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Research article

Design and performance of a cyclone separator integrated with a bottom ash bed for the removal of fine particulate matter in a palm oil mill: A simulation study

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Abstract: Long-term exposure to pollution from particulate matter in palm oil mills can result in chronic respiratory diseases, cardiovascular diseases and mortality. Particulate matter with a size of less than 2.5 μm (PM2.5) has a greater impact than one with a size of 10 μm. The current PM cleaning equipment in palm oil mills consists of cyclones that are incapable of optimally filtering PM2.5. For this reason, it is necessary to design cyclone applications for fine particle separation in palm oil mills. Normal cyclones are incapable of segregating particles smaller than 2.5 μm. This study's objective was to design a cyclone with a filter on the vortex detector. These cyclones are utilized in PM2.5 fine particle filtration systems. Using computational fluid dynamics, cyclone performance is analyzed in terms of removal efficiency and pressure decrease. The research was conducted utilizing the Reynolds tress model with varying inlet velocities of 10, 15, 20, 25 and 30 meters per second. The filter is composed of boiler bottom ash refuse from palm oil mills; 0.310 meters is the height of the filter bed inserted in the vortex finder. The obtained results demonstrated that the PM2.5 removal efficiency reached 98%, while the pressure decrease was only 93 Pa greater than that of conventional cyclones. Thereby, cyclone designs with bottom ash filters can be used to filter fine particulate matter, particularly particles smaller than 2.5 μm.

Keywords: cyclone; particulate matter; CFD; vortex finder; bottom ash

1. Introduction

Particulate matter (PM) must be removed from exhaust gases because PM, along with O_3, CO, CO_2, NO_x and SO_x, is a primary component of air pollutants [1–2]. PM varies in dimension. PM10 is defined as PM with an aerodynamic diameter between 2.5 and 10 µm, whereas PM2.5 has a diameter of less than or equal to 2.5 µm. Long-term exposure to PM pollution can result in chronic respiratory diseases, cardiovascular diseases and even mortality. Examining a substantial increase in PM2.5 pollution, the risk of mortality following PM2.5 exposure is greater than PM10 exposure [3,4]. PM2.5 concentration impacts cerebrovascular disease more than PM10 concentration. PM2.5 is primarily generated by the combustion of biomass in palm oil industrial boiler units [4–6]. The simplest equipment currently used to reduce PM2.5 concentrations in the palm oil industry is a cyclone [7]. A cyclone is an equipment for separating particulate from gases. Cyclones employ centrifugal force to separate particulates. Despite the fact that particle sizes greater than 10 µm are frequently used in operational contexts, cyclones are evaluated based on their high separation efficiency with particles of 5 µm. Cyclones are comparatively straightforward and inexpensive equipment for separating particles and gases, and their industrial use has increased, especially in the agricultural sector [8,9].

Numerous efforts have been made to improve the performance of cyclones, including the modification of cyclone geometry, the effect of which has been extensively studied. Among these are the dimensions of the cyclone body's cylinder diameter component, which correspond to the height of the cone in the design at three times the cylinder diameter. Modification of inlet dimensions has been achieved through the use of optimal inlet width-to-height ratios [8], cone height and shape [9–11] and inlet width-to-height ratios [7,8]. This enhances particle collection efficiency, although it is not optimal for the collection of small particles.

Additionally, attempts have been made to modify the cyclone by adding a filter to the gas discharge section. Youn et al. [12] did this to enhance the efficacy of cyclones that collect smaller particles (PM). Duran and Caldona [13] performed PM recirculation on the vortex finder using multiple cyclones to improve cyclone performance. Additionally, Hayashi et al. [14] have tested the use of activated carbon as a filter in the cyclone input section. Several studies demonstrate that activated carbon is effective at removing various industrial contaminants, such as organic micropollutants, in advanced wastewater treatment and water reuse systems. Activated carbon is also effective at capturing PM and other gaseous pollutants, such as VOCs, mercury and ozone [15–17]. In addition to commercial activated carbon, bottom ash can also be used as a filter. Bottom ash is a carbon-rich byproduct of palm oil boilers that can absorb dyes [18] and CO_2 [19–22] and generate filters [18,19].

