieve accurate simulation results in a dual bed system. To the authors' knowledge, a hybrid application of the EMMS drag models in the different beds in a dual-bed system has not explored so far. In addition, the solid inventory influences significantly the heat transfer capability between sand and fuel particle in a dual bed system. However, the effect of solid inventory on hydrodynamics is rarely investigated in the existing CFD simulations of dual fluidized bed systems.

The main objective of this work is to apply and validate a hybrid EMMS drag models to simulate the hydrodynamics of a full-loop dual fluidized bed system. Experimental results from a pilot-scale dual fluidized bed system for biomass gasification were used for model validation. The validated model was applied to evaluate the effect of solid inventory on the hydrodynamics in the dual fluidized gasification system.

2 Experiments

A pilot-scale dual fluidized bed system for biomass gasification is schematically shown in Fig. 1. The system was constructed in Institute of Process Engineering, Chinese Academy of Sciences. The system includes a FFB for char combustion, a cyclone, two loop-seals, and a BFB for biomass gasification. The riser is about 10 m high, and the diameters of the upper and the bottom section are 0.124 m and 0.30 m, respectively. The total height of the BFB is 2.60 m, with an inner diameter of 0.25 m in the dense region. The origin position, marked as “0” in Fig.1, is in the center of the FFB bottom. Nine pressure transducers are installed along the riser and the BFB for measuring the pressure profile in the looping system. The pressures in the bottom of two loop-seals are also monitored.

Biomass particles are fed to the top of BFB by a screw feeder. The full-load of the dual fluidized gasification system is 70 kg (biomass)/h. The pyrolysis and gasification of biomass takes place in the BFB. The remained char in the BFB is transported together with sand particles through the lower loop-seal to the bottom of FFB, where char combustion take place. The heat generated by char

83 combustion is transported to BFB by solid circulation to provide heat for the biomass pyrolysis and
 84 gasification. Both air and steam gasification have been investigated in the experiments, with the
 85 conditions shown in Table 1. For air gasification, the operating temperatures of the FFB and BFB
 86 are 890 °C and 775 °C, with superficial gas velocities of 9.29 m/s and 0.76 m/s, respectively. For
 87 steam gasification, the operating temperatures of the FFB and BFB are 820 °C and 690 °C, with
 88 superficial gas velocities of 9.17 m/s and 0.25 m/s, respectively. The sand solid inventory of both
 89 cases is 120 kg. The solid circulation rate based on the mass and heat balance calculation is 0.246
 90 kg/s for air gasification and 0.250 kg/s for steam gasification, respectively. The physical properties
 91 of the gas in the FFB are estimated by using the gas composition (18% CO₂, 79% N₂, and 3% O₂)
 92 at the outlet of the cyclone. The physical properties of the gas in the BFB is based on the gas
 93 composition of the outlet of BFB, which is shown in Appendix A. The particle size distribution of
 94 the sand particles is shown in Fig. 2. The Sauter mean diameter of sand particles is 323 μm which
 95 belongs to Group B particle based on the classification of Geldart [34].

96
 97 Fig. 1 Schematically plot of the pilot-scale dual fluidized bed system for biomass gasification with
 98 geometry and mesh. (1): main gas for char combustion, (2) inlet of sand at the start of the setup,
 99 (3) outlet of cyclone, (4) fluidization gas for the upper loop-seal, (5) gasification gas for BFB, (6)
 100 fluidization gas for the lower loop-seal.

Fig. 2 The particle size distribution of the sand particles used in the experiments

Table 1. Operating conditions of air and steam gasification

	Air gasification	Steam gasification
Main gas(1), m/s	9.288	9.170
Inlet gas temperature, °C	890	820
Fluidized gas(4,6), m/s	0.088	0.088
Gasification gas (5), m/s	0.758	0.252
Gasification gas temperature, °C	775	690
Temperature of FFB, °C	890	820
Temperature of BFB, °C	775	690
Gauge pressure at cyclone outlet (3), kPa	1.55	2.00
Gauge pressure at BFB outlet, kPa	4.8	3.30
Solid inventory, kg	120	120
Gas viscosity at FFB, Pa.s	5.52e-5	5.22e-5
Gas viscosity at BFB, Pa.s	5.03e-5	2.77e-5
Gas density at FFB, kg/m ³	0.302	0.322
Gas density at BFB, kg/m ³	0.335	0.228
Particle density, kg/m ³	2600	2600
Mean particle size, μm	323	323

