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COMPUTATIONAL FLUID DYNAMICS OF A FLUID BED EMPLOYING TUNED GAS-SOLID DRAG MODELS

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Abstract. *Fluidized beds are devices in which a fluid flows from the bottom through a bed of particles, keeping them under suspension. Fluidized beds find many applications as reactors for combustion and gasification of solid fuels. For a given fluid-particulate combination, there is a minimum fluidization velocity (U_{mf}) which exerts a drag force that equals the weight of the bed, fluidizing the system. Therefore, it is possible to calculate gas-solid drag forces parameters from a minimum fluidization velocity (Umf) obtained experimentally. In the present work, the objective was to tune gas-solid drag correlations to be used in the Computational Fluid*

Dynamics (CFD) of a fluidized bed employing the Umf and to analyze the improvement of CFD results. The particles employed were one of Geldart-B (sand-like) and two of Geldart-D (spoutable) types, fluidized in a cylindrical riser with 0.114 m internal diameter. The CFD multiphase model employed was the Two-Fluid-Model (TFM). In this model both gas and solid phases are assumed interpenetrating continua, mapped along the domain via its volume fraction, and the Kinetic Theory of Granular Flows (KTGF) is used to model solids phase viscosity term. The force interactions between phases are modeled using gas-solid drag correlations, which in this work were based on Syamlal-O'Brien and Di Felice models. A finite volume method CFD code was used to perform the simulations. The simulations for superficial velocity of 1.5 Umf was performed in order to confront experimental and numerical results of pressure drop and bed height. So far tuned models were better than the original ones in the prediction of fluidization curves (pressure drop versus superficial velocity), and in the prediction of bed expansion and bubble formation. ***Keywords:*** *Tuned drag model, adjusted drag model, Di Felice, Syamlal-O'Brien, fluidized bed.*

1 INTRODUCTION

Fluidized beds with gas-solid flow occur in many industrial applications such as drying, fluid catalytic cracking, solid fuels combustion, gasification, among others. In order to simulate gas-solid fluidized bed flows, Computational Fluid Dynamics (CFD) has been recognized as a promising tool for gas-solid reacting or non-reacting flows. Besides, CFD models can be a tool for understanding and developing fluidized systems, providing detailed information for flow and chemical reactions that gap the lack of information between bench scale and commercial scale. (Pannala et al., 2011)

Among diferent approaches employed to model gas-solid flows, the Two Fluid Model (TFM) is largely used in CFD, for it is less computational demanding than other models available. The TFM recognizes both gas and solid phases as interpenetrating continua. The mathematical model is given by mass and momentum balance equations for each phase. The solid viscosity and the exchange of linear momentum between pahses are needed to close the system. The first is usually modeled using the Kinetic Theory for Granular Flows (KTGF) (Lun et al., 1984)(Agrawal et al.,2001). The models for the exchange of momentum are correlations based on the knowledge of the drag in fluidized systems. These gas-solid drag models play a major role in the results obtained using TFM.

For a given fluid-particulate combination, there is a minimum fluidization velocity (U_{mf}) which exerts a drag force that equals the weight of the bed, fluidizing the system. Therefore, it is possible to calculate gas-solid drag forces parameters from a minimum fluidization velocity (U_{mf}) obtained experimentally.

Syamlal and O'Brien (1987) have shown a way to adjust drag correlation parameters correlation using the minimum fluidization velocity. Esmaili and Mahinpey (2011) have shown a comparison between different drag models in modeling a real system. They showed how adjusted models - Syamlal-O'Brien and Di Felice - presented a better prediction of experimental results.

The purpose of the present study is to improve gas-solid drag models using experimental results of U_{mf} from a lab scale test bench. The TFM implemented in a CFD code (MFIX – Multiphase Flow with Interphase Exchanges, DOE-NETL) is used to test and evaluate the tuned drag models by comparing numerical and experimental results. The lab scale fluidized bed is a prototype located at SATC.