The carbon content of bottom ash generated by palm oil mills can vary based on variables such as the origin of the raw materials and the conditions of combustion. Typically, bottom ash consists of approximately 40% carbon and mineral components such as silica, alumina and calcium oxide [18]. In contrast, commercial activated carbon contains between 70 and 90% carbon [19], depending on its type and production process. Even though bottom ash has a lower carbon content than commercial activated carbon, depending on its physical and chemical properties, it can still be an effective molecule and chemical filter. Several studies have been conducted to evaluate the effectiveness of bottom ash as a filter for removing pollutants from water and wastewater, and the results suggest that bottom ash has the potential to be a cheaper and more environmentally responsible alternative to commercial activated carbon.

The separation of particles and gas is one of the most difficult phenomena to study experimentally. In these circumstances, computational fluid dynamics (CFD) proved to be the most cost-effective alternative to expensive experimental methods. This study employs CFD in order to estimate cyclone performance metrics (CFD). Here, the commercial CFD code 2021 R1 from Ansys is utilized.

This study aims to demonstrate the effectiveness of cyclones equipped with bottom ash in reducing PM emissions. We plan to enhance the separation of fine particulates in cyclone designs used in palm oil mills equipped with bottom ash as a filter on the vortex finder. Compared to the current method, this new design offers the benefits of high efficiency, low energy consumption, uncomplicated construction and straightforward operation. Importantly, it can dependably absorb fine-sized particles at the outflow (vortex finder) to reduce smooth PM to the greatest extent possible. Future applications of the study's equipment can be made in palm oil mills, as depicted in Figure 1.

