CHEMICAL ENGINEERING TRANSACTIONS

VOL. 32, 2013

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-23-5; **ISSN** 1974-9791

DOI: 10.3303/CET1332262

Effects of Phases' Numbers and Solid-Solid Interactions on the Numerical Simulations of Cyclones

Karina K. Costa*[a], Oscar L. Sgrott Jr[a], Rodrigo K. Decker[a], Edelberto L. Reinehr[a], Waldir P. Martignoni[b], Henry F. Meier[a].

[a]Regional University of Blumenau
São Paulo St., 3250, Room I-204, Zip Code 89030-000, Blumenau-SC, Brazil
[b]PETROBRAS/AB-RE/TR/OT
República do Chile Ave., 65, Zip Code 20031-912, Rio de Janeiro-RJ, Brazil
karina.klock@yahoo.com.br

Despite being simple equipment with wide range of operation, low investment cost and maintenance, the cyclones present a complex turbulent flow, with recirculation zones, high-intensity turbulent, high vorticity conservation, among others. The mathematical models used to describe these phenomena have a very complex solution, leading to a high computational cost, and several studies in this framework have been done. One way to balance the computational cost of simulations with the accuracy in the flow description is the use of Euler-Euler models that has been applied in this work. Also, the numerical analysis of the flow was performed by using different particle diameters to represent distinct solid phases. The model was set to represent one, three and five solid phases (Cyclo EE_1, Cyclo EE_3 and Cyclo EE_5, respectively) to compare the number of solid phases influence. Furthermore, it was analyzed the effect of the solid-solid interaction between the different solid phases on the cyclone performance, through the proposition of an interface force model similar to the fluid dynamic drag force. Numerical and experimental data were combined and the influence of the 4-way coupling (solid-solid interaction) on the response variables was noticed. By using the 4-way coupling, the numerical solution was more stable and the dynamic behavior of the overall efficiency of separation oscillating was damped. So, the numerical study shows that the solid phases' representation by the particle size describes the multiphase flow with greater fidelity. The combination of physical and numerical studies to refine the computational code and the proposal suggested in this work proved to be very promising for the advancement of multiphase flow studies in cyclones.

1. Introduction

The mathematical models used to describe cyclones flow have a very complex solution, leading to a high computational cost because of phenomena like as high-intensity turbulent, vorticity conservation, recirculation zones and others.

The improvement of the fluid dynamic modeling of multiphase flows is an excellent tool to optimization in the separation performance. Euler-Euler gas-solid models have been used in the multiphase ambit because allows balancing the computational cost and the flow accuracy (Passalacqua and Fox, 2011). Traditionally the gas-particle flow is modeled with two phases, one gas and one solid, represented by an average diameter. However, some researches proposed numerical models using *n* solid phases to represent the particles in the flow, this can describe the fluid and particles movement peculiarities with greater fidelity than the usual way (two phases) (Ibsen et al., 2000; Mathiesen et al., 2000; Vegini et al., 2008; Meier et al., 2011; Sgrott Jr. et al., 2012.).

In this study it was evaluated the effect of the number of solid phases in the cyclone performance. Experimental data were combined with numerical simulations using the computational code Cyclo-EE_n dedicated for cyclones considering two, four and six phases, one gas and one, three or five solid phases, respectively. Each solid phase was represented by a diameter and a volume fraction. Also it was realized

Please cite this article as: Costa K.K., Sgrott Jr O.L., Decker R.K., Reinehr E.L., Martignoni W.P., Meier H.F., 2013, Effects of phases' numbers and solid-solid interactions on the numerical simulations of cyclones, Chemical Engineering Transactions, 32, 1567-1572 DOI: 10.3303/CET1332262

a numerical study of the four-way coupling (solid-solid interaction) parameter sensibility with the six-phase Eulerian model. Thereunto, it was proposed the constitution of an interface force model between the *n* solid phases similar to the drag force model between the gas and the solid phases for the propose of consider the solid-solid interaction applied to cyclones.

2. Mathematical Modelling

Some assumptions were adopted for the use of Euler-Euler multiphase model. It is suggested therefore the interpenetrability hypothesis between the phases, and the continuum hypothesis physical and mathematical, neglecting the molecular characteristics of the material. In gas-solid multiphase model there is the presence of two fluids - the solid phase, which is referred to as hypothetical fluid and the gas phase. The hypothetical fluid assumes the fluid dynamic behavior of the real fluids due to physic-chemical interactions between them, but do not have the viscous tension term (inviscid model).