3. Model description

The Eulerian multiphase granular model in ANSYS Fluent version 18.0 is employed. Kinetic theory of granular flow (KTGF) is used as closure correlation of solid stress and viscosity. The algebraic form of the granular temperature model is selected for sand particle instead of the full granular energy balance model, because both models give similar results and the former one has been shown performing better in computational efficiency and numerical convergence [27,35,36]. The no-slip boundary condition is prescribed for both gas and solid phases, since it has been used in previous studies [37,38] to simulate bubbling fluidized beds with a size of $\varnothing 154 \times 924$ mm and $\varnothing 155 \times 400$ mm, and the EMMS drag model seems to be insensitive to the wall conditions [24,39]. The solids leaving the cyclone outlets (3) are recirculated to the sand inlet of FFB (2) by using User Defined Functions (UDFs) to maintain the mass balance of incoming and outgoing bed materials. The sand particles are initially patched in the FFB, two loop-seal, and the BFB dense region. The volume averaged solid concentration in FFB and BFB, and the solid flux at different heights of FFB and BFB are monitored to determine when the simulation reaches quasi-steady state. A time step size of 5×10^{-4} s and the maximum iteration of 50 is chosen to ensure continuity equations with a convergence of 10^{-3} and momentum equations with a convergence of 10^{-6} . We found those parameters converged to quasi-steady values after 30s. Therefore, all simulations of the reactors ran for 50s and the data of the last 20s were collected to obtain time-averaged data. All simulations were carried out by using 16 cores in High Performance Computing system of Technical University of Denmark, with one simulation case taking approximately 2 weeks. The simulation settings are summarized in Table 2. The governing equations of the Eulerian multiphase granular model are provided in Appendix B.

Table 2 Simulation settings for the dual fluidized bed system

Unsteady formulation	Unsteady, 2nd-order Implicit
Spatial discretization	Green-Gauss Cell based
Pressure-velocity coupling methods	Phase coupled SIMPLE
Granular viscosity	Gidaspow
Granular bulk viscosity	Lun et al.
Frictional viscosity	Schaeffer
Granular temperature	Algebraic
Frictional pressure	Based KTGF
Solid pressure	Lun et al.
Radial distribution	Lun et al.
Angle of internal friction	30
Time step	0.0005 s

For the dual fluidized bed gasification system, the FFB is in fast fluidization regime, while the BFB is operated at bubbling fluidization regime. Therefore, the EMMS/matrix model which was proposed by Wang and Li [30] and further developed by Lu et al. [24] is selected to simulate the FFB, while the EMMS/bubbling model developed by Hong et al. [32] is chosen for the BFB. For comparison with the hybrid EMMS drag model, the conventional Gidaspow drag model [23] is also used to simulate the dual fluidized bed gasification system. Both the Gidaspow drag model and the hybrid EMMS drag model are shown below.

The Gidaspow drag model:

$$\beta = \begin{cases} \frac{3}{4} C_{D0} \frac{\varepsilon_s \varepsilon_g \rho_g |u_g - u_s|}{d_s} \varepsilon_g^{-2.65} & (\varepsilon_g \geq 0.8) \\ 150 \frac{(1 - \varepsilon_g)^2 \mu_g}{\varepsilon_g d_s^2} + 1.75 \frac{(1 - \varepsilon_g) \rho_g |u_g - u_s|}{d_s} & (\varepsilon_g < 0.8) \end{cases} \quad (1)$$

The hybrid EMMS drag model:

$$\beta = \frac{3}{4} C_{D0} \frac{\varepsilon_s \varepsilon_g \rho_g |u_g - u_s|}{d_s} \varepsilon_g^{-2.65} H_D \quad (2)$$

Where,

$$C_{D0} = \begin{cases} \frac{24(1 + 0.15 \text{Re}_s^{0.687})}{\text{Re}_s} & (\text{Re}_s < 1000) \\ 0.44 & (\text{Re}_s \geq 1000) \end{cases} \quad (3)$$

Here Re_s is Reynolds number, u_g and u_s is gas and solid velocity, m/s, respectively, ε_g and ε_s are gas and solid volume fraction, respectively, ρ_g and ρ_s are gas and solid density, kg/m³, and d_s is particle diameter, m, β is the drag coefficient, kg/(m³·s).

For the hybrid EMMS drag model, H_D is the heterogenous index as defined in Wang and Li [30].

The H_D is based on operating conditions of the dual fluidized bed. The inputs of the EMMS/matrix drag model are superficial gas velocity, solid circulation rate, and their physical properties (particle diameter and density, gas viscosity and density). The inputs of the EMMS/bubbling drag model are superficial gas velocity, and physical properties of gas and solid. A plot of H_D coefficients of air and steam gasification conditions is shown in Fig. 3. For the EMMS/matrix drag model, the H_D coefficients show a large reduction as compared to the homogenous Wen-Yu drag model [24], indicating the drag force between gas and solid is significantly affected by heterogenous flow structure. When the voidage is close to 1, the H_D is equal to unity due to a transition of the heterogenous flow structure to homogenous. For the EMMS/bubbling drag model, the reduction of drag force is much smaller than that of EMMS/matrix drag model, which means the BFB with Group B particle is close to homogenous flow structure [40]. The formulations of H_D coefficients for both air and steam gasification are shown in Appendixes C in supplementary material.