2 MODEL FORMULATION

2.1 Drag Models

Two drag models were considered for adjustment, Syamlal-O`Brien (SO) and Di Felice (DF), and are compared to Wen-Yu (Wen and Yu, 1966) and Ergun (Ergun, 1952). The "Eqs. 3-7" shows the equations used for Syamlal-O`Brien and "Eqs. 8-11" shows the equations used for Di Felice drag model. There are two different Reynolds number used, one is "Re" (Eq. 1) that is for a single particle, and "Re_s" (Eq. 2) that consider the void fraction of particles. For one particle, the "Eq. 2" become equal to "Eq. 1" as void fraction, ε_g, assume value one.

$$Re = \frac{\rho_g d_s |\vec{u}_s - \vec{u}_g|}{\mu_g} \quad (1)$$

$$Re_s = \frac{\varepsilon_g \rho_g d_s |\vec{u}_s - \vec{u}_g|}{\mu_g} \quad (2)$$

where ρ_g means gas density, μ_g gas viscosity, d_s, mean particle diameter, u_s, superficial solids velocity, and u_g,, superficial gas velocity.

Syamlal-O'Brien drag model correlation:

$$\beta_{SO} = \frac{3\rho_g \varepsilon_g (1-\varepsilon_g)}{4 d_s v_r^2} C_D |u_s - u_g| \quad (3)$$

where "β" is the drag factor of solid phase in gas phase, "C_D" is the drag coefficient of Dalla Valle.(1948) presented at "Eq. 4" modified by Syamlal and O'Brien (1988) and the original at "Eq. 9"

$$C_{D,SO} = \left[0,63 + \frac{4,8}{\sqrt{\frac{Re}{v_r}}}\right]^2 \quad (4)$$

$$v_r = 0,5\left(A - 0,006Re_s + \sqrt{(0,006Re_s)^2 + 0,12Re_s(2B - A) + A^2}\right) \quad (5)$$

$$A = \varepsilon_g^{4,14} \quad (6)$$

$$B = \begin{cases} C_2 \varepsilon_g^{1,28}; \varepsilon_g < 0,85 \\ \varepsilon_g^{C1}; \varepsilon_g \geq 0,85 \\ C_1 = 2,65\,, C_2 = 0,8 \end{cases} \quad (7)$$

where C_1 and C_2 are adjustable values.

Di Felice Drag Model correlation:

$$\beta_{DF} = \frac{3\rho_g (1-\varepsilon_g)}{4 d_s} C_D |u_s - u_g| f(\varepsilon_s) \quad (8)$$

$$C_{D,DF} = \left[0,63 + \frac{4,8}{\sqrt{Re_s}}\right]^2 \quad (9)$$

$$f(\varepsilon_s) = (1 - \varepsilon_s)^{-x} \quad (10)$$

$$x = P - Q \cdot exp\left[\frac{-[1.5 - log(Re_s)]^2}{2}\right] \quad (11)$$

where original values of "P" and "Q" are 3.7 and 0.65, respectively.

Wen-Yu:

$$\beta_{WY} = \frac{3}{4} \frac{\rho_g \varepsilon_g (1-\varepsilon_g)}{4 d_s} C_d |u_s - u_g| \varepsilon_g^{-2.65} \quad (12)$$

Ergun:

$$\beta_{Ergun} = 150\frac{\mu_g*(1-\varepsilon_g)^2}{\varepsilon_g d_s^2} + 1.75\frac{(1-\varepsilon_g)\rho_g}{d_s}\left| u_s - u_g \right| \tag{13}$$

2.2 Drag adjusting

At minimum fluidization velocity, a fluidized bed is suspended and is considered that the fluid supports the weight of the whole bed. No forces of contact between particles are taken into account, so the particles are suspended by a balance of weight, buoyancy and drag forces. The balance of mass leads to “Eq. 14” that is used for Di Felice drag model adjustment.

In order to obtain adjusted values of “P” and “Q”, experimental “β” is calculated through minimum fluidization velocity, “U_{mf}”, and gas fraction, “ε_g”, at minimum fluidization. Through “Eqs. 2,8-12”, considering “$u_s = 0$” and “$\varepsilon_g = \varepsilon_{g,mf}$”, “x” function can be linearized in order to obtain “P” and “Q” values.

$$\beta_{mf} = \frac{\varepsilon_{g,mf}\,(1-\varepsilon_{g,mf})(\rho_s-\rho_g)g}{U_{mf}} \tag{14}$$

For Syamlal-O`Brien, the parameter C_2 is related to minimum fluidization velocity through velocity voidage correlation “Re_t”. C_2 is changed until the “Eq. 15” match.

$$U_{mf}^{exp} - Re_{ts}\frac{\varepsilon_g\mu_g}{\rho_g d_s} = 0 \tag{15}$$

After “C_2” being found, the “Eq. 16” is used to define “C_1” in order to guarantee the continuity of Syamlal-O`Brien Drag Model.

