Numerical Simulation of a Small-Scale Cyclone Separator using MP-PIC Method

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Abstract. This paper presents a numerical study of a small-scale cyclone separator performance by means of computational fluid dynamics (CFD). The family of Euler-Lagrange approach named multiphase particle-in-cell (MP-PIC) is employed for modelling gas-solid interaction. The three-dimensional small-scale cyclone separator geometry was discretized with hexahedral-dominant mesh. The gas phase is assumed to be a flue gas which density is 0.363 kg/m³ and dynamic viscosity is 7.47E⁻⁵ Pa s. The solid particles are catalyst used in a small-scale fluid catalytic cracking (FCC) unit which are having 2400 kg/m³ of density and diameters vary from 90 µm to 130 µm. Large Eddy Simulation (LES) turbulence model was used to accurately predict turbulent flow behaviour of flue gas inside the cyclone. The simulation was performed for 7.82 m/s inlet velocity for both flue gas and catalyst. The pressure drop and catalyst collection efficiency were the variables of interest to be analysed, which were compared to the analytical solutions. It was found that the results generated from numerical simulation using MP-PIC method reflect a good agreement with the analytical solutions.

1. Introduction

Cyclone separator is a device that utilize the centrifugal forces to remove solid particles from flue gases. It has been used in a wide range of industries, such as power generation, oil and gas, incineration plants, iron and steel industry, sand plants, cement plants, coking plants, coal fired boilers, and food industries (Dutta, Gera, Sharma, Singh, Ghosh, & Kushawa, 2009). The simplicity of the design, low-cost manufacturing, easy to maintain, and the ability to adapt in various operating conditions are the reasons behind its extensive use. At the same time, it comes with disadvantage since the cyclone are not capable of collecting the solid particle that is smaller than 10 µm.

The performance of a cyclone separator can be measured by its pressure drop and collection efficiency [19]. These two parameters of cyclone performance are related to each other. Increasing collection efficiency will also increase pressure drop and vice-versa. Hence, the study of a cyclone separator performance is instrumental in cyclone design and analysis.

One of the convenience methods to perform such study is computational fluid dynamics (CFD). CFD became a promising tool to carry out fluid dynamics analysis due to its ability to predict the flow field pattern in a detail manner, by producing the primary flow variables such as pressure and velocity at a given location in a domain. It can be used with some degree of accuracy which depends on several...
aspects: geometry modelling, mesh configurations, mathematical models, numerical schemes, and algorithms. Under those circumstances, efficient simulation strategy must be employed to obtain the accurate results in a cost-effective means.

There are two multiphase models which can be applied to simulate gas-solid particles flow in a cyclone separator; the Eulerian-Eulerian method and the Eulerian-Lagrangian method. In the Eulerian-Eulerian method, governing equations for both continuous and discrete phase are solved inside a computational cell by weighting the equations terms with continuous phase volume fraction. In the Eulerian-Lagrangian method, computational cell is a placeholder only for continuous phase solution. To determine the trajectory and the other properties of the discrete phase, the statistical calculations are imposed for each particle. It implies that a number of equations that must be solved will be vast. Despite this minor fact, the Euler-Lagrangian method is still a widely used approach to investigate the efficiency of a cyclone separator since it takes into account the wide particle size distribution.

The examination of a cyclone separator performance by making use of computational fluid dynamics (CFD) have been conducted by many researchers. Snider, A. and Johnson, R.A. [18] performed MP-PIC simulations of dense-phase flows in cyclone separators. The CFD results showed excellent agreement with measured experimental data which efficiency value is the order of 85%. Razmi, H. et. al. [19] applied MP-PIC method to investigate the hydrocyclone performance with spiral inlet in Sarcheshmeh copper complex. The variation of the cyclone performance value due to the effect of operating parameters such as particle density, inlet mass flow rate of solid particles, inlet feed velocity, and the effect of design parameters like diameter and height of the vortex finder, the length of the cylinder and conical section, and the type of inlet were analyzed. They came across the conclusion that increasing inlet feed velocity and the height of the vortex finder will improve the cyclone performance.

The present study will carry out the CFD simulation of gas-solid flow with MP-MPIC method inside a small-scale cyclone separator. The cyclone geometry is based on the pilot-scale Fluid Catalytic Cracking (FCC) research project by PTKEBTKE, which is located after regenerator unit to recollect the solid catalyst particles back to the reactor. This research used CFDSOF-NG® software, a CFD software developed by CCIT Group Indonesia with capability of simulating a wide range of fluid flow and heat transfer phenomena on complex geometry. The pressure drop and particle collection efficiency will be compared to the analytical solutions as an effort to verify the implementation of MP-PIC method in the software.