Fig. 3 A plot of H_D coefficient of air and steam gasification by using the EMMS/matrix model for FFB and the EMMS/bubbling model for BFB.

The hybrid EMMS drag model is implemented in ANSYS Fluent® 18.0 by using UDFs. A plot of mesh is shown in Fig.1 (b). The total grid number used in this study is about 266000, and the average grid size used is about 60 times of the particle size, which is acceptable for the EMMS drag model, as it was proved to give grid-independent simulation results when the grid size is smaller than 100 times of the particle size [24].

For a dual fluidized bed gasification system, the gas composition and operating conditions of BFB and FFB are significantly different as shown in Table 1. The inlet gas temperature is specified as the same to the FFB and BFB temperature, respectively. The other gas properties in the FFB and BFB are estimated based on the temperature and compositions, with the viscosities and densities shown in Table 1. The mass content of fuel particle is typically less than 5% for biomass gasification in fluidized bed [41,42]. Therefore, it is reasonable to assume that the hydrodynamic behaviors of the dual fluidized bed are dominated by the sand particles. The effect of biomass/char particle is negligible. This assumption has been adopted in many previous studies [9,11,43–46] which focus

on the hydrodynamic in fluidized bed systems. In this paper, we also focus on the hydrodynamic behaviors, thus the biomass/char particles and chemical reactions are ignored in our simulations.

4. Results and discussions

4.1 Model validation

4.1.1 Solid circulation rate

Table 3 shows the solid circulation rates obtained at the outlet of FFB by using the hybrid EMMS drag model and the Gidaspow drag model. As compared with the results from mass and heat balance based on the experimental data, the Gidaspow drag model overpredicts the solid circulation rate, the results predicted by the EMMS drag model are underestimated but it is much better than that of Gidaspow drag model. This tendency is consistent with a previous study showing that the Gidaspow drag model predicts a higher solid flux than the EMMS/matrix drag model, because it neglects the heterogenous flow structure in the fast fluidization regime [25]. The probable reason of the underestimated the solid circulation rate by the hybrid EMMS drag model is that the heterogeneity index H_D , which is determined by using the operating conditions of the upper region of FFB, is underestimated for the bottom region of the FFB. Developing an operating condition dependent EMMS/matrix drag model may resolve this problem, but it is out of the scope of current study.

Table 3 Solid circulation rate (kg/s) predicted by using the hybrid EMMS drag model and Gidaspow drag model.

	Gidaspow	EMMS	Mass and heat balance*
Air	0.888	0.214	0.246
Steam	1.034	0.150	0.250

*The results of mass and heat balance is calculated on the basis of the experimental data.

4.1.2 Pressure

Figure. 4 shows the simulated axial profiles of pressure in the FFB. Under air gasification condition,

the pressure drop in FFB predicted by the hybrid EMMS drag model is ~ 5.0 kPa, which is comparable with experimental data (~ 4.5 kPa). However, the pressure drop predicted by using the Gidaspow drag model is ~ 10.8 kPa, which is significantly overestimated. Under steam gasification conditions, the pressure drop predicted by the hybrid EMMS drag model is ~ 5.0 kPa which is close to the experimental results of 5.1 kPa, while, the pressure drop predicted by using the Gidaspow model is ~ 10.6 kPa, which is remarkably higher. Looking at the axial pressure profiles in the FFB, it is obvious that the results from the hybrid EMMS drag model are in good agreement with the experimental data. However, the Gidaspow drag generally overestimates the pressure along the height of FFB.

Fig. 4 A comparison of the predicted and measured axial profiles of pressure in the FFB.

Figure. 5 compares the simulated and experimental axial profiles of pressure in the BFB. The two drag models give similar pressure profiles. The reason is that the drag coefficients from the EMMS/bubbling model and the Gidaspow drag are similar in bubbling fluidization for Group B particles with a low superficial gas velocity [31]. Both the Gidaspow and hybrid EMMS drag model simulated experimental data well under both the air and steam gasification conditions.

Fig. 5 A comparison of the simulated and measured axial profiles of pressure in the BFB.

Table 4 compares the predicted and measured pressures at the bottom of the loop-seals. For both cases of air and steam gasification, the Gidaspow drag model overestimates significantly the pressure of the lower loop-seal. However, the hybrid EMMS model gives more reasonable results for both the upper and lower loop-seals. Combining with the results in Fig. 4 and Fig. 5, it can be concluded that the hybrid EMMS drag model agrees much better with experimental data for the FFB, BFB, and recycle loop.

Table 4. A comparison of the predicted and measured pressure at the bottom of loop-seals

		Exp.	Predicted pressure (kPa)		Relative error (%)	
			Gidaspow	EMMS	Gidaspow	EMMS
Air	Upper loop-seal	11.2	10.01	10.33	-10.63	-7.77
	Lower loop-seal	10.2	16.66	10.07	55.70	-5.89
Steam	Upper loop-seal	10.1	8.51	8.69	-15.74	-13.96
	Lower loop-seal	11.9	17.03	10.51	43.11	-11.68

4.1.3 Solid inventory in the FFB and BFB

Table 5 shows the simulated solid inventory (kg) in the FFB and BFB by using the hybrid EMMS drag model and the Gidaspow drag model under air gasification conditions. The experimental solid inventory is measured by weighting the particles remained in the FFB and BFB after the experiment.

