NUMERICAL MODELING OF PARTICLE DYNAMICS IN A CYCLONE SEPARATOR

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Abstract. *The purpose of this study is to investigate though Computational Fluid Dynamics (CFD) simulations if the sphericity of particles affects significantly the grade collection efficiency of a cyclone separator. Published experimental data for two cyclones is used to compare with data obtained by numerical simulation. The collection efficiency of the simulation was done considering spherical particles and non-spherical particles of 3 to 7 microns of diameter. It is observed in the simulation that the sphericity of particles is a factor that differentiates the movement of particles inside the cyclone and distinguishes the collection efficiency obtained by CFD. This phenomenon is due to variation in the drag coefficient (C_D). In modeling, the transport equations were used in 3D, turbulent gas flow was simulated by the Reynold Stress Model (RSM) and the coupling of the fluid phase to the discrete phase was done by the Euler-Lagrange model. The results suggest that the form factor of the particle is an important parameter that cannot be neglected in the simulations of the collection efficiency of particles smaller than 6 micron..*

Keywords*: cyclone separator, form factor, RSM, collection efficiency*

1. INTRODUCTION

Cyclones are gas cleaning devices used in many chemical processes. These equipments can collect particles larger than 5 microns with high efficiency. They are inexpensive devices, with low maintenance and operational costs.

The calculation of particle trajectories is an important part of the design of gas-solid separators. In the vast majority of the literature, these calculations are performed with the assumption that the solid particles are spherical. However, in industrial practice, particles present irregular shapes (Mando *et al*., 2007). Only a few studies, however, stress the importance of taking into account the particle's shape. Jeffery (1922) was one of the first authors to investigate the effect of different shapes on particle dynamics. The concepts of sphericity and form factor were first introduced by Wadell (1934).

Haider and Levenspiel (1989) presented a generalized correlation for the drag coefficient which takes into account the form factor of the particles. Their correlation has been applied to calculate the drag force on particles of different shapes. It predicts a higher drag coefficient for decreasing form factor.

The majority of studies with non-spherical particles have been performed on simple geometries such as cylinders and ducts. Although cyclones are relatively simple devices, the flow inside them is very complex. It is characterized by the presence of swirl flow. As the gas is forced to swirl, the particles are thrown towards the walls by the centrifugal force. The drag force, on the other hand, opposes this movement towards the walls. As the shape factor of the particles modifies the drag force, it is expected that it can affect particle deposition on the walls, and thus, collection efficiency. The purpose of this study is to investigate whether the form factor of particles in the micron sized range have a significant effect on cyclone's collection efficiency. This investigation was made through Computational Fluid Dynamics (CFD) simulations, a tool that has proved to be of high value in modern engineering practice. The simulation results were compared to experimental data available in the literature (Obermair, 2001; Zi *et al*., 2009).

2. METHODOLOGY

The dynamics of a particle moving in a fluid is given by Newton's second law:

$$m_p \frac{dv_p}{dt} = \sum \mathbf{F} \tag{1}$$

where **F** represent the forces responsible for the particle's motion. These forces can be classified as field forces (such as the gravity force) which act at a distance and surface forces which result from the fluid motion around the particle (examples of surface forces are the aerodynamic drag and lift forces). The Basset-Boussinesq-Oseen (BBO) equation for the motion a particle immersed in a fluid, which is probably the most common equation to solve for a particle's trajectory, takes into account the following forces: a) The aerodynamic steady-state drag force $\mathbf{F}_D$; b) The pressure (buoyancy) force $\mathbf{F}_P$; c) The virtual mass force $\mathbf{F}_{VM}$; d) The Basset force $\mathbf{F}_B$; and e) The gravitational force $\mathbf{F}_G$:

$$m_p \frac{dV_p}{dt} = \boldsymbol{F}_D + \boldsymbol{F}_P + \boldsymbol{F}_{VM} + \boldsymbol{F}_B + \boldsymbol{F}_G \tag{2}$$

A more complete equation would also include the lift forces of Saffman ($\mathbf{F}_S$) and Magnus ($\mathbf{F}_M$) which arise due to particle rotation. However, in most studies of trajectories of micron sized particles in fluids, only the steady-state drag is considered. This force is at least one order of magnitude larger than the other forces (Xiaodong *et al*., 2003).