$$C_1 = 1.28 + \frac{\log(C_2)}{\log(0.8)} \tag{16}$$

2.3 Experimental results

The experimental setup was the bench scale fluidized bed system located at SATC, in Criciúma, SC. The circuit is composed by compressor, plenum, tuyere distributor, riser, top exit with curve, cyclone, downcomer and three switchable types of valve for reinjection. Those are L valve, loop seal valve and loop seal with three stages. The air flow was measured using an orifice plate and a differential pressure transducer. There are some pressure taps distributed along the circuit, allowing choosing between different positions to measure the pressure drop. The differential pressure was sampled at a frequency of 1 Hz, due to the limitation of the AD converter. The bed pressure drop was determined by measuring the differential pressure between one point upwind the distributor and one point somewhere in the riser, discounting the void bed pressure drop which is determined previous to the loaded bed experiments. The particles empoyed in the tests were sand and glass beads of two types. The results for their minimum fluidization velocity are summarized in Table 1.

Table 1. Properties of particles tested experimentally and used for simulation.

Property	Unit	AF1	EV2	EV3
Material	-	Sand	Glass bead	Glass bead
ρ_s	kg/m^3	2640	2490	2490
ρ_g	kg/m^3	1.18	1.18	1.18
d_s	mm	1.216	0.80	0.30
$\varepsilon_{g,fixed\ bed}$	-	0.40	0.38	0.39
ε_{mf}	-	0.43	0.40	0.42
U_{mf}	m/s	0.055	0.380	0.784

2.4 Simulation

Simulation were carried out in a 2D domain with 0.11 meters length and 1 meter high using the MFIX 2015-2. It was considered the TFM with KTGF for solids viscosity. In order to introduce Di Felice model into MFIX code, it was used “usr_drag.f” and for boundary conditions change during simulation, the subroutine file changed was “usr1.f”.

Table 2. Parameters of simulation

	Unit	Values
Length	m	0.11
Height	m	1.0
Cells through length	-	40
Cells through height	-	320
Wall boundary condition	-	No Slip
Inlet gas velocity	-	1.5 U_{mf}
Bed height	m	0.3
Bed voidage	-	$\varepsilon_{g,mf}$
Discretization method	-	superbee

3 RESULTS

3.1 Adjust of Di Felice Drag Model

Experimental data were treated to obtain values of "x" of Di Felice drag model, plotted against "Z", as showed at "Figure 1" and linearized in order to obtain adjusted values "P" and "Q". Where "P" is the value when "Z" is equal to zero and "-Q" is the angular coefficient.

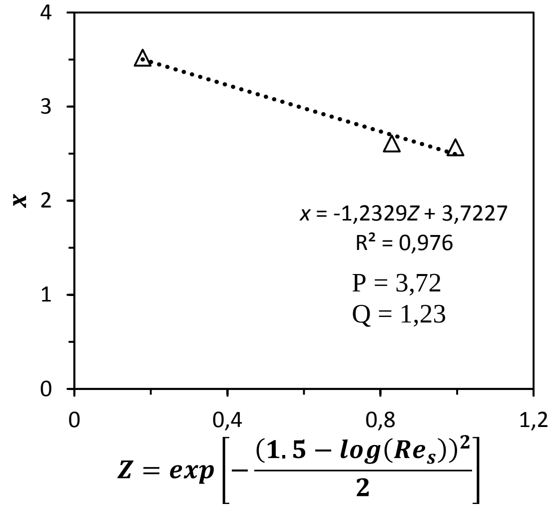

Figure 1. Linearization of x using experimental values

From the values obtained of "P" and "Q" the new function of "x" is plotted along with experimental values and original Di Felice drag model that can be seen at "Figure 2".