In the FFB, the hybrid EMMS drag model shows a higher solid inventory than the Gidaspow drag model and is closer to the experimental data. It is the results are seemingly inconsistent with the pressure drop shown in Fig. 4. However, it should be noted that the FFB outlet has a strong restriction for the solid particles transported from FBB to cyclone when the solid circulation rate is large. As shown Table 5, the solid circulation rate predicted by the Gidaspow drag model is much larger than that of the EMMS drag model. Consequently, a large pressure drop is predicted at the FFB top. In the BFB, the hybrid EMMS drag model gives a lower solid inventory than that of the Gidaspow model. The hybrid EMMS drag model also predicts a lower solid inventory in lower loop-seal, possibly because of a lower solid circulation rate predicted by the hybrid EMMS drag model. Although both the hybrid EMMS and the Gidaspow drag model over-predict the solid inventory of the BFB, the hybrid EMMS drag model still gives more reasonable results than the Gidaspow drag model.

Table 5 Predicted and measured solids inventory (kg) in the FFB and BFB in the case of air gasification

	Exp.	Solid inventory (kg)		Relative error (%)	
		Gidaspow	EMMS	Gidaspow	EMMS
FFB	25	20.4	28.9	-18.4	15.6
BFB	35	46.2	43.8	32.0	25.1
Lower loop-seal	-	25.1	20.1	-	-
Upper loop-seal	-	24.1	26.1	-	-
Other part	-	4.2	1.1	-	-

4.1.4 Solid volume fraction

Figure. 6 compares the simulated time averaged solid volume fraction in the FFB. Both models can capture the so-called “core-annulus” structure in the FFB. However, compared to the EMMS drag model, the Gidaspow drag model predicts a higher solid hold up at the outlet of FFB for both air and steam gasification cases. Similar results can be seen in Fig. 7, which shows the time averaged axial profiles of the solid volume fraction in the FFB. According to Fig.7, the axial profile of solid volume fraction predicted by the Gidaspow drag model is close to a shape of “C”, indicating that

there is a strong restriction at the outlet of FFB. That is why the Gidaspow drag model shows a significant pressure drop at the top of FFB. However, the measured pressure drop is small which implies the restriction at the outlet of FFB is insignificant. The axial profile of solid volume fraction should be close to an “L” shape according to the discussion of Bi et al. [47]. Therefore, the EMMS drag model gives more reasonable results in solid volume fraction than the Gidaspow drag model.

Fig. 6 The simulated solid concentration distribution by using the Gidaspow and hybrid EMMS drag model for the case of air (a) and steam (b) gasification.

Fig. 7 The simulated solid axial profiles of FFB by using the Gidaspow and EMMS drag model for the case of air (a) and steam (b) gasification

Figure.8 shows the simulated time averaged solid volume fraction of the BFB by using the Gidaspow and the hybrid EMMS drag model under air and steam gasification conditions. Both models can capture the “core-annulus” flow structure in the BFB at heights of 3.5, 3.7, and 3.9 m. A flat radial profiles of solid volume fraction at a height of 3.3 m are captured due to a uniform inlet gas velocity used in the simulation. In the enlarge and freeboard region of the BFB, both models show a low solid concentration. Fig. 9 shows the simulated axial profile of time averaged solid volume fraction of the BFB. Both models show a dense bubbling phase, a decreasing solid concentration along the height in the enlarge region, and a low solid concentration in the freeboard. The simulation results of the hybrid EMMS drag model and Gidaspow drag model are similar.

Fig. 8 The simulated solid concentration distribution by using Gidaspow and EMMS based drag model for air (a) and steam (b) gasification.

Fig. 9 The simulated solid axial profiles of BFB by using the Gidaspow and hybrid EMMS based drag model

Based on the results and discussions in Section 4.1.1 - 4.1.4, we can conclude that the hybrid EMMS drag model gives more reasonable results than the Gidaspow drag model.

4.2 Effects of solid inventory

The hybrid EMMS drag model validated with solid inventory 120 kg is used to investigate the effects of solid inventory on the hydrodynamics in the dual fluidized bed system. It should be noted that the H_D coefficient may be required to be updated for new operating conditions, since the H_D of the EMMS/matrix model depends not only on voidage but also on the Particle Reynolds number. However, the change of solid inventory in this study is not significant (in a range of 100 kg – 200 kg), and it has been shown in literature that a EMMS/matrix drag model validated at a specified condition could be used to study the effects of solid inventory on hydrodynamic behaviors [26]. Thus, the H_D coefficient are kept unchanged in our simulations for different solid inventory. For the EMMS/bubbling model, since the solid flux is assumed to be zero in the EMMS/bubbling model, H_D is the same for the case with different solid inventory.

4.2.1 Solid circulation rate

Figure. 10 shows the effects of solid inventory on the solid circulation rate in the dual fluidized bed system for biomass gasification. For both cases of air and steam gasification, the solid circulation rate increases slowly with an increase of solid inventory in the range of 100-120 kg, while it increases dramatically in the range of 160-200 kg. The results are consistent with previous studies [6,26,48], showing that it is possible to convey more heat generated by char combustion from FFB to BFB by increasing the solid inventory. The solid circulation rates predicted for air and steam gasification are very similar. The minor difference is caused by the slightly different operating conditions in the FFB and BFB.

Fig. 10 A plot of solid inventory versus the time averaged solid circulation rate (kg/s) for the case of air and steam gasification.

Figure. 11 shows the transient solid circulation rate for the cases of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg). The standard deviation ($\sigma = \sqrt{\frac{(x_i - \bar{x})^2}{N-1}}$, where x_i is i value of variable x , $\bar{x}$ is averaged value of the variable x , N is total number of variable x) of the solid circulation rate (determined by using the data from 30~50 s) is also shown in Fig. 11. The fluctuation of the solid circulation rate increases with an increase of solid inventory for both air (The standard deviation changes from 0.1 to 2.28) and steam gasification (The standard deviation changes 0.01 to 1.94) conditions. The probable reason is that the choking occurs in the recycle loop for the case $I = 200$ kg, which is typical type B “choking” [49]. The solid circulation rate is over the maximum value that the recycle loop can be conveyed. It should be noted that the large fluctuation of solid circulation rate may influence significantly on the operation of the upper loop-seal and the heat balance in the BFB. Therefore, it may challenges a stable condition on the dual fluidized bed gasification system [6].

Fig. 11 The transient solid circulation rate (kg/s) for the case of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg).

4.2.2 Solid volume fraction

Figure. 12 shows the transient volume averaged solid volume fraction of the upper loop-seal for the case of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg). For both cases of air (a) and steam (b) gasification, the fluctuation of solid volume fraction increases with an increase of solid inventory. Therefore, the operations of upper loop-seal may become more unstable with increasing solid inventory. The solid inventory of the operating condition is recommended to be in a range of 100-160 kg.

Fig. 12 The transient volume averaged solid volume fraction of upper Loop-seal for the case of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg).

Figure. 13 (a) shows the time averaged axial profiles of solid volume fraction in the FFB. For the cases of solid inventory of 100 kg and 120 kg, the restriction at the outlet of FFB is relatively weak

due to the low solid circulation rate (0.186 kg/s, and 0.214 kg/s) and the time averaged axial profile of solid volume fraction is close to a “L” curve. With the increase of solid inventory, a dramatical increase of solid circulation rate leads to accumulation of solid in the top outlet of FFB. Therefore, the curve is close to “C” curve as reported by Bai et al. [47]. Fig. 13 (b) shows the time averaged axial profiles of solid volume fraction of FFB for the case of steam gasification with different solid inventory. The results show the similar phenomena of steam gasification to those of air gasification.

Fig. 13 The time averaged axial profiles of solid volume fraction of FFB for the case of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg).

Figure. 14 shows the time averaged axial profiles of solid volume fraction of the BFB for the case of air and steam gasification with different solid inventory. The solid volume fraction in the BFB bottom is similar. However, the height of bed expansion increases with increasing solid inventory, meaning that the solid inventory in the BFB is increased to keep the pressure balance between the FFB and BFB. In the enlarge region of BFB, the solid volume fraction decreases with an increase of height of BFB, due to the decrement of superficial gas velocity. In the freeboard region of BFB, the solid concentration is very small, because the superficial gas velocity at this part is not high enough to support the entrainment of a large amount of solid.

Fig.14 The time averaged axial profiles of solid volume fraction of BFB for the case of air (a) and steam (b) gasification with different solid inventory (100, 120, 160, 200 kg).

5. Conclusion

A three dimensional full-loop CFD simulation of the hydrodynamics of a dual fluidized bed system for biomass gasification has been conducted by using a Eulerian multiphase granular model. A hybrid EMMS drag model (the EMMS/matrix model for FFB and the EMMS/bubbling drag model for BFB) is proposed to simulate the system. The Gidaspow drag model is also applied for comparison. The pressure distributions predicted by the hybrid EMMS drag model are in good agreement with the measurement in the FFB, BFB, and the whole loop. However, the Gidaspow drag model overestimates the solid concentration in the top FFB as well as at the bottom of the lower loop-seal, because of an over estimation of momentum exchange between gas and solid. The results suggest that the hybrid EMMS drag model perform better than the Gidaspow drag model. The effects of solid inventory on the hydrodynamics of the dual fluidized bed system have been evaluated by the hybrid EMMS drag model. The results show that the solid circulation rate increases with an increase of solid inventory. But it leads to the operation condition in an unstable regime. In the simulation, a solid inventory of 100-160 kg gives adequate heat carrier capability and stable operation of the dual fluidized bed system