2. Mathematical model and methodology

2.1. Mathematical model for continuous phase

The governing equations describing the conservation of mass and momentum are solved in each particular computational cell for gas phase. By solving these equations, the pressure and velocity value can be obtained by first defining gas properties such as density and viscosity. Large Eddy Simulation (LES) turbulence model is used in order to accurately capture the velocity field, which is a prominent variable in the cyclone separator case. Henceforth, the governing equations of continuous phase are given in (1) and (2) respectively [19].

\[
\frac{\partial (\alpha \rho_g)}{\partial t} + \frac{\partial (\alpha \rho_g u_i)}{\partial x_i} = 0
\]

\[
\frac{\partial (\alpha \rho_g u_i)}{\partial t} + \frac{\partial (\alpha \rho_g u_i u_j)}{\partial x_j} = -\alpha \nabla p + \frac{\partial}{\partial x_j} \left( \alpha \tau_{\mu j} + \alpha \tau_{d ij} + \alpha \tau_{t ij} \right) + \alpha \rho g - \frac{1}{\rho} F
\]
and $\tau_{tij}$ is the stresses on the grid scale. Eventually, $F$ represents the momentum transfer between continuous and discrete phase.

The tensor viscosity stress $\tau_{\mu ij}$ is defined by the following equation:

$$
\tau_{\mu ij} = 2\mu \bar{S}_{ij}
$$

where $\bar{S}_{ij}$ is the mean tension rate and $\mu$ is the gas molecular viscosity.

The two others tensor stresses $\tau_{di j}$ and $\tau_{ti j}$ are solved by following equation (4) and (5) successively.

$$
\tau_{di j} = \sum_{p=1}^{n} \alpha_p \rho_p u_{pmi} u_{pmj}
$$

$$
\tau_{ti j} = \mu_{sgs} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right)
$$

The term $\mu_{sgs}$ indicates subgrid-scale eddy viscosity which is expressed as:

$$
\mu_{sgs} = \rho l_s^2 \sqrt{2 \bar{S}_{ij} \bar{S}_{ij}}
$$

where $l_s$ is the intermediate local grid.

2.2. Mathematical model for discrete phase

The discrete phase in MP-PIC method is treated differently with the continuous phase. Here, Liouville equation (8) is used to elucidate the discrete phase kinematic behaviour by solving for $f(x, u, m, t)$ which is called the particle distribution function [17].

$$
\frac{\partial f}{\partial t} + \frac{\partial f u_{si}}{\partial x_i} + \frac{\partial f A}{\partial u_i} = \left( \frac{\partial f}{\partial t} \right)_{coll}
$$

The right-hand side of the above equation represents the collision term, where the detail discussion can be found in elsewhere (O’Rourke and Snider, 2012; O’Rourke and Snider, 2010; Snider, 2001).

$$
\left( \frac{\partial f}{\partial t} \right)_{coll} = \frac{f_D - f}{\tau_D} + \frac{f_A - f}{\tau_A}
$$

The term $u_s$ is the time derivative of the solid particle position and the term $A$ is the time derivative of the solid particle velocity, which in turn is given by:

$$
A = D(u_g - u_s) - \frac{1}{\rho_s} \frac{\partial p}{\partial x_i} + g - \frac{1}{a \rho_s} \frac{\partial \tau}{\partial x_i}
$$

where $D, \rho_s,$ and $\tau$ are the drag function, the solid particle density, and the isotropic solid stress sequentially. Drag function is expressed as:

$$
D = \frac{C_d}{8} \frac{3 \rho_g |u_g - u_s|}{R}
$$
where $C_d$ is drag coefficient which in this research is modelled by using sphere drag model and $R$ is particle radius. Moreover, isotropic solid stress in equation (9) is obtained by adopting the expression from (Harris and Crighton, 1994) and is given in equation (10) below.

$$\tau = P_s \frac{a^\beta}{\max[a_{cp} - a, \omega(1 - a)]}$$  \hspace{1cm} (11)

In the equation (10), $P_s$ is a constant with units similar to pressure and $a_{cp}$ is the particle-phase volume fraction when particle is the closed pack condition. $\beta$ is a constant which value is ranging from 2 to 5 and $\omega$ is a small magnitude number in the order of $10^{-7}$. The relationship between the particle volume fraction and the distribution function is given by:

$$a_{cp} = \iint f \frac{m}{\rho_s} dm du_p$$  \hspace{1cm} (12)

The total volume fraction for both phases must be equal to 1, hence

$$a_{cp} + a = 1$$  \hspace{1cm} (13)

Finally, in order to close the governing equations for gas-solid flow, the interphase momentum transfer function $F$ can be defined as:

$$F = \iint f m \left[ D(u_g - u_s) - \frac{1}{\rho_s} \nabla p \right] dm du_p$$  \hspace{1cm} (14)

2.3. Mathematical model for analytical solutions

The derivation of analytical solutions for cyclone separator had been conducted by several scientists to calculate pressure drop, efficiency, and cut-off particle diameters.

Figure 1. Cyclone with dimensions [2].
The pressure drop in a cyclone will be considered as that between points 1 and points 2 in Figure 1. Based on the calculated correlation coefficients [2], the Shepherd and Lapple method appear to give results as good as the others despite its simplicity. Shepherd and Lapple calculate the pressure drop results with the following equation:

\[ \Delta H = K \frac{ab}{De^2} \]  

(15)

where \( K = 16 \) for a cyclone with standard tangential inlet, and \( K = 7.5 \) for a cyclone with an inlet vane.

The cyclone pressure loss is expressed as inlet velocity head (\( \Delta H \)). The inlet velocity head can be converted to pressure drop in terms of static pressure head, \( \Delta P \), by:

\[ \Delta P = \frac{v_g^2 \rho_g \Delta H}{2g\rho_l} \]  

(16)

where \( v_g \) is the gas inlet velocity, \( \rho_g \) is the gas density, \( g \) is the gravity, and \( \rho_l \) is the fluid density that is used to calculate the head pressure.

Furthermore, the capacity of the cyclone to collect particles is measured by its efficiency \( \eta \), defined as the fraction of the inlet flow of solids separated in the cyclone. Leith and Licht [2] formulated the collection efficiency as:

\[ \eta = 1 - \exp\left\{-2(C\psi)^{1/(2n+2)}\right\} \]  

(17)

where \( \eta \) is the efficiency, \( C \) is the cyclone dimension factor, \( \psi \) is the impaction parameter, and \( n \) is the vortex exponent. Further, the cyclone dimension factor is the dimensionless ratio that follows:

\[ C = \frac{8K_c}{K_aK_b} \]  

(18)

\( K_a \) and \( K_b \) are the cyclone inlet height and weight divided by cyclone diameter, while \( K_c \) is the cyclone volume constant that is defined the following equation:

\[ K_c = \frac{V_s + V_{nl}/2}{D^3} \]  

(19)

With \( V_s \) is the annular shaped volume above exit duct to midlevel of entrance duct and \( V_{nl} \) is the volume of cyclone below gas outlet to the natural length \( (l) \). Both \( V_s \) and \( V_{nl} \) are defined as the function of geometry only as follows:

\[ l = 2.3De\left(\frac{D^2}{ab}\right)^{0.333} \]  

(20)

\[ V_s = \frac{\pi}{4}\left(S - \frac{a}{2}\right)(D^2 - De^2) \]  

(21)
\[ V_{nl} = \begin{cases} \frac{\pi l}{4} (D^2 - De^2), & l < (h - S) \\ \frac{\pi D^2}{4} (h - S) + \left( \frac{\pi D^2}{4} \right) \left( \frac{S + l - h}{3} \right) \left( 1 + \frac{d}{D} + \left( \frac{d}{D} \right)^2 \right) - \frac{\pi De^2}{4} (l), & (h - S) < l < (H - S) \\ \frac{\pi D^2}{4} (h - S) + \left( \frac{\pi D^2}{4} \right) \left( \frac{H - h}{3} \right) \left( 1 + \frac{B}{D} + \left( \frac{B}{D} \right)^2 \right) - \frac{\pi De^2}{4} (H - S), & l > (H - S) \end{cases} \] (22)

with

\[ d = D - (D - B) \frac{(S + l - h)}{H - h} \] (23)

Furthermore, \( \psi \) is defined as:

\[ \psi = \frac{\rho_p d_p^2 v_g}{18 \mu_g D} (n + 1) \] (24)

with

\[ n = \frac{(12D)^{0.14}}{2.5} \] (25)

2.4. Simulation methodology

Simulation of gas-solid flow inside a small-scale cyclone separator was conducted by first creating the geometry and transform it into a number of discrete non-overlapping cells which is dominated by hexahedral shape. In order to ensure that the generated mesh is sufficient to provide the accurate solution, mesh independency study was performed by varying number of cells of 18628, 29829, and 43819. The physical properties for both gas and solid particles were then defined as shown in table 1 and followed by imposing boundary conditions. The gas-solid flow was solved by implemented MPPIC model in the CFDSoF® software. The calculation of turbulent velocity flow employed large eddy simulation (LES). The PIMPLE algorithm (combination of PISO and SIMPLE) was used to solve the pressure-velocity coupling problem. The simulations were carried out for the 90 \( \mu m \), 110 \( \mu m \), and 130 \( \mu m \) solid particles diameter throughout 10 s with time-step of 0.001 s.

| Properties                  | Value | Units |
|-----------------------------|-------|-------|
| **Particle Properties**     |       |       |
| Particle density            | 2400  | kg/m³ |
| Void fraction               | 0.6   |       |
| Particle size               | 90-130| \( \mu m \) |
| **Gas properties**          |       |       |
| Gas density                 | 0.363 | kg/m³ |
| Gas temperature             | 800   | \( ^\circ C \) |
| Gas viscosity               | 7.47 \times 10^{-5} | kg/m s |
| **Operating conditions**    |       |       |
| Cyclone diameters, D        | 0.2030| m     |
| Throughput, Q               | 0.1   | m³/s  |
| Temperature, T              | 800   | \( ^\circ C \) |
2.5. Geometry and meshing
The geometry of a small-scale cyclone separator is created by considering the non-dimensional parameters as shown in table 2 below. The definitions of the parameters can be referenced to figure 1.

| Parameters | Value | Units |
|------------|-------|-------|
| a/D        | 0.500 | -     |
| b/D        | 0.200 | -     |
| S/D        | 0.500 | -     |
| De/D       | 0.500 | -     |
| h/D        | 1.500 | -     |
| H/D        | 4.000 | -     |
| B/D        | 0.375 | -     |

The mesh is generated using snappyHexMesh, which is an automatic mesh generator that takes and chisels a base hexahedral mesh to fit the mesh with the geometry shape. The resulting mesh is illustrated in figure 2.

2.6. Boundary conditions
Figure 2 shows that the computational domain consists of three boundaries as the inlet, outlet gas, and outlet particle. Velocity of 7.82 m/s for gas and particle was defined at the inlet. Outlet gas was considered to be an atmospheric condition which pressure was defined as zero-gauge pressure. Outlet particle was defined as a patch where the particles leave the domain. Particle interaction with wall was modeled by rebound boundary condition with restitution coefficient value of 0.0.

3. Results
3.1. Mesh independency study
Mesh independency study is a necessity in CFD simulation to convince that the solutions are assumed to be free from numerical error due to the mesh configurations. It is done by first taking the small number of cells and monitor the value of the variable interest. Then, increase the number of mesh and recheck
the interest value. This work must be undertaken until the interest value does not change with respect to
the number of cells. In this study, mesh independency study was performed by simulating gas flow only
to reduce the computational cost and consider the pressure drop between inlet and gas outlet as the
variable to be monitored. The result is given in figure X

![Figure 3. Pressure drop curve for mesh independency study](image)

According to this figure, the difference between the mesh of 18628 cells and 29829 cells is
noticeable, while increasing number of cells from 29829 to 43819 would only produces 0.3% difference.
Hence, the mesh with 29829 cells is selected in this simulation.

3.2. Analytical solutions
Pressure drop of the cyclone can be calculated through equation (1) and (2). Moreover, the efficiency
and cut-off size can be obtained by following equation (3) through (11). Below are the analytical
solutions for this cyclone.

Table 3. Analytical solutions of cyclone performance

| Variable            | Value | Units |
|---------------------|-------|-------|
| Pressure drop       | 0.008 | bar   |
| Cut-size particles  | 1.62  | μm    |
| Efficiency at 90 μm | 99.99 | %     |
| Efficiency at 110 μm| 100.00| %     |
| Efficiency at 130 μm| 100.00| %     |
3.3. **Numerical Solutions**

The cyclone efficiency was obtained from number of particles fraction between outlet particles and cyclone inlet. The visualization of particle trajectories for 3 diameters value is illustrated in figure 5.

| Diameter (μm) | Efficiency (%) |
|---------------|----------------|
| 90            | 100            |
| 110           | 100            |
| 130           | 100            |
Moreover, pressure drop from CFD was calculated by subtracting average value of pressure on the cyclone inlet patch and outlet gas patch.

Table 5. Pressure drop from CFD

| Diameter ($\mu$m) | Pressure Drop (bar) |
|------------------|---------------------|
| 90               | 0.0071              |
| 110              | 0.0074              |
| 130              | 0.0074              |

4. Conclusions
The numerical simulations of gas-solid flow in a small-scale cyclone separator have been done by using multiphase particle-in-cell (MP-PIC) method. The resulting efficiency and pressure drop from numerical simulations were compared with analytical solutions. It was found that the pressure drop from both methods showed a good agreement while the efficiency value from numerical simulations exhibited lower values than the analytical solutions. However, this deviation was not profound with order of 3 to 4%. This research concludes that the multiphase particle-in-cell (MP-PIC) method could be adopted for simulating gas-solid flow in some circumstances.

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