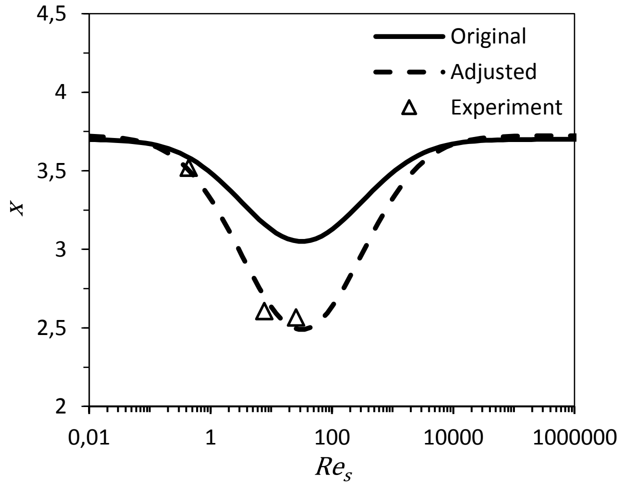

Figure 2. Graph of x obtained experimentally, original function of x and adjusted function of x for Di Felice drag model

Figure 2 shows lower values of "x" for intermediary Reynolds than original one but a little higher values for low and high Reynolds. Experimental results for minimum fluidization velocity are at intermediate values of Reynolds and consequently will present a lower drag force, requiring higher velocities to fluidized than original model as can be seen at "

By using Syamlal-O'Brien adjustment, the one point used fits perfectly on the curve. The same would happen for the method proposed for adjustment by using two points to fit. As it were used three points, the curve did not fit perfectly, and calculated results of minimum fluidization velocity differ slightly from experimetal. "Table 3" presents the minimum fluidization velocities predicted by different drag models of properties presented at "Table 1".

Table 4", that presents minimum fluidization velocity obtained from the different models, except for SO adjusted because it is exactly the same of the experiment. "Figure 3"shows the ratio between drag forces of original model and adjusted one for velocities ranging from 0.5 to 3 m/s (Re_s ranging from about 15 to 230) for properties of particle "EV3" at "Table 1". The difference increases as velocity increase but decrease until match the same value as voidage increases from 0.4 to 1.

3.2 Adjust of Syamlal-O'Brien drag model

Using the method of Syamlal and O'Brien (1987) the values of "C1" and "C2" are found in "Table 3"

Table 3. Adjustment of "C1" and "C2" of Syamlal-O'Brien drag model for the particles.

	AF1	EV2	EV3
C1	0.21	0.64	0.84
C2	10.9	4.0	2.33

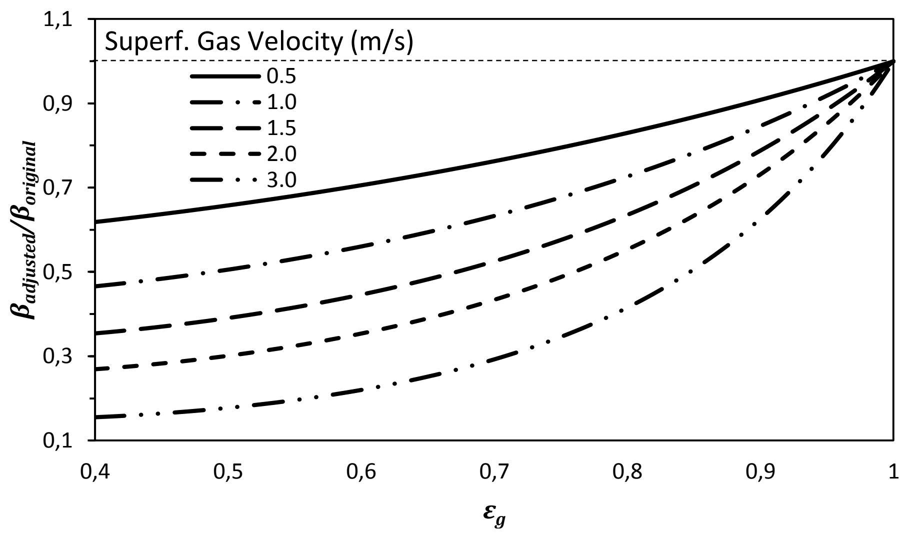

Figure 3. Ratio Between adjusted drag force and original drag force of Di Felice drag model against voidage for velocities from 0.5 to 3.0 m/s.

3.3 Comparison of minimum fluidization velocity prediction

By using Syamlal-O'Brien adjustment, the one point used fits perfectly on the curve. The same would happen for the method proposed for adjustment by using two points to fit. As it were used three points, the curve did not fit perfectly, and calculated results of minimum fluidization velocity differ slightly from experimetal. "Table 3" presents the minimum fluidization velocities predicted by different drag models of properties presented at "Table 1".