Acknowledgments

This study is supported by Sino-Danish collaboration project (DANCNGAS) funded by Innovation Fund Denmark, and Minerals and Cement Process Technology (MiCeTech) funded by the Danish National Advanced Technology Foundation, Innovation Fund Denmark, FLSmidth A/S, Hempel A/S, and DTU Chemical Engineering. This study is also supported by International S&T Cooperation Program of China (2013DFG62640) funded by MOST

References

- [1] A.G. Stern, Design of an efficient, high purity hydrogen generation apparatus and method for a sustainable, closed clean energy cycle, *Int. J. Hydrogen Energy*. 40 (2015) 9885–9906. doi:10.1016/J.IJHYDENE.2015.05.111.
- [2] J. Karl, T. Pröll, Steam gasification of biomass in dual fluidized bed gasifiers: A review, *Renew. Sustain. Energy Rev.* 98 (2018) 64–78. doi:10.1016/J.RSER.2018.09.010.
- [3] F. Benedikt, J.C. Schmid, J. Fuchs, A.M. Mauerhofer, S. Müller, H. Hofbauer, Fuel flexible gasification with an advanced 100 kW dual fluidized bed steam gasification pilot plant, *Energy*. 164 (2018) 329–343. doi:10.1016/J.ENERGY.2018.08.146.
- [4] Q. Xiong, Y. Yang, F. Xu, Y. Pan, J. Zhang, K. Hong, G. Lorenzini, S. Wang, Overview of Computational Fluid Dynamics Simulation of Reactor-Scale Biomass Pyrolysis, *ACS Sustain. Chem. Eng.* 5 (2017) 2783–2798. doi:10.1021/acssuschemeng.6b02634.
- [5] H. Liu, CFD Modeling of Biomass Gasification Using a Circulating Fluidized Bed Reactor, University of Waterloo, 2014.
- [6] S. Kaiser, G. Löffler, K. Bosch, H. Hofbauer, Hydrodynamics of a dual fluidized bed gasifier. Part II: simulation of solid circulation rate, pressure loop and stability, *Chem. Eng. Sci.* 58 (2003) 4215–4223. doi:10.1016/S0009-2509(03)00233-1.
- [7] J. Li, S. Liao, W. Dan, K. Jia, X. Zhou, Experimental study on catalytic steam gasification of municipal solid waste for bioenergy production in a combined fixed bed reactor, *Biomass and Bioenergy*. 46 (2012) 174–180. doi:10.1016/J.BIOMBIOE.2012.08.026.
- [8] X. Wang, J. Lei, X. Xu, Z. Ma, Y. Xiao, Simulation and experimental verification of a hydrodynamic model for a dual fluidized Bed gasifier, *Powder Technol.* 256 (2014) 324–335. doi:10.1016/J.POWTEC.2014.01.087.
- [9] T.D.B. Nguyen, M.W. Seo, Y.-I. Lim, B.-H. Song, S.-D. Kim, CFD simulation with experiments in a dual circulating fluidized bed gasifier, *Comput. Chem. Eng.* 36 (2012) 48–56. doi:10.1016/j.compchemeng.2011.07.005.
- [10] H. Liu, R.J. Cattolica, R. Seiser, C. hsien Liao, Three-dimensional full-loop simulation of a dual fluidized-bed biomass gasifier, *Appl. Energy*. 160 (2015) 489–501. doi:10.1016/j.apenergy.2015.09.065.
- [11] S.I. Ngo, Y. Il Lim, B.H. Song, U. Do Lee, C.W. Yang, Y.T. Choi, J.H. Song, Hydrodynamics of cold-rig biomass gasifier using semi-dual fluidized-bed, *Powder Technol.* 234 (2013) 97–106.

doi:10.1016/j.powtec.2012.09.022.

[12] M.W. Seo, T.D.B. Nguyen, Y. Il Lim, S.D. Kim, S. Park, B.H. Song, Y.J. Kim, Solid circulation and loop-seal characteristics of a dual circulating fluidized bed: Experiments and CFD simulation, *Chem. Eng. J.* 168 (2011) 803–811. doi:10.1016/J.CEJ.2011.01.041.

[13] L. Yan, Y. Cao, H. Zhou, B. He, Investigation on biomass steam gasification in a dual fluidized bed reactor with the granular kinetic theory, *Bioresour. Technol.* 269 (2018) 384–392. doi:10.1016/J.BIORTECH.2018.08.099.

[14] S. Wang, J. Chen, H. Lu, G. Liu, L. Sun, Multi-scale simulation of chemical looping combustion in dual circulating fluidized bed, *Appl. Energy*. 155 (2015) 719–727. doi:10.1016/J.APENERGY.2015.05.109.

