Effect of inlet speed on gravitational air separator for cenospheres accumulation from fly ash: modeling using computational fluid dynamics (CFD)

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Abstract. Dry gravity separation is widely used in industries due to its low operational cost. Furthermore, it does not require water to perform its separation process. Commonly used gravity separator is cyclone separator. Unfortunately, this type of separator is unable to yield various purities for its products. A modified gravity separator as an alternative relies on terminal velocity difference for different diameter and density is evaluated in this paper. The separated particles are coal fly ash and cenosphere which are the results of coal combustion where the content of cenosphere is generally 0.1% of total mass. Separated cenosphere can be used for various applications in the field of materials. In this simulation we use a particle model with a ratio of fly-ash to cenosphere mass of 1:1. Particles behavior in this gravity separator is affected by terminal velocity, linear speed, as well as rheology. Modeling with CFD (Computational Fluid Dynamics) using the Discrete Phase Model can take into account the behavior of particles that are affected by these factors. This model assumes that the simulated particles are perfectly round in shape. It uses the Euler-Lagrange framework in which the perfectly rounded particles (discrete phases, Lagrange frames) interact with air (continuous phase, Euler framework) and performed with ANSYS Fluent software. This study evaluates the effect of speed variation on Newton efficiency (NE) on a given geometry. Simulations were performed with variations of inlet velocity: 0.1 m/s; 0.25 m/s; 0.5 m/s; 1 m/s; 2 m/s; and 3 m/s. It was found that the lower the speed, the higher the NE and the optimum NE of 0.41 is obtained with 0.25 m/s inlet velocity.

1. Introduction
Developing countries like Indonesia rely on coal-fired power plants in large quantities to fulfill their energy. It is because of the low price and abundance of mass energy source of coal that could not be found in any other energy resources. In a case of Indonesia, the need of energy is increasing along with the increase of its population. Thus, the Indonesian government through Presidential Decree No. 22 year 2017 determines the energy supply management to result 135.5 GW at which coal poseses 30% of the national energy consumption until the year of 2025 as it can be seen in Figure 1.
In line with the increase of coal needs up to the year of 2025, there will be also fly ash resulted from the coal combustion with the estimated amount of 200 tonnage per year. It will surely pose problems to the environment, if the fly ash is not treated carefully. Exiting fly-ash from coal combustion process has no selling value and usually only disposed in landfill while in the developed countries coal-fly ash is used in cement industries [2]. However, fly-ash actually contains a type of micro particle called a cenosphere mainly consists of quartz, alumina, Calcium Oxide and Hematite [3] which has a hollow spherical structure and has many applications in the industry due to its superior nature. Cenosphere is made by a process similar to a glass-making process that makes cenosphere has a distinctive properties [4]. This material has low bulk density, high thermal resistance, and high mechanical strength [5].

The commonly used separation technique is based on the density difference at which the separation provides high efficiency to separate cenosphere from fly ash [6]. This separation process is effective but it currently consumes large amount of water and add to water pollution due to leaching of toxic material from fly-ash. Thus, the exploration of dry separation processes have been conducted by some researchers to minimize the propensity of water pollution [7,8]. One of the commonly used tools is cyclone, but it cannot separate different fly-ash diameters at once needing multistage of cyclones. Therefore, a new separation device is proposed as shown in section 3.1. This geometry is expected to separate fly-ash into several different product fractions.

Before running the CFD calculation, two models have been selected which are turbulence model and particle model. Standard k-epsilon model with standard wall treatment are used for turbulence condition because this method is easier to use in the first simulation [9]. Discrete Phase Model (DPM) is used for particle model approach.

2. Mathematical Modeling

2.1. Governing Equation

The main equations govern this modeling are based on the continuity law (equation 1) and momentum conservation (equation 2, 3, and 4). The latter equation is also known as Navier-Stoke equation.

\[ \rho \frac{\partial \rho}{\partial t} + \nabla (\rho \mathbf{V}) = 0 \]  
(1)
Momentum conservation in x direction
\[
\frac{\partial (\rho u)}{\partial t} + \nabla (\rho u V) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{xx}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{xz}}{\partial z} + \rho f_x
\]  
(2)

Momentum conservation in y direction
\[
\frac{\partial (\rho v)}{\partial t} + \nabla (\rho v V) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{yy}}{\partial x} + \frac{\partial \tau_{xy}}{\partial y} + \frac{\partial \tau_{yz}}{\partial z} + \rho f_y
\]  
(3)