The steady-state drag force is given by:

$$\boldsymbol{F}_w = \frac{\pi}{8} \rho_F d_P^2 c_D \boldsymbol{v}_{rel} \boldsymbol{v}_{rel} \tag{3}$$

where $\mathbf{v}_{rel}$ is the relative velocity between particle and fluid ρ_f is the fluid's density, d_p is the particle diameter and C_D is the drag coefficient.

$$\boldsymbol{v}_{rel} = \boldsymbol{v}_F - \boldsymbol{v}_p \tag{4}$$

The drag coefficient for spherical particles is a function of the Reynolds number (Re_p), defined as:

$$Re_p = \frac{\rho d_P v_{rel}}{v_F} \tag{5}$$

where μ_f is the fluid's viscosity. For non-spherical particles, the drag coefficient is also a function of particle form and orientation. The correlation of Haider and Levenspiel (1989), given below as Equation (6), was used in this work to calculate the drag coefficient for non-spherical particles. This equation was recommended by Gabitto et al., 2007)

$$C_D = \frac{24}{Re}\left(1 + b_1 Re^{b_2}\right) + \frac{b_3 Re}{b_4 + Re} \tag{6}$$

where:

$$b_1 = exp\ (2.3288 - 6.4581\emptyset + 2.448\emptyset^2) \tag{7}$$

$$b_2 = 0.0964 + 0.5565\emptyset \tag{8}$$

$$b_3 = exp\ (4.905 - 13.8944\emptyset + 18.4222\emptyset^2 - 10.2599\,\emptyset^3) \tag{9}$$

$$b_4 = exp\ (1.4681 + 12.258\emptyset - 20.7322\emptyset^2 + 15.8855\,\emptyset^3) \tag{10}$$

The form factor ϕ is defined as:

$$\emptyset = \frac{s}{S} \tag{11}$$

Where s is the surface are of the sphere that has the same volume as the particle and S is the actual surface area of the particle. The form factor varies between 0 and 1. A perfect sphere would have a form factor of 1.

In this work, the flow turbulence was modeled by the Reynolds Stress Model (RSM). This model is recommended for the characteristic swirl flow in cyclones, as it can account for turbulence anisotropy. The disadvantage of this model is the high computational time required to solve the equation. The turbulence transport equation in the RSM model is given by:

$$\frac{\partial}{\partial t}\left(\rho \overline{u_i' u_j'}\right) + \frac{\partial}{\partial x_k}\left(\rho u_k \overline{u_i' u_j'}\right) = D_{ij} + P_{ij} + \pi_{ij} + \varepsilon_{ij} + S \tag{12}$$

The first two terms on the left side represent the local temporal derivate and the convective transport, respectively. The last term in the right side is the source term. The other four terms in the right side represent the diffusion stress tensor (D_{ij}), turbulence production tensor (P_{ij}), the pressure strain tensor (π_{ij}) and the turbulence dissipation tensor (ε_{ij}), givens respectively by equation (13) to (15).

$$D_{ij} = -\frac{\partial y}{\partial x}\left[\rho \overline{u_i' u_j' u_k'} + \overline{(P' u_j')}\delta_{ik} + \overline{(P' u_j')}\delta_{jk} - \mu\left(\frac{\partial}{\partial x_k}\overline{u_i' u_j'}\right)\right] \tag{15}$$

$$P_{ij} = -\rho\left[\overline{u_i' u_k'}\frac{\partial u_j}{\partial x_k} + \overline{u_j' u_k'}\frac{\partial u_i}{\partial x_k}\right] \tag{16}$$

$$\pi_{ij} = P\left(\overline{\frac{\partial u_i^{'}}{\partial x_j} + \frac{\partial u_j^{'}}{\partial x_i}}\right) \tag{17}$$

$$\varepsilon_{ij} = -2\mu \overline{\frac{\partial u_i^{\prime}}{\partial x_k}\frac{\partial u_j^{\prime}}{\partial x_k}} \tag{18}$$

The software used for the simulations was ANSYS-FLUENT® 12. The pressure-velocity coupling algorithm was SIMPLE. The discretization scheme was the following: PRESTO for the pressure and QUICK for momentum and turbulence equations. The dispersed phase was modeled using the Discrete Random Walk (DRW) model, which uses a Langrangian approach. Gravity and buoyancy were included. The reference pressure used was 101325 Pa.

Two cyclones, selected from published papers (Obermair, 2001; Zi *et al*., 2009), were used in the simulations. The selection criteria were: availability of experimental collection efficiency data for particles smaller than 10 μm, low concentration of particles and use of particles with form factors between 0.6 and 0.8. In cyclone A (Obermair, 2001), the particulate material used was limestone, while calcium carbonate was used in cyclone B (Zi *et al*., 2009). Limestone is a sedimentary rock consisting mainly of $CaCO_3$, with smaller quantities of other minerals. The density of limestone and calcium carbonate are 2770 kg/m^3 and 2700 kg/m^3, respectively. The geometry of the cyclones used is given in Figure 1 and Table 1.