[15] C.H. Ibsen, E. Helland, B.H. Hjertager, T. Solberg, L. Tadrist, R. Occelli, Comparison of multifluid and discrete particle modelling in numerical predictions of gas particle flow in circulating fluidised beds, *Powder Technol.* 149 (2004) 29–41. doi:10.1016/J.POWTEC.2004.09.042.

[16] Y. Guan, J. Chang, K. Zhang, B. Wang, Q. Sun, Three-dimensional CFD simulation of hydrodynamics in an interconnected fluidized bed for chemical looping combustion, *Powder Technol.* 268 (2014) 316–328. doi:10.1016/j.powtec.2014.08.046.

[17] W. Shuai, Y. Yunchao, L. Huilin, W. Jiaying, X. Pengfei, L. Guodong, Hydrodynamic simulation of fuel-reactor in chemical looping combustion process, *Chem. Eng. Res. Des.* 89 (2011) 1501–1510. doi:10.1016/j.cherd.2010.11.002.

[18] C. Geng, W. Zhong, Y. Shao, D. Chen, B. Jin, Computational study of solid circulation in chemical-looping combustion reactor model, *Powder Technol.* 276 (2015) 144–155. doi:10.1016/J.POWTEC.2015.01.077.

[19] A. Bougamra, L. Huilin, Modeling of Chemical Looping Combustion of Methane Using a Ni-Based Oxygen Carrier, *Energy & Fuels*. 28 (2014) 3420–3429. doi:10.1021/ef500114z.

[20] S. Wang, H. Lu, F. Zhao, G. Liu, CFD studies of dual circulating fluidized bed reactors for chemical looping combustion processes, *Chem. Eng. J.* 236 (2014) 121–130. doi:10.1016/j.cej.2013.09.033.

[21] H. Kruggel-Emden, S. Rickelt, F. Stepanek, A. Munjiza, Development and testing of an interconnected multiphase CFD-model for chemical looping combustion, *Chem. Eng. Sci.* 65 (2010) 4732–4745. doi:10.1016/J.CES.2010.05.022.

[22] C. Manchasing, P. Kuchonthara, B. Chalermisinsuwan, P. Piumsomboon, Experiment and computational fluid dynamics simulation of in-depth system hydrodynamics in dual-bed gasifier, *Int. J. Hydrogen Energy*. 38 (2013) 10417–10430. doi:10.1016/J.IJHYDENE.2013.06.033.

[23] D. Gidaspow, *Multiphase flow and fluidization: continuum and kinetic theory descriptions*, Academic press, 1994.

[24] B. Lu, W. Wang, J. Li, Searching for a mesh-independent sub-grid model for CFD simulation of gas-solid riser flows, *Chem. Eng. Sci.* 64 (2009) 3437–3447. doi:10.1016/j.ces.2009.04.024.

[25] B. Lu, W. Wang, J. Li, Eulerian simulation of gas-solid flows with particles of Geldart groups A, B and D using EMMS-based meso-scale model, *Chem. Eng. Sci.* 66 (2011) 4624–4635. doi:10.1016/j.ces.2011.06.026.

[26] N. Zhang, B. Lu, W. Wang, J. Li, Virtual experimentation through 3D full-loop simulation of a circulating fluidized bed, *Particuology*. 6 (2008) 529–539. doi:10.1016/J.PARTIC.2008.07.013.

[27] H. Luo, B. Lu, J. Zhang, H. Wu, W. Wang, A grid-independent EMMS/bubbling drag model for bubbling and turbulent fluidization, *Chem. Eng. J.* 326 (2017) 47–57. doi:10.1016/J.CEJ.2017.04.145.

[28] B. Lu, N. Zhang, W. Wang, J. Li, J.H. Chiu, S.G. Kang, 3-D full-loop simulation of an industrial-scale circulating fluidized-bed boiler, *AIChE J.* 59 (2013) 1108–1117. doi:10.1002/aic.13917.

[29] N. Yang, W. Wang, W. Ge, J. Li, CFD simulation of concurrent-up gas-solid flow in circulating fluidized

beds with structure-dependent drag coefficient, *Chem. Eng. J.* 96 (2003) 71–80. doi:10.1016/j.ces.2003.08.006.

[30] W. Wang, J. Li, Simulation of gas-solid two-phase flow by a multi-scale CFD approach-of the EMMS model to the sub-grid level, *Chem. Eng. Sci.* 62 (2007) 208–231. doi:10.1016/j.ces.2006.08.017.

[31] Z. Shi, W. Wang, J. Li, A bubble-based EMMS model for gas-solid bubbling fluidization, *Chem. Eng. Sci.* 66 (2011) 5541–5555. doi:10.1016/j.ces.2011.07.020.