Table 4. Minimum Fluidization Velocity obtained for different drag models and adjusted Di Felice

Particle	Unit	Experiment	Di Felice Original	Di Felice Adjusted	Syamlal-O'Brien	Wen-Yu	Ergun
EV3	m/s	0.784	0.57	0.82	0.74	0.67	0.76
EV2	m/s	0.380	0.24	0.35	0.47	0.39	0.42
AF1	m/s	0.055	0.052	0.056	0.18	0.072	0.11

The orginal models and adjusted models of Di Felice and Syamlal-O'Brien, together with Ergun (Ergun, 1952) and Wen-Yu (Wen and Yu, 1966), were calculated through MFIX-2015 TFM CFD cases accordingly to "Table 1" and "Table 2".

3.4 Simulation results

3.4.1 Dependency of mesh size

For mesh dependency verification it was used the case for finest particle and ten times minimum fluidization velocity. It is expected to simulations with higher velocities and small particles to require the finest mesh. "Figure 4" shows that even coarsest mesh can describe similar particle distribution over bed height. Even though finest mesh were used to guarantee calculation of other cases.

3.4.2 Transitioning

For transition visualization from fixed bed up to fluidized bed of particle EV3, "Figure 5" shows fluidization starting from velocity equal to zero until $1.5U_{mf}$ for Di Felice and Syamlal-O`Brien models, both original and modified ones. Di Felice modified model started fluidization of particle EV3 just as velocity reaches minimum fluidization velocity opposing to original model that starts fluidization at $0.8U_{mf}$ (0.67m/s), that is above minimum fluidization velocity predicted at “Table 4”. Modified Syamlal-O`Brien have not changed much as “C1” and “C2” are similar to original and both started fluidization near U_{mf}., but original Symlal-O’Brien started slightly before minimum fluidization velocity.

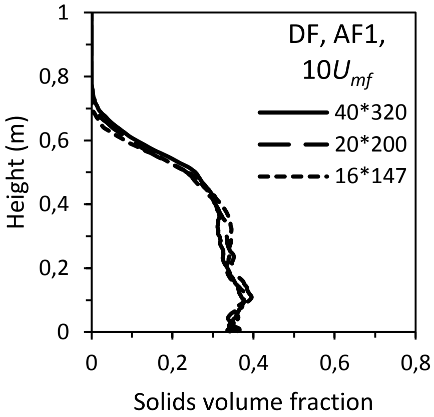

Figure 4. Solids volume fraction over height for different mesh sizes using Di Felice drag model at ten times minimum fluidization velocity, $10U_{mf}$, of AF1 particle.

3.4.3 Bed size

Using the values of time averaged solids volume fraction over height, it is possible to compare bed height for simulation of different drag models. “Figure 6 (a)” shows the void fraction of solids along bed height for velocity of 0.08m/s ($1.5U_{mf}$) for particle AF1. As expectation shown on “Table 4”, simulation with Symlal-O’Brien model did not fluidized at 0.08m/s, since it is below minimum fluidization velocity predicted by the model. As adjusted and original Di Felice model predict values of “x”(see “Figure 2”), and consequently for “f”, close to each other for Reynolds near minimum fluidization condition, it was expected the fluidization behaviour and bed height to be similar. “Figure 6(a)” ratify those expectations showing that for particle AF1, at low Reynolds condition, both models give drag force very similar, with similar buble size and shape, with no visible difference,making both curves being practicaly coincident.

Figure 6 (b) shows a very curious result when it shows that Syamlal-O’Brien adjusted resulted in similar values compared to Di Felice original. It can be seen, by observing “Figure 6 Figure 7”, that Di Felice drag model have shown lower bed hieghts on simulation, except for AF1 particle whose results are similar. The opposite is seen for Syamlal-O’Brien adjust, with exception of simulation of particle EV3 that have shown similar results.“Figure 7” shows the comparison among the original and adjusted models together with Wen-Yu and Ergun drag models. It can be seen on “Figure 7 (a)” that both original and adjusted Di Felice drag model have predicted smaller bed heights with denser beds, being the adjusted model the one that predicted the smallest bed height. The other drag models (Syamlal-O’Brien original and adjusted, Wen-Yu and Ergun) have shown very similar results.