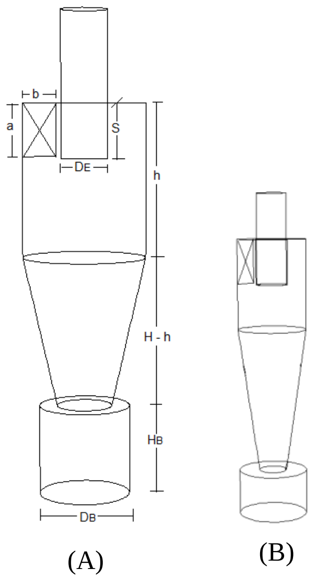

Figure 1. Drawings of the cyclones used. Cyclone A: Obermair, 2001; Cyclone B: Zi et al., 2009

Table 1. Cyclone dimentions (m).

Symbol	Cyclone A: Obermair (2001)	Cyclone B: Zi *et al*. (2009)
D_C	0.400	0.150
h	0.500	0.200
H-h	0.490	0.320
B	0.180	0.060
D_B	0.296	0.150
H_B	0.294	0.100
S	0.180	0.100
D_E	0.150	0.065
a	0.175	0.100
b	0.100	0.040

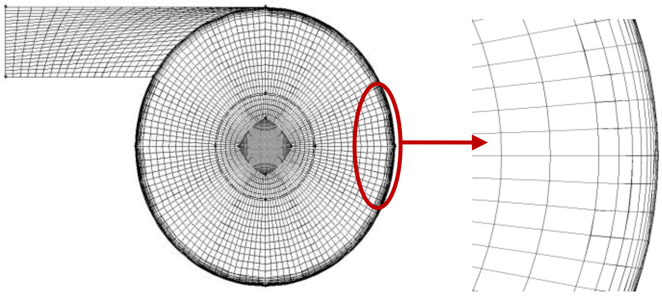

Figure 2. Details of the mesh used in this work.

Hexahedral cells were used to discretize the domain, as shown in Figure 2, which exhibits the YZ plane view. An inflation layer was applied to all the cylindrical walls of the cyclones, as it was expected that this would improve the cyclone's collection efficiency simulation results. The deposition of particles is dependent on their trajectories near the walls, which, in turn, as we have seen, depend on the drag and the pressure forces near the walls. As the velocity and pressure exhibit large gradients near the walls, a refined mesh is necessary to calculate these forces correctly. Kim and Lee (2000) and Xiaodong *et al* (2003) have argued for the necessity of the inflation layers for simulating correctly cyclone collection efficiency. Based on their results, the inflation layer used in this study consisted of 10 layers, with the first layer depth equal to 10^{-4} m and a growth factor of 1.5.

For purposes of establishing grid independency, two grids with different number of cells were made. For cyclone A, the grids had approximately 350,000 and 650,000 cells, which for cyclone B, grids with 68,000 and 115,000 cells were generated. After running collection efficiency and pressure drop simulations on both sets of grids for a few experimental conditions, it was observed that the results were similar within a 5% value. On this basis, it was decided to proceed the studies with the smaller grid (350,000 cells) for the larger cyclone A. For cyclone B, the larger grid was used (115,000 cells), as the smaller volume of this cyclone allowed for reasonable simulation times.

As both Obermair (2001) and Zi *et al*. (2009) used a low concentration of solids in their experimental work, it was possible to consider in the simulations that the presence of the discrete phase did not affect significantly the continuous phase velocity and pressure fields (Gimbum, 2008). This allowed performing the simulations in two distinct steps. Firstly, the velocity and pressure fields were obtained without considering the presence of solids. Then, the Langragian Discrete Walk Model was used to calculate the particle trajectories under the influence of the previous calculated fields. Also, because of the dilute nature of the discrete phase, collisions between particles were neglected. Particles started their trajectories from different points on the inlet face, with a velocity equal to the local gas velocity. Particles hitting the hopper wall were trapped, while the hits with other walls were considered fully elastic, with a restitution coefficient equal to 1. The simulations considered particles with diameters of 3, 4, 5, 6 and 7 μm, and form factors of 0.6, 0.8 and 1. A load of 0.01 kg/s was used in the simulations. The inlet air velocity was 12.7 m/s for cyclone A and 12 m/s for cyclone B.