For constitution of the n-phase model, presuppose some simplifying assumptions: (a) *n* different solid phases can be represented each by a particle size, density and volume fraction; (b) diluted and inviscid flow for solid phases; (c) disturbances in the flow near the inlet region due to asymmetry of the tangential or in volute gas inlet to the cyclone quickly disappear, which makes it possible to use axial symmetry and apply the 3-D symmetry model; (d) incompressible and isothermal flow; (e) pressure force acts only on the thermodynamic gas phase; (f) the hybrid turbulence model is used, which is composed of a combination of the k-ε standard model for the radial and axial components of the Reynolds's Tensor, and Prandt's Longitudinal Mixing Model for tangential components; (g) transfer of momentum at the interface between the phases is predicted by a constituted drag force model, with two and four-way coupling.

2.1 The six-phase Eulerian model

Modeling the multiphase flow in general Eulerian approach begins with the use of the mass and momentum conservation equations. It is used the gas phase volume fraction (f_g) for developing the model. This fraction represents the ratio between the volume of gaseous phase and the total volume. The mathematical modeling of fluid-dynamic flow in cyclones used in this work is based on the Navier-Stokes equations. In multiphase flow is necessary to consider the influence of solid phases on the flow. This can be accomplished by introducing the volume fraction of each phase. The equations of momentum and mass for the solid and gas phases, in Eulerian approach, can be written as follows.

Mass conservation in the gas phase:

$$\frac{\partial}{\partial t}\left(f_g \rho_g\right) + \nabla.\left(f_g \rho_g \mathbf{v}_g\right) = 0; \tag{1}$$

Mass conservation in the solid phase:

$$\frac{\partial}{\partial t}\left(f_{si} \rho_{si}\right) + \nabla.\left(f_{si} \rho_{si} \mathbf{v}_{si}\right) = 0 \;; \tag{2}$$

Momentum conservation in the gas phase:

$$\frac{\partial}{\partial t}\left(f_g \rho_g \mathbf{v}_g\right) + \nabla.\left(f_g \rho_g \mathbf{v}_g \mathbf{v}_g\right) = -f_g \nabla.\left(\mathbf{T}_g^{eff}\right) + f_g \rho_g \mathbf{g} - \nabla p + \sum_{i=1}^{n}\left(\mathbf{F}_{drag}\right)_{g,si} \;; \tag{3}$$

Momentum conservation in the solid phase:

$$\frac{\partial}{\partial t}\left(f_{si} \rho_{si} \mathbf{v}_{si}\right) + \nabla.\left(f_{si} \rho_{si} \mathbf{v}_{si} \mathbf{v}_{si}\right) = f_{si} \rho_{si} \mathbf{g} - \left(\mathbf{F}_{drag}\right)_{si,g} - \sum_{j=1 \neq i}^{n} (\mathbf{F}_{drag})_{si,sj} \text{ . with i = 1,...,5} \tag{4}$$

In Eq (1) to Eq (4), the variables f, ρ and v represent respectively the volume fraction, the density and the velocity. The subscripts *g*, *si* and *sj* indicate the gas phase, and the solid phases *i* and *j*. In Eq (3) and Eq (4), the terms T_g^{eff}, g, p e F_{drag}, represent, respectively, the effective stress tensor in the gas phase, the acceleration of gravity, the thermodynamic pressure and the drag forces acting between the phases.

The equations for turbulence closure, numerical methods, the initial and the boundary conditions used by the computer code CYCLO-EE_n can be found in Meier et al. (2011; 2002a; 2002b). The model for gas-solid interaction can be found in Meier et al. (2011) and is the basis for developing the solid-solid interaction.

2.2 Model for solid-solid interaction

A proposal of this work is to establish a model of interface force between the solid phases similar to the fluid dynamic drag force model for gas-solid interaction. Therefore, the drag force between the phase *j* and *i* can be written by:

$$\left(F_{drag}\right)_{sj,si} = \beta_{j,i}\left(\mathbf{v_{sj}} - \mathbf{v_{si}}\right), \text{ with } i = 1,\ldots,5 \tag{5}$$

Where it is found that particles with a smaller diameter (*i*) are dragged by the larger particles (*j*); $\beta_{j,i}$ is the coefficient of interface between the phases *j* and *i*, and v the velocity of each phase.

A model for the coefficient of the interface between the solid phases may be proposed by analogy to the gas-solid interaction model. The interface coefficient between the solid phase *j* and *i* can be expressed by:

$$\beta_{j,i} = \frac{3}{4}\left(C_D\right)_{sj,si} \frac{f_{sj}\rho_{sj}\left|\mathbf{v_{sj}} - \mathbf{v_{si}}\right| f_{si}}{\Psi_2 d_{si}\phi_{si}} \tag{6}$$

Where β is symmetrical, such that: $\beta_{i,j} = \beta_{j,i}$. It is possible to find various empirical correlations for calculating the coefficient of drag as a function of the Reynolds number. Coelho and Massarani (Massarani, 1997) published a correlation that establishes values for all flow regimes (Stokes, transition and Newton), and it can be expressed by:

$$\left(C_D\right)_{sj,si} = \left[\left(\frac{24}{K_{1_{si}}\ Re_{sj,si}}\right)^{0,85} + K_{2_{si}}{}^{0,85}\right]^{1,18} \tag{7}$$

With,

$$K_{1_{si}} = 0,843\ \log_{10}\left(\frac{\phi_{si}}{0,065}\right), \tag{8}$$

and

$$K_{2_{si}} = 5,31 - 4,88\ \phi_{si}, \tag{9}$$

The Reynolds number for the solid phase *i*, on condition of drag by the solid phase j can be expressed by:

$$Re_{sj,si} = \frac{\rho_{sj}\left|v_{sj} - v_{si}\right| d_{si}}{\mu_{sj}} \tag{10}$$

In the model used the solid phases are considered inviscid for calculating the Reynolds number of the phase i, under drag condition by the solid phase j in Eq (10). As a new proposal, in this study it is adopted a linear dependence between a kinematic viscosity of the hypothetical solid phase j and the viscosity kinematics of the gas phase. This dependence was studied in this work by changing the parameter Ψ_1.

$$\upsilon_{sj} = \Psi_1 \upsilon_g \tag{11}$$

or,

$$\frac{\mu_{sj}}{\rho_{sj}} = \Psi_1 \frac{\mu_g}{\rho_g} \tag{12}$$

Replacing the Eq (12) into Eq (10), it is possible to calculate the Reynolds Number for the solid phase *j* relating to the kinematics viscosity of the gas phase.

$$Re_{sj,si} = \frac{\rho_g\left|v_{sj} - v_{si}\right| d_{si}}{\Psi_1 \mu_g} \tag{13}$$

Where the empirical parameters Ψ_1 and Ψ_2 included in Eq (13) and Eq (6), respectively, must be adjusted from experimental data.

In this work, it was done a parametric analysis of the parameter Ψ_1 observing the answer variables – drop lost, overall and individual efficiency, keeping constant Ψ_2 and equal to ρ_{si} to conserve the magnitude order of $\beta_{j,i}$ close to $\beta_{g,si}$. The parameter Ψ_1 was fixed in three values that correspond to different magnitude order of the Reynolds number.

3. Experimental setup

The experimental readings include: pressure drop, individual and global efficiency of collection; and the controllable parameters were the input velocity in the cyclone (12 m/s) and the solids concentration (11 g/m³).

4. Numerical setup

The numerical simulations were performed under the same conditions of the physical experiments and it was applied the particle size and volume fraction for each case described in Table 1.

Table 1: Solid phases' characteristics applied in the n-phases models.

	Two-phase		Four-phase		Six-phase	
Diameter	Particle size (µm)	Volume Fraction (%)	Particle size (µm)	Volume Fraction (%)	Particle size (µm)	Volume Fraction (%)
d_{s1}	21.066	100	62.019	15.870	62.019	15.870
d_{s2}	-	-	21.066	68.260	29.492	22.753
d_{s3}	-	-	5.811	15.870	21.066	22.754
d_{s4}	-	-	-	-	14.656	22.753
d_{s5}	-	-	-	-	5.811	15.870

The solid-solid interaction was evaluated in the three n-phase models by using the parameter Ψ_1 set as 0 (two-way coupling), 0.01 and 0.1.

5. Results

The results of global efficiency are presented by Figure 1. It is possible to observe that the using of four-way coupling (solid-solid interaction model) improved the results nearing to experimental results. The use of parameter Ψ_1 set as 0.01 showed the best results in this case, where both four and six-phase model remained inside the standard deviation of the experimental results. The number of solid phases also presented great change at the results. The six-phase model had the results closer to the experimental data.

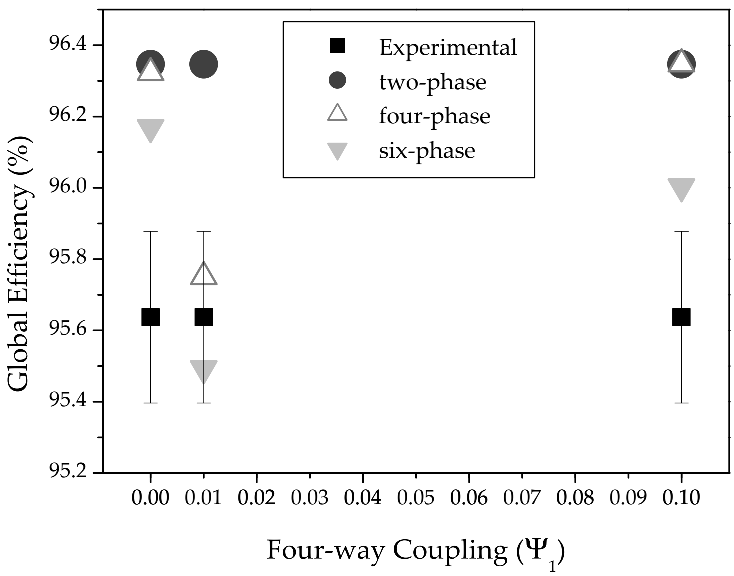

Figure 1: Global efficiency of collection experimental and numerical using n-phase and solid-solid interaction model

When it was analyzed the cyclone pressure drop (Figure 2), the best results were found using the six-phase model and Ψ_1 set as 0.1. Compared to the traditional two-phase model (one gas and one particle), the use of three and five solid phase had results near to the experimental data although overestimated.

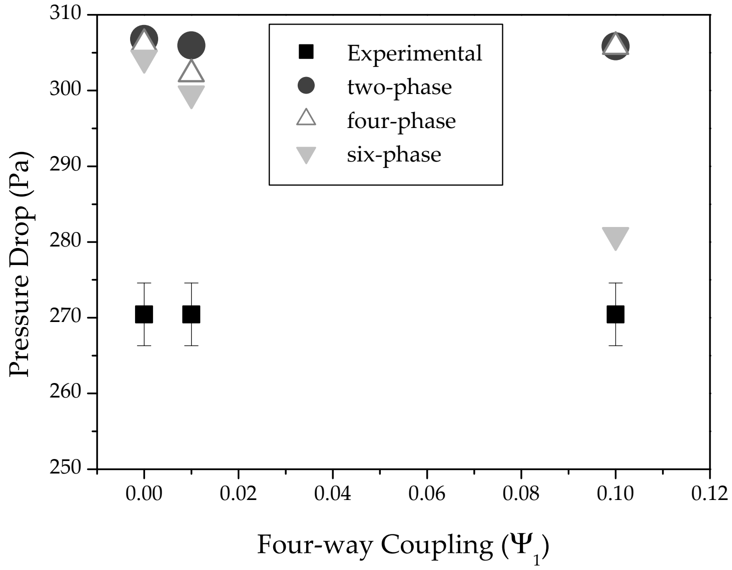

Figure 2: Cyclone pressure drop experimental and numerical using n-phase and solid-solid interaction model

The use of n-phase model is very influent on the individual efficiency of collection (Figure 3). Once the two-phase model considers only one diameter as solid phase, the individual and global results are the same (close to 100%). The diameters above 15μm presented overestimated results and underestimated for the smallest diameter, these results have some differences compared to the experimental data. Despite this the four and the six-phase models presented efficiency curves more similar to the experimental results.

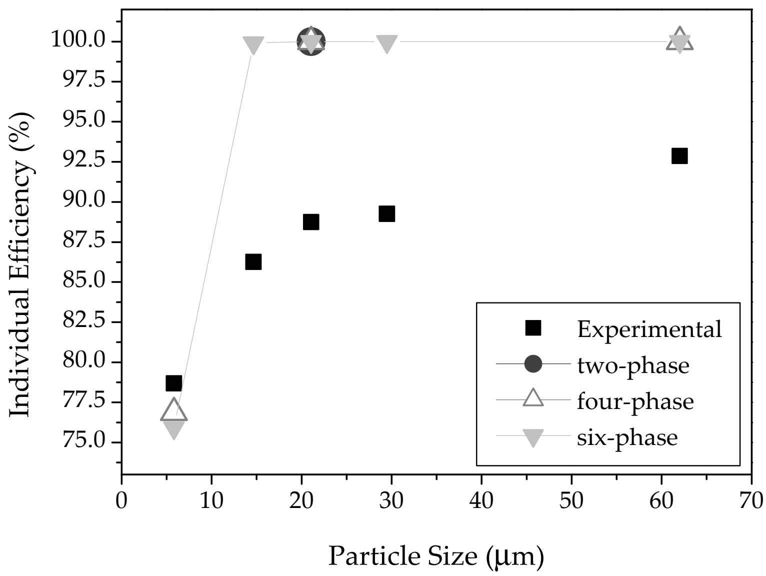

Figure 3: Individual efficiency of collection experimental and numerical using n-phase models

Since the best results of individual efficiency were using the six-phase model, the solid-solid interaction was applied to this case in order to analyze the best value of the parameter Ψ_1 (Figure 4). The efficiency curves presented overestimated values for the biggest diameters and understimated value to the smallest particle size.

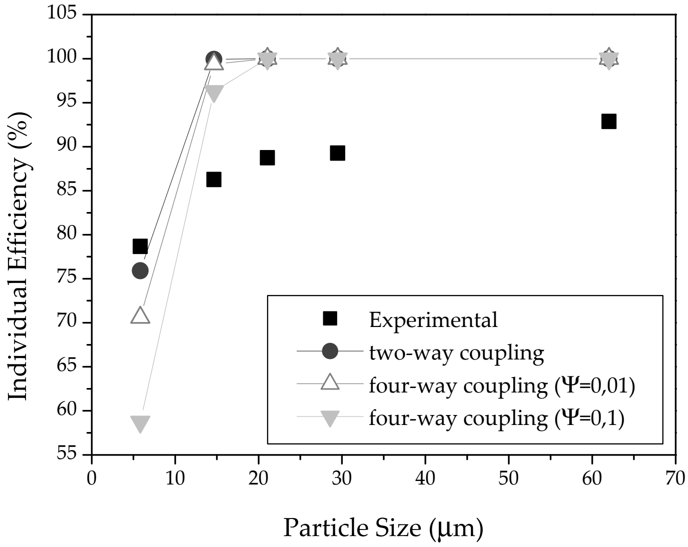

Figure 4: Individual efficiency of collection experimental and numerical using six-phase and solid-solid interaction model (four-way coupling)

6. Conclusions

The combination of experimental and numerical techniques allowed the verification, validation and parameter sensibility analysis of the six-phase Eulerian-Eulerian model implemented at the CFD code CYCLO-EE_n.

As affirmed in previous works, the representation of solids phases by particle diameters is very appropriate, even to diluted conditions. The six-phase model presents a great alternative that allows to balance accuracy in the results and computational cost of simulations.

It was observed by comparing the numerical and physical results the 4-way coupling influence, representing the solid-solid interaction. All the studied variables presented sensibility to the proposed modification. The value of Ψ_1 which fits better to the experimental data of global and individual efficiency was 0.01. It was possible to improve the computational code used and the model modification suggested in this work is very promising in the multiphase flow studies applied to cyclones.

7. References

Gidaspow D., 1994, Multiphase Flow and Fluidization, 1st ed. Academic Press, New York, United States.

Ibsen C. H., Solberg T., Hjertager B. H., 2000, The influence of the number of phases in Eulerian Multiphase Simulations. CHISA, 14th International Congress of Chemical and Process Engineering, Praha, The Czech Republic, 27-31.

Massarani G., 1997, Particulate Fluid Systems (in Portuguese). Publisher UFRJ, Rio de Janeiro-RJ, Brazil.

Mathiesen V., Solberg T., Hjertager B. H., 2000, An experimental and computational flow behavior in a circulating fluidized bed. International Journal of Multiphase Flow 26, 387-419.

Meier H. F., Ropelato K., Forster H., Iess J. J., Mori M., 2002a, Computational Fluid Dynamics (CFD) for the calculation and interpretation of cyclones Part 1. (in German). ZKG International 55, 04, 64-75.

Meier H. F., Ropelato K., Forster H., Iess J. J., Mori M., 2002b, Computational Fluid Dynamics (CFD) for the calculation and interpretation of cyclones Part 2. (in German). ZKG International 55, 06, 58-64.

Meier H. F., Vegini A. A., Mori M., 2011, Four-Phase Eulerian-Eulerian Model for Prediction of Multiphase Flow in Cyclones. The Journal of Computational Multiphase Flows 3, 93-106.

Passalacqua A., Fox R. O., 2011, Implementation of an iterative solution procedure for multi-fluid gas-particle flow models on unstructured grids. Powder Technology 213, 174-187.

Sgrott Jr. O. L., Costa K. K., Noriler D., Martignoni W. P., Meier H. F., 2012, Geometric optimization of cyclones for combination of nonlinear mathematical programming and computational fluid dynamics techniques (CFD), 2012 AIChE Annual Meeting, Pittsburgh, PA.

Vegini A. A., Meier, H. F., Iess J. J., Mori M., 2008, Computational Fluid Dynamics (CFD) Analysis of Cyclone Separators Connected in Series. Industrial & Engineering Chemistry Research, v.47,192-200.