[32] K. Hong, Z. Shi, W. Wang, J. Li, A structure-dependent multi-fluid model (SFM) for heterogeneous gas – solid flow, 99 (2013) 191–202. doi:10.1016/j.ces.2013.05.050.

[33] K. Hong, Y. Gao, A. Ullah, F. Xu, Q. Xiong, G. Lorenzini, Multi-scale CFD modeling of gas-solid bubbling fluidization accounting for sub-grid information, *Adv. Powder Technol.* 29 (2018) 488–498. doi:10.1016/J.APT.2018.02.024.

[34] D. Geldart, Types of gas fluidization, *Powder Technol.* 7 (1973) 285–292. doi:10.1016/0032-5910(73)80037-3.

[35] B.G.M. van Wachem, J.C. Schouten, C.M. van den Bleek, R. Krishna, J.L. Sinclair, Comparative analysis of CFD models of dense gas–solid systems, *AIChE J.* 47 (2001) 1035–1051. doi:10.1002/aic.690470510.

[36] A. Bakshi, C. Altantzis, A.F. Ghoniem, Towards accurate three-dimensional simulation of dense multi-phase flows using cylindrical coordinates, *Powder Technol.* 264 (2014) 242–255. doi:10.1016/J.POWTEC.2014.04.052.

[37] P. Fede, O. Simonin, A. Ingram, 3D numerical simulation of a lab-scale pressurized dense fluidized bed focussing on the effect of the particle-particle restitution coefficient and particle-wall boundary conditions, *Chem. Eng. Sci.* 142 (2016) 215–235. doi:10.1016/j.ces.2015.11.016.

[38] C. Loha, H. Chattopadhyay, P.K. Chatterjee, Euler-Euler CFD modeling of fluidized bed: Influence of specular coefficient on hydrodynamic behavior, *Particuology.* 11 (2013) 673–680. doi:10.1016/j.partic.2012.08.007.

[39] M. Zeneli, A. Nikolopoulos, N. Nikolopoulos, P. Grammelis, E. Kakaras, Application of an advanced coupled EMMS-TFM model to a pilot scale CFB carbonator, *Chem. Eng. Sci.* 138 (2015) 482–498. doi:10.1016/j.ces.2015.08.008.

[40] A. Ullah, K. Hong, S. Chilton, W. Nimmo, Bubble-based EMMS mixture model applied to turbulent fluidization, *Powder Technol.* 281 (2015) 129–137. doi:10.1016/j.powtec.2015.03.016.

[41] F. Fotovat, J. Chaouki, J. Bergthorson, The effect of biomass particles on the gas distribution and dilute phase characteristics of sand–biomass mixtures fluidized in the bubbling regime, *Chem. Eng. Sci.* 102 (2013) 129–138. doi:10.1016/J.CES.2013.07.042.

[42] H. Cui, J.R. Grace, Fluidization of biomass particles: A review of experimental multiphase flow aspects, *Chem. Eng. Sci.* 62 (2007) 45–55. doi:10.1016/J.CES.2006.08.006.

[43] P. Arora, A.F.A. Hoadley, S.M. Mahajani, A. Ganesh, Compartment model for a dual fluidized bed biomass gasifier, *Chem. Eng. Res. Des.* 117 (2017) 274–286. doi:10.1016/j.cherd.2016.10.025.

[44] E. Esmaili, N. Mahinpey, E. Mostafavi, An extensive simulation of coal gasification in bubbling fluidized bed: Integration of hydrodynamics into reaction modelling, *Can. J. Chem. Eng.* 92 (2014) 1714–1724. doi:10.1002/cjce.22041.

[45] X. Yu, P.H. Blanco, Y. Makkawi, A. V. Bridgwater, CFD and experimental studies on a circulating fluidised bed reactor for biomass gasification, *Chem. Eng. Process. - Process Intensif.* 130 (2018) 284–295. doi:10.1016/J.CEP.2018.06.018.

[46] H. Liu, R.J. Cattolica, R. Seiser, Operating parameter effects on the solids circulation rate in the CFD simulation of a dual fluidized-bed gasification system, *Chem. Eng. Sci.* 169 (2017) 235–245.

doi:10.1016/J.CES.2016.11.040.

[47] D.-R. Bai, Y. Jin, Z.-Q. Yu, J.-X. Zhu, The axial distribution of the cross-sectionally averaged voidage in fast fluidized beds, *Powder Technol.* 71 (1992) 51–58. doi:10.1016/0032-5910(92)88003-Z.

[48] Z.. Li, C.. Wu, F. Wei, Y. Jin, Experimental study of high-density gas–solids flow in a new coupled circulating fluidized bed, *Powder Technol.* 139 (2004) 214–220. doi:10.1016/J.POWTEC.2003.12.005.

[49] H.T. Bi, J.R. Grace, J.-X. Zhu, Types of choking in vertical pneumatic systems, *Int. J. Multiph. Flow.* 19 (1993) 1077–1092. doi:10.1016/0301-9322(93)90079-A.