Momentum conservation in z direction
\[
\frac{\partial (\rho w)}{\partial t} + \nabla (\rho w V) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{zz}}{\partial x} + \frac{\partial \tau_{zy}}{\partial y} + \frac{\partial \tau_{zz}}{\partial z} + \rho f_z
\]  
(4)

2.2. Standard k-epsilon Model (Standard k-ε Model)
Two-equation turbulence models allow the determination of both turbulent length and time scale by solving two separate transport equations. The standard k-ε model in ANSYS Fluent falls within this class of models and has become the workhorse of practical engineering flow calculations in the time since it was proposed by Launder and Spalding. Robustness, economy, and reasonable accuracy for a wide range of turbulent flows explain its popularity in industrial flow and heat transfer simulations. It is a semi-empirical model, and the derivation of the model equations relies on phenomenological considerations and empiricism. The standard k-ε model is a model based on model transport equations for the turbulence kinetic energy (k) shown by equation (5) and its dissipation rate (ε) shown by equation (6).

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x} (\rho k u_i) = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x} \right] + G_k + G_b - \rho \varepsilon - Y_M + S_k
\]  
(5)

and

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x} (\rho \varepsilon u_i) = \frac{\partial}{\partial x} \left[ \left( \mu + \frac{\mu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x} \right] + C_{1\varepsilon} \frac{\varepsilon}{k} (G_k + C_3 \varepsilon G_b) - C_{2\varepsilon} \rho \frac{\varepsilon^2}{k} + S_\varepsilon
\]  
(6)

The turbulent (or eddy) viscosity, \( \mu_t \), is computed by combining k and ε as follows:

\[
\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}
\]  
(7)

2.3. Discrete Phase Model
This model assumes individual particle is perfectly spherical and uniform in its mass distribution throughout the sphere. Trajectory of particle/droplet are computed in a Lagrangian frame and coupled with the momentum of Eulerian frame by integrating equation (8). This model is preferred because it is able to track particles individually and hence giving off information of a particle’s detail such as diameter and mass at the selected pressure-outlet.

\[
\frac{\partial u_i^p}{\partial t} = F_D (u_i - u_i^p) + g_i \left( \frac{\rho_p - \rho}{\rho_p} \right) + \frac{F_{i,1}}{\rho_p}
\]  
(8)

3. Results and discussion
3.1. Geometry Specification and Nomenclature
In order to be able to separate cenosphere from fly ash with different fraction based on their diameter, the air separator has been developed with geometry as it can be seen in Figure 1 and 2.

![Figure 2. Side view of geometry](image)

![Figure 3. Isometric view of geometry](image)

By having such an air separator as shown in Figure 2 and 3, the terminal velocity of the cenospheres will drop that the classification can be conducted along the fractionated collectors. The dimension of the separator is shown in Table 1.

Table 1. Geometry of the Air Separator

| Marker | Dimension |
|--------|-----------|
| L1     | 0.1 m     |
| L2     | 0.5 m     |
| L3     | 0.1 m     |
| V1     | 0.3 m     |
| H1     | 0.3 m     |
| V2     | 0.1 m     |
| A      | 0.1 m     |

3.2. Model Particle

Real cenosphere concentration commonly found in coal-fueled power plant is less than 1% [6] which is very small. This study uses a model particle with a total mass of 2e-6 kg and a cenosphere : fly-ash mass ratio of 1:1 in order to fully map every diameter distribution and still uses a reasonable computing power. Particle distribution is based on particle distribution found in [7]. It is then fitted for Rosin-Rammler particle distribution which is shown by equation (9) and mapped for every diameter. Result is shown on figure 3.

\[ Y_d = e^{-\left(\frac{d}{d_{mean}}\right)^n} \]  \hspace{1cm} (9)

where:

\[ Y_d \] = mass fraction of particle with the diameter greater than \( d \)
\[ d_{\text{mean}} = \text{size constant} \]
\[ n = \text{size distribution parameter} \]

Figure 4. Particle size distribution for model particle of raw material

3.3. Particle Trajectory
The separation of cenosphere from fly ash will be highly affected by the rheology inside the air separator. Providing the trajectory of the air flow as a function of inlet velocity as it can be seen in Figure 4-9 will underline the separation mechanism that will be further represented by Newton efficiency.
Figure 5 to Figure 10 show that particle trajectory is heavily affected by inlet speed variation. Particles are more likely to spread further from the inlet position with the increase of inlet speed. There is a backflow starting from 0.5 m/s velocity variation which is caused by stream and particle collides with the outlet wall. This phenomenon causes the separation efficiency of this gravitational separator is not merely controlled by linear velocity and terminal velocity.
3.4. Newton efficiency (NE) of each collector

Newton efficiency of each collector is calculated by assuming that each collector is a cenosphere concentrated product and the other 10 collectors are fly-ash concentrated product for every collector’s NE calculation. This method is described in equation (10) found in Hirajima et.al. (2010) [7].

\[
NE (i) = \frac{mc(i)}{mct} - (1 - \frac{mft - mf(i)}{mft})
\]  

(10)

Rearranging equation (10) above yields :

\[
NE (i) = Rc(i) - Rfa(i)
\]  

(11)

where :

- \(i\) = index of collector
- \(NE\) = newton efficiency of specific collector
- \(mc\) = mass of cenosphere in a specific collector
- \(mct\) = total mass of cenosphere
- \(mft\) = total mass of fly-ash
- \(mf\) = mass of fly-ash in a specific collector
- \(Rc\) = recovery of cenosphere in a specific collector
- \(Rfa\) = recovery of fly-ash in a specific collector

Detailed calculation result will be shown for inlet speed = 0.1 m/s in Table 2, while Newton efficiency for each collector for every inlet speed variation will be visualized in Figure 11 to figure 16.

Table 2. Detailed Calculation for Each Collector at Inlet Speed = 0.1 m/s

| (i) | 1     | 2      | 3       | 4       | 5       | 6       | 7       | 8       | 9       | 10      | 11      |
|-----|-------|--------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Rc  | 0.498772 | 0.22608 | 0.10672 | 0.057416 | 0.040439 | 0.017048 | 0.014098 | 0.01061 | 0.007267 | 0.009973 | 0.011126 |
| Rfa | 0.308726 | 0.143193 | 0.120941 | 0.100971 | 0.073772 | 0.059547 | 0.041558 | 0.03328 | 0.032026 | 0.041275 | 0.044711 |
| NE  | 0.190047 | 0.082887 | -0.01422 | -0.04356 | -0.03333 | -0.0425  | -0.02746 | -0.02222 | -0.02476 | -0.0313  | -0.03359 |
The NE distributions shown above effectively shows the cenosphere and fly-ash distribution across the geometry. The higher the inlet speed, the more scattered cenosphere is. This is mainly due to the size distribution of cenosphere and fly-ash. Fly-ash mainly consist of small particles with 20% of its mass fraction is under 2.5e-5 m in diameter as shown in section 3.2. Fly-ash particle distribution is more evenly
distributed compared to cenosphere particle distribution. This unique particle distribution causes the cenosphere to be concentrated at the 1st and 2nd collector at low speed (0.1 m/s ; 0.25 m/s ; 0.5 m/s). Even at low inlet speed variations, small fly-ash particles is blown further than cenosphere particles and causes the 1st and 2nd collector to be less occupied by fly-ash particles. This phenomenon is further confirmed in Figure 17 and 18. It can be seen that particles with the biggest diameter are accumulated in collector-1 for both fly-ash and cenosphere.

![Particle size distribution kumulatif untuk Cenosphere](image)

**Figure 17.** Cumulative particle size distribution for cenosphere in every collector at inlet speed =0.5 m/s
Figure 18. Cumulative particle size distribution for fly-ash in every collector at inlet speed =0.5 m/s

3.5. Overall efficiency
Collector(s) with positive value of NE (>0) described in section 3.4 are considered as cenosphere concentrated product and collector(s) with negative value of NE (<0) are considered as fly-ash concentrated product thus yielding a single parameter to measure the separation performance for every inlet speed variation. This method is described in equation (12)

\[ \text{NET} = \frac{mcs}{mct} - (1 - \frac{mfs}{mft}) \]  

(12)

Where:
NET = Overall newton efficiency
mcs = mass of cenosphere in the cenosphere concentrated product
mct = total mass of cenosphere
mft = total mass of fly-ash
mfs = mass of fly-ash in the fly-ash concentrated product
Figure 19. Inlet speed vs overall newton efficiency

Optimum speed is obtained at inlet speed = 0.25 m/s. This phenomenon is explained at section 3.4 where cenosphere is concentrated at the 1st collector thus yielding the largest value of newton efficiency by retaining most of injected cenosphere in a single collector resulting in a newton efficiency of 0.41.

4. Conclusion
Gravitational separation is an environmentally friendly and practical method for separating cenosphere and fly-ash. It uses no water as its medium of separation while offering the reasonable separation efficiency. Computational Fluid Dynamics (CFD) can provide detail information related to the potential of the modified air separator studied in this paper which offers the reasonable separation efficiency (Newton efficiency) up to 0.41.

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