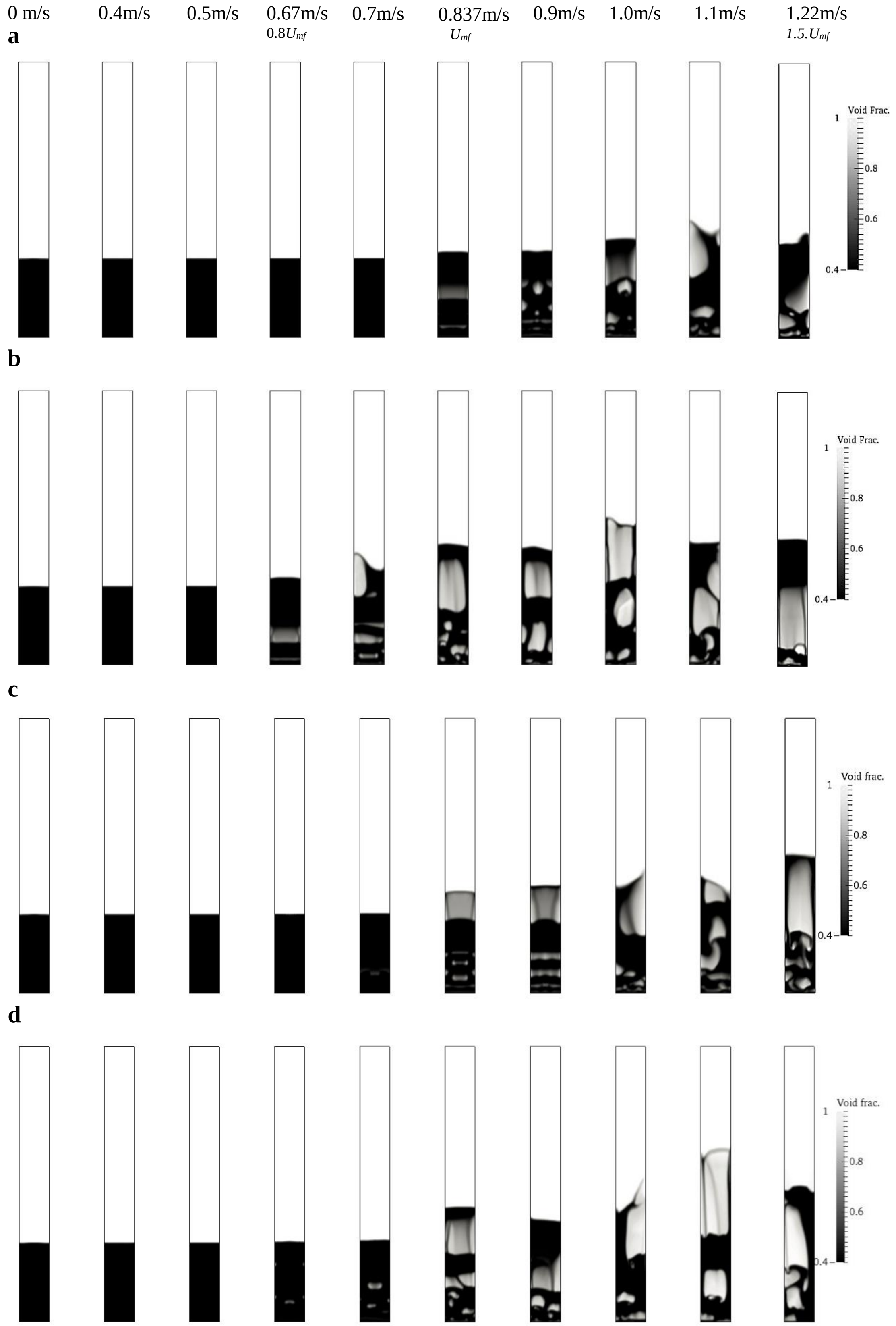

Figure 5. Transition of Di Felice adjusted (a) and original (b) drag model, Syamlal-O`Brien adjusted (c) and original (d) from 0 to 1.5U_{mf}: every 1 second superficial gas velocity changes: from 0 to 0.4m/s, 0.5m/s, 0.669m/s, 0.7m/s,0.837m/s, 0.9m/s, 1.1m/s 1.225 m/s.