3. RESULTS AND DISCUSSION

Figures 3 and 4 present the simulated grade efficiencies for cyclones A and B, respectively, parameterized by the shape factor. The experimental data is also plotted in the same Figures for comparison purposes. One can observe that the use of the form factor in the drag coefficient estimation resulted in different predictions of collection efficiency. This difference was bigger for the smaller particles. For larger particles (7 μm), however, it can be seen that the predictions were nearly independent of the shape factor.

One can also observe in Figures 3 and 4 that the simulated efficiency generally decreased with decreasing shape factors. This was expected, as, according to equations (6) to (10), the drag coefficient (and thus the drag force, if particle diameter and Reynolds number remain unchanged) increases with decreasing form factor. If particle diameter and Reynolds number remain unchanged, the increase in the drag coefficient leads to an increase in the drag force, which is the force that resists the particle's outward radial motion. This results in a decrease of the collection efficiency.

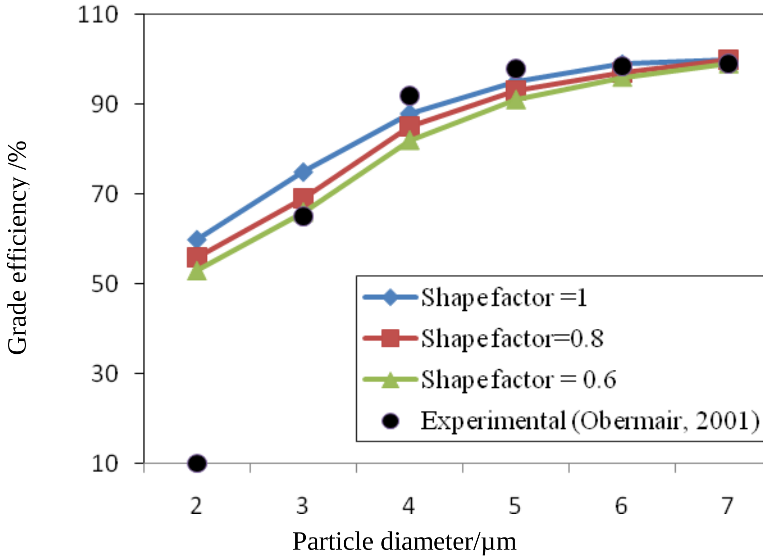

Figure 3. Grade efficiency for different shape factors for Cyclone A (Obermair, 2001).

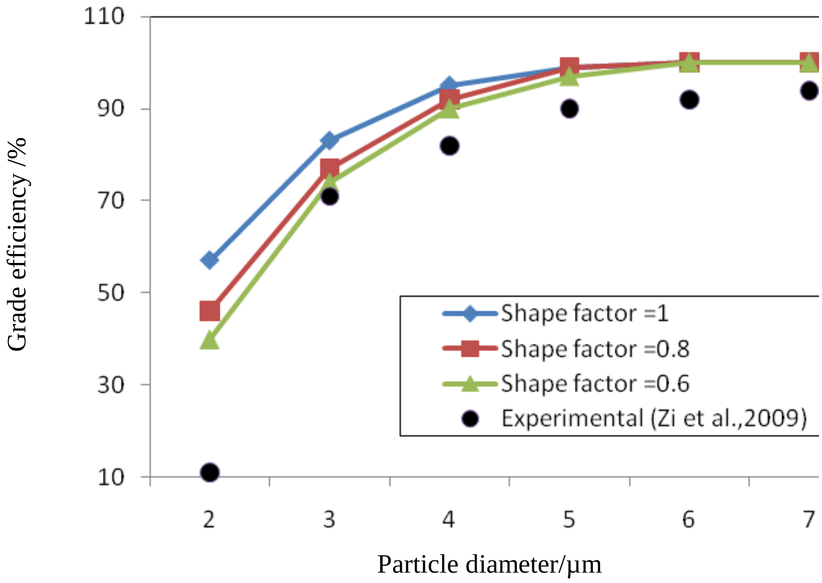

Figure 4. Grade efficiency for different shape factors for Cyclone B (Zi *et al.*, 2009).

The comparison with the experimental results shown Figures 3 and 4 suggest that the model predicts reasonably well the collection efficiency for particles greater than 3 μm, failing for particles of 2 μm. For limestone (cyclone A), the assumption of a shape factor of 1 gave the best predictions in most cases, although for the particles smaller than 3 μm, the consideration of a shape factor equal to 0.6 gave better results. For the calcium carbonate particles (cyclone B), the best predictions were obtained for the form factor of 0.6.

3. CONCLUSIONS

- For particles smaller than 6 μm, the form factor can affect significantly its collection efficiency in cyclone separators.
- The smaller the form factor, the smaller the collection efficiency.

4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE