Cenosphere Separation from Fly Ash Using Modified Gravity Separator: Feed Ratio Assessment and Stream Velocity Optimization

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Abstract. The increase of the population causing increased energy needs, one of which is electricity. Coal constitutes one of the largest carbon sources to generate electricity where the combustion leaves a by-product in the form of fly ash. Inside the fly ash, there are round-shaped hollow particles whose its density is lower than water of about 0.9 g/cm³. These particles called cenosphere containing alumino-silicate. Due to its lighter and tougher nature, it makes the cenosphere appealing to use as a lightweight and robust material. Cenosphere can be separated using both dry separation and wet separation. Separation using the wet process produces another impact on the side of the liquid media processing that is used because it potentially carries toxic compounds inside the fly ash. While the separation using the dry separation method still has problems regarding its efficiency. Modified Gravity Separator is a new design for cenosphere separation using air as a fluid medium. This research was conducted to evaluate the performance of the proposed geometry by looking at the effect of the feed velocity to the geometry expansion space using a CFD (Computational Fluid Dynamic) computing software. The feed particles are assumed to be spherical shape and are observed with the Euler-Lagrange equation where the particles interact with continuous airflow. The simulations were carried out at speeds of 0.1 m/s, 0.25 m/s, 0.5 m/s, and 1 m/s. This simulation successfully illustrates the flow pattern and predicts the recovery rate of each collector so that it can be evaluated and optimized for future investigation.

1. Introduction

Coal is one of the biggest sources of carbon used to produce energy. Indonesia has a lot of sources of these resources. In 2018, 548 million tons of coal have been explored and 91.14 million tons (14.78% wt of coal production) had been used to generating electricity [1]. The coal production is increased since 2015 which the production reaches 405 million tons [2]. After burning, this kind of fossil fuel left the by-product such as bottom ash, slag and fly ash. The particle has been collected by Electro-Static Precipitation (ESP), bag filter, stack, and other recovery units to avoid the particle spread to the environment. The utilization of this waste is limited due to the components that are inside the fly ash such as high density, dangerous element and so on.
Inside the fly ash, there are hollow particles that formed from silica and had a density lower than water. This particle is called a cenosphere. The fraction is small compared to the other particle, it was 0.01 – 4.8% [3,4]. The diameter has been observed around 20 – 500 µm [5] and usually between 20 – 300 µm [5]. Cenosphere formation and character are different depending on burning temperature and molten drop chemical composition [5,6].

Because it has much excellence such as good hardness ability and light [7], the cenosphere should be separated from fly ash for further application. The wet-separation process and Dry-Separation process can be used. The cheapest media used in Wet-Separation is water. But there is an environmental issue due to toxic elements which is inside the fly ash. The rare earth element and other dangerous material will be leached to the water. When the toxic material accumulates, this phenomenon will impact the environment [8].

Some research has been developed to collect the cenosphere from the fly ash. Li et al. (2014) developed a separation tool using a wet-separation process called Inverted Reflux Classifier (IRC). Their work compared IRC with standard RC on a pilot plant scale. The tool used the Boycott effect which means that the slope will affect the separation process. The work claiming that the efficiency of separation reaches 80% [9].

Another project has been worked for the dry process, micron separator and closed-type pneumatic separator was evaluated. Closed-type pneumatic separator did not work better than micron separator. The evaluation found that micron separator reaches the Newton Efficiency value of 0.44 and cenosphere recovery reaches 80% [5,10]. This work claim that the separation process can be used to compete with the wet-separation process due to no environmental issue and less space needed.

One side with Petrus et al. (2010) project, Sutijan et al. (2019) established another type of dry-separator unit called modified gravity separator. This unit was evaluated using CFD simulation with injection particles of cenosphere and fly ash respectively 1:1 in mass. The Newton efficiency grade reaches 0.41 with a feed velocity of 0.25 m/s [11]. Their reported work is not using the real injection fraction of the cenosphere so that the major aim of this work is to evaluate the particle track and netton efficiency using a small fraction of the cenosphere inside the fly ash. The particles are assuming sphere in shape and following the Rosin-Rammler distribution.

2. Simulation Setup
2.1. Geometry and Grid Arrangement
The geometry consists of four parts. There are inlet particle chamber, main body, collectors chamber, and an outlet chamber. In the simulation condition, the outlet chamber and the collector chambers are joined together to simplify the result calculation. The detail dimension describes in Fig. 1. Grid arrangement was developed using automatic meshing from ANSYS. There were two examinations to see the better shape of the grid used. The first one is the triangular model and the second shape is the hexagonal model.

![Figure 1. Modified Gravity Separator detail (from [11])](image-url)
2.2. Simulation Environment

Fly ash from the combustion is variable by the size. For the conventional fly ash, meaning that fly ash coming from the boiler process, the density is about 2.2 – 2.5 g/cm$^3$ [12]. The diameter range is around 9.63 – 47.6 µm [13] or in the range of 0.01 – 350 µm [12]. Inside the fly ash, the fraction of the cenosphere generally about 0.3 – 1.5 % wt [4] and the density of the cenosphere is in the range of 0.9 – 1.8 g/cm$^3$ [10]. Like previous work, this sample of simulation is using the same size of the particle. The diameter distribution is using the Rossin-Rammler equation [11]. For the easiest computation, the total mass amount is 8.58e-9 kg/s (cenosphere 0.15% wt), 596 cenosphere individual particles, and 100,909 fly ash particles.

This work simulation is using ANSYS Fluent. The turbulent model is used in this scheme. There is a lot of turbulence models such as Direct Numerical Simulation, Large-Eddy Simulation, Reynolds Stress Model, Two-equation Models, One-equation Models, and zero-equation Models. Direct Numerical Simulation equation has a higher cost of simulation and higher resolution than the others model but has a higher level of approximation. The lower one is the zero-equation model, this model consumes the lowest cost of computational cost but, of course, uses lower approximation and the medium-cost computational is the two-equation models [14]. K-ε and k-ω are kinds of two-equation models. Hard to find the same case of turbulence using this scheme from another work that had been done to choose the better model used. From Andersson et al. (2012), k-ε is the most used model due to its calculation for the turbulence kinetic energy, k, provide the value of the energy-dissipation rate ($\epsilon$) from the calculation. For the first simulation observation and medium-cost of the simulation, this project uses the standard k-ε model. The following transport equation (1 and 2) has gained the value of the kinetic energy and the rate of dissipation and the turbulence viscosity, $\mu_t$, can be calculated using $k$ and $\epsilon$ which is showed by eq. (3) [15].

$$\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho k u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k$$  \hspace{1cm} (1)

$$\frac{\partial}{\partial t} (\rho \epsilon) + \frac{\partial}{\partial x_i} (\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + C_1 \epsilon \frac{\rho k}{k} (G_k + C_3 \epsilon G_b) - C_2 \rho \frac{k^2}{\epsilon} + S_\epsilon$$  \hspace{1cm} (2)

$$\mu_t = \rho C_{\mu} \frac{k^2}{\epsilon}$$  \hspace{1cm} (3)

Where:

$G_k$ : The generation of turbulence kinetic energy caused by the mean velocity gradients,

$G_b$ : The generation of turbulence kinetic energy caused by buoyancy,

$Y_M$ : Value of the fluctuating dilatation in compressible turbulence to the overall dissipation rate,

$C$ : Constant

$\sigma$ : Turbulent Prandtl number

$S$ : User-defined source term

For tracking the particle, the Discrete Phase Model is used in this simulation condition with the maximum iteration of 10,011. The model used the Euler-Lagrange approach and neglected the particle-particle interaction which means that the dispersed phase occupied a low volume fraction. But high mass loading still acceptable [15].


Table 1. The boundary condition of the simulation

| Boundary Zone     | Type        | Momentum                        | DPM   |
|-------------------|-------------|---------------------------------|-------|
| Input chamber     | Velocity inlet | Velocity: 0.1, 0.25, 0.5, 1 m/s | Escape|
|                   |              | Turbulence: default             |       |
| Collector chamber | Pressure outlet | Default                        | Escape|
| Outlet chamber    | Pressure outlet | Default                        | Escape|
| Main body         | Wall         | Stationary wall; others: default| Reflect|
| Body interior     | Interior     | -                               | -     |

For the boundary condition, the input chamber was set to be velocity inlet. This velocity is different for every simulation depends on running variables. For Discrete Particle Material condition when walk at this zone is escaping. The boundary condition for the collector and outlet chambers is a pressure outlet. A convergence iteration was not achieved by using the wall type. The SIMPLE model used for the calculation with default Spacial Discretization condition. For the initialization, the computation will begin from the input zone.

2.3. Computing Result

Data of the simulation are collected to the external file. Format of the report based on user-defined function. Then, the data will be treated using MatLab software to know the effectiveness of the Modified Gravity Separator. The diameter, position, and density data are the major information that must be extracted for the calculation. From the particle tracking data, the collectors and overall efficiency can be calculated using the Newton Efficiency formula in equation (4) and (5) [10].

Collector efficiency:

\[
NE (i) = \frac{m_{c(i)}}{m_{ct}} - \left(1 - \frac{m_{ft} - m_{f(i)}}{m_{ft}}\right)
\]  

Overall efficiency:

\[
NET = \frac{m_{cs}}{m_{ct}} - \left(1 - \frac{m_{ft} - m_{fs}}{m_{ft}}\right)
\]

Where:

- \(NE\) : Newton Efficiency
- \(NET\) : Overall Newton Efficiency
- \(m_{c/f}\) : Mass of cenosphere/fly ash
- \(m_{c/f(t)}\) : Total mass of cenosphere/fly ash
- \(m_{c/f(s)}\) : Concentrated mass of cenosphere/fly ash
- \(i\) : Collector index

ANSYS can extract the mass per particle to the report file. The reported data will be collected to know the total mass of the specific particle in a specific collector. So, its information can be used to know the collector Newton Efficiency. A positive value of the NE is cenosphere concentrated and if the NE is negative that is fly ash concentrated.

3. Results and Discussion

Firstly before trying to run the computation, a configuration of the grid condition is needed. For this geometry, using the tetrahedron shape was better than using the hex-dominant shape. It shows from the skewness and element quality evaluation of the grid. The skewness average reaches 0.4957 by the hex-dominant shape and 0.2663 is achieved by the tetrahedron shape. This evaluation is calculated using automatic medium-mesh generation. If the value is closer to zero, the shape is better to be applied.
Figure 2. Effect of grid numbers to the overall Newton Efficiency for the velocity of 0.25 m/s

From Fig. 2 above, the result shows that the number of grid elements is affecting the NE. The size of the element is smaller following by increasing the number of the element. This condition makes the iteration more detail for tracking the particle and the rotation of the turbulence pathline is better known. The next discussing simulation was using a fine grid with an amount of 83,942 tetrahedron elements.

Figure 3. NE (overall) evaluation from each velocity variables

Fig. 3 is describing the effect of the overall NE of the geometry with the stream velocity. It can be seen that the best NE reaches for the speed of 0.25 m/s. Increasing NE happened at 1 m/s after decreasing at 0.5 m/s. This condition occurs because of the turbulence effect. Logically, the speed makes the flow more turbulence and the particles are flying more disordered. Because of the turbulent swirling, some particle collapses to the collectors more random. This hypothesis is supported by Fig 4. At 1 m/s, more particle doesn’t reach the terminal velocity and going through with the airflow to the outlet chamber. But different from other velocities, the collector 11 (outlet chamber) reaches a positive NE (cenosphere concentrated).
Figure 4. NE for each collector (a) 0.1 m/s; (b) 0.25 m/s; (c) 0.5 m/s; (d) 1 m/s

The size distribution at 0.25 m/s for fly ash evenly distributed in all collectors zone (Fig. 6). In contrast with the cenosphere, the size distribution in every collector is random (Fig. 5). This phenomenon occurs because of the amount of the particle injected. Cenosphere particle size distribution was injected 0.15% inside the total amount of feed. Fly ash particles very numerous compare with cenosphere particles.

Figure 5. Cenosphere cumulative particle distribution for 0.25 m/s
The standard k-ε turbulence model and the DPM (Discrete Particle Model) have been successfully described the tracking particle (Fig. 7a,b). The high concentrated flow which is crash into the wall is conducted above the 10th collector and makes the pressure higher at this location (Fig. 7c). It caused the particle track at this point more random than the tracking pathline at the beginning. There is a particle that has a reverse flow inside the geometry interior after colliding with the wall and there is a particle that is not in turbulence condition mostly at the start point of analysis. This visualization occurs due to the effect of particle diameter and particle mass on the flow of the air.
Figure 7. Particle tracking pathline for 0.25 m/s (a) ISO view; (b) positive x-direction view; (c) pressure prediction at positive x-direction

4. Conclusion
Different from previous work, the evaluation based on the real condition of the fly ash sample has been evaluated. The simulation used standard k-ε and resulting a good explanation of particle tracking data. The best NE reaches for speed of 0.25 m/s with NE of 0.229, but this value is not better than Sutijan et al. (2019) works. This means that the fraction of the cenosphere influences the separation quality. A high-velocity speed affected the rheology of the turbulence track where the particle going through on the bottom of the Modified Gravity Separator and crash the wall at the endpoint. This phenomenon induces the pressure increase around the corner at the end of the wall. The pressure makes the particle flowing reverse to the inlet chamber point. In the real condition, this problem may cause a collision between the particles to occur. For the future optimization investigation, the authors suggest comparing another model of turbulence and dense particle injection to see the best model that can describe the better simulation. A lot of variables added, more costly computation occurs.

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