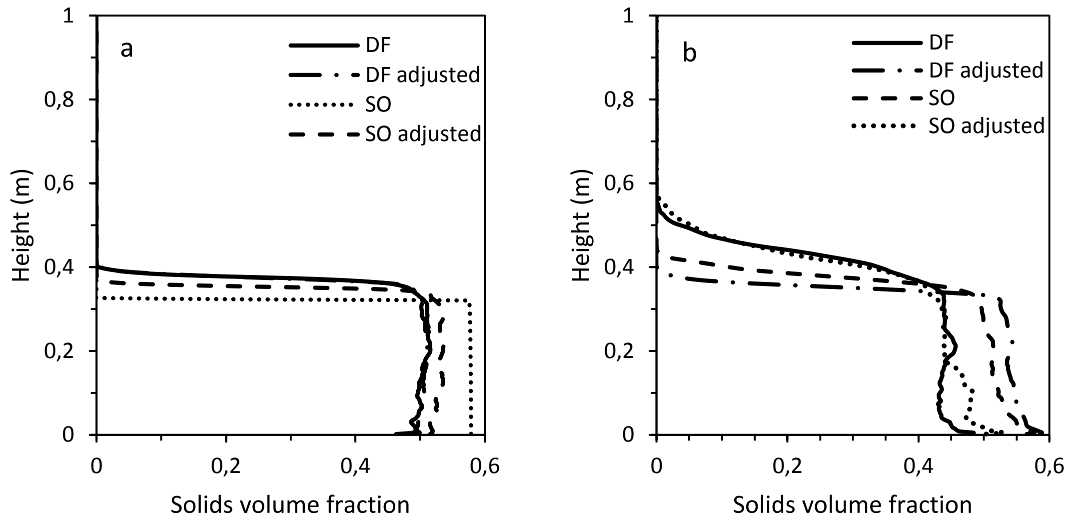

Figure 6. Comparison between different drag models for solid fraction of particle AF1 (a) and EV2 (b) with velocity of 1.5U_{mf}

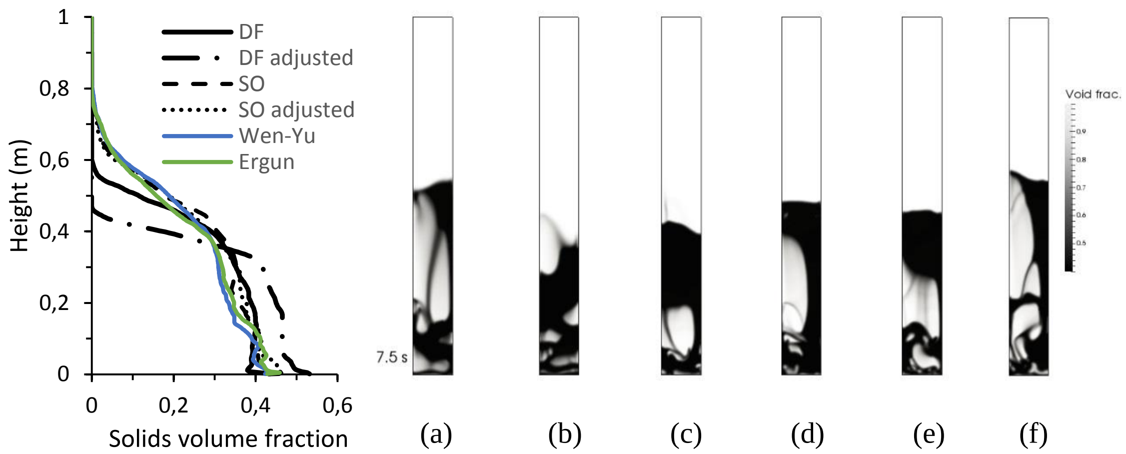

Figure 7. (Left) Time averaged solids volume fraction over height. (Right) Simulation with original Di Felice drag model (a) and Di Felice modified (b), Symlal-O'Brien original (c), Syamlal-O'Brien adjusted (d), Ergun (e) and Wen-Yu (f) for particle EV3 and 1.225 m/s.

4 CONCLUSIONS

The model of Di Felice adjusted well to experimental results of the three particles used, being two of them Geldart D and one Geldart B. The CFD results for the fluidization of glass beads by air were highly affected by the gas-solid drag model. Transition from fixed to fluidized bed was well predicted by adjusted models as expected, for they use the coditions of incipient fluidization to model gas-solids drag. The three different particle sizes were essential to verify the difference between drag models since Syamlal-O'Brien adjust is very close to original for particle EV3 and Di Felice is very close to original for particle AF1. The model of Di Felice adjusted well to experimental results of the three particles used, being two of them Geldart D and one Geldart B. In the results in which original and adjusted parameters were the farest, the main feature of adjusted models were detected: they predict lower bed expansion and less bubble formation. Despite pressure drop had shown differences, the data are nonclonclusive.

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