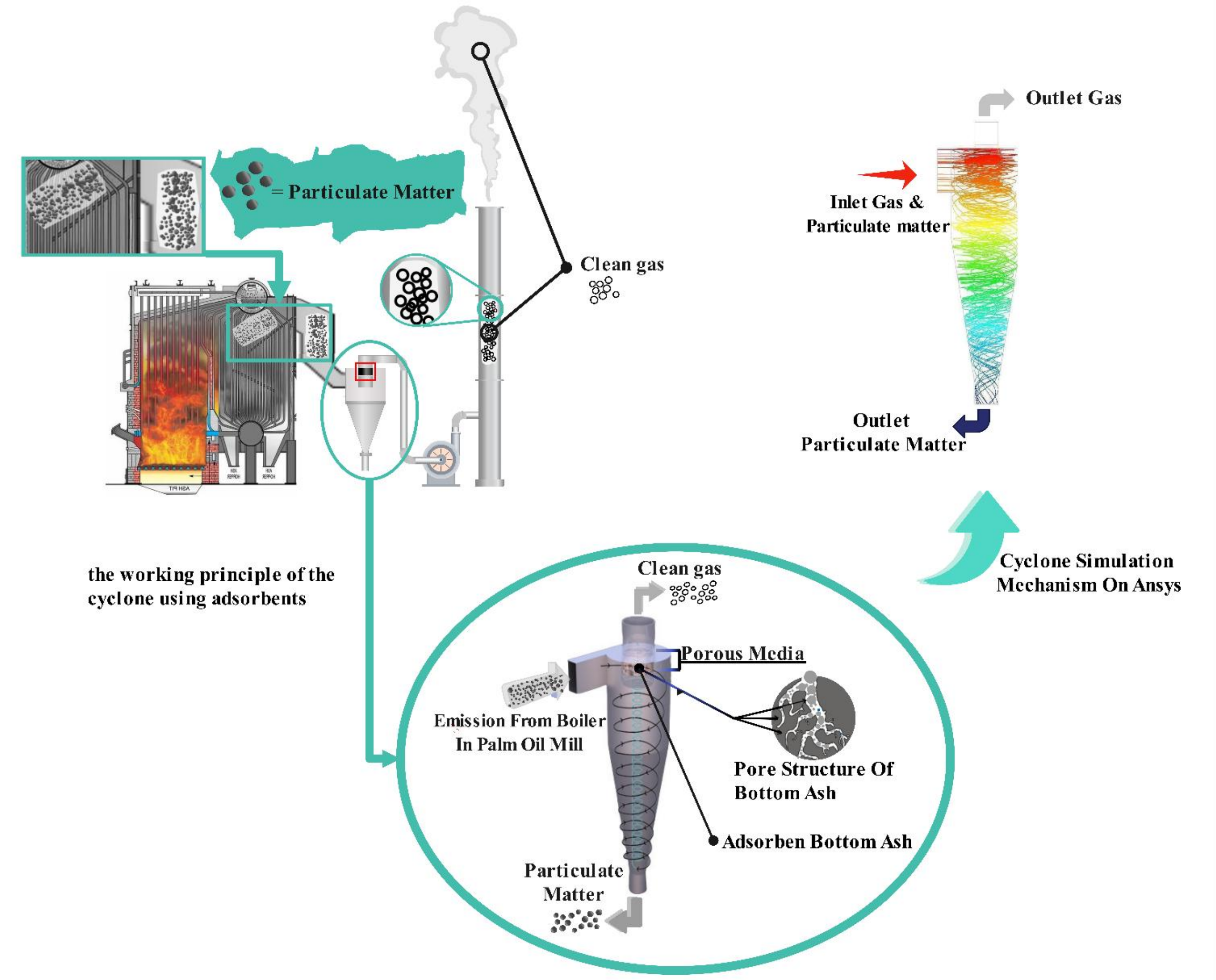


Figure 1. Mechanism study.

This study focuses on palm oil mills because palm oil is one of the most important industrial commodities in Indonesia and Southeast Asia. Improving the quality of production in palm oil mills is a potentially essential area of study. In a variety of industries, cyclone separators are a prevalent waste and material processing technology. Nevertheless, integrating them with a bottom ash layer to remove fine particulates can be viewed as an innovative method for enhancing the performance of cyclone separators. Simulation as a research method has the potential to save money and time, as well as to allow researchers to test and optimize the design and performance of the cyclone separator prior to conducting actual testing.

This research has the potential to provide new contributions to waste and material processing in the palm oil industry, specifically in the separation of fine particles using cyclone separators incorporated with a bottom ash bed.

2. **Research and method**

2.1. Simulated basic equations

CFDs utilizing the Ansys 2021 R1 software are able to simulate extremely complex and precise fluid dynamics. ANSYS 2021 R1 incorporates more complex mathematical equation models, exact boundary conditions and meshing levels [22]. Using partial differential equations derived from the laws of conservation of mass, momentum and energy, CFDs also measure flow patterns and behaviors. CFDs solve fluid flow patterns utilizing numerical analysis and contemporary methods. To simulate the interaction of gases and solids with a specified surface under boundary conditions, a powerful computer is necessary. CFDs use the Navier-Stokes equation and function according to Newton's second law. Equations 1 and 2 [23] represent the fundamental continuity and momentum conservation equations.

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho U_i)}{\partial x_i}=0 \tag{1}$$

$$\rho\left(\frac{\partial u_i}{\partial t}+u_j\frac{\partial u_i}{\partial x_j}\right)=\frac{\partial p}{\partial x_i}+\frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}-\overline{\rho u_i' u_j'}\right]+\rho g_i+F_d \tag{2}$$

where U_i = initial velocity, t = time, ρ = density and μ = viscosity of the liquid. u_i and u_i' denote components of average velocity and speed fluctuations, respectively. g = gravity, p = pressure and F_d = drag force; $\rho u_i' u_j'$ represent components of the turbulent moment flux, known as the Reynolds voltage.

A Reynold stress model (RSM) was utilized in this investigation. The RSM is derived from the Reynolds–averaged Navier-Stokes equation.

This model's CFD study is quite useful for evaluating the efficiency of particle separation in cyclone designs. Fluid velocity, fluid characteristics (density, specific gravity), particle size and inlet and outflow are determined as input parameters. Analyzing particle trajectories in the region of 0.5–2.5 μm involves the Eulerian-Lagrangian method and the discrete phase model. By calculating the proportion of loose and absorbed particles, the separation efficiency of each particle size may be determined. The following are the limit conditions for CFD analysis:

a. The entrance is labeled as a particle trajectory escape, the gas outlet as an escape, the particle outlet as a trap and the cyclone wall as a reflect.
b. Outside pressure equivalent to atmospheric pressure (assumed 1 atm).
c. Outdoor temperature equivalent to room temperature (assumed 27 °C).

Table 1. Boundary condition.

Parameter	Value
Mass loading particle	0.1 kg/s
Velocity inlet	10; 15; 20; 25; 30 m/s
Diameter particle	0.5–2.5 μm
Pressure outlet	1 atm

Table 2. Filter parameters.

Parameters	Value
Bulk density	108.9 kg/m^3
Diameter bottom ash	100 μm
Porosity	0.881
Bed Height	0.310 m

Table 3. Dimensions of cyclone.

Dimension	Size (m)
D_c	0.48
D_e	0.48
D	1.45
L_d	0.30
L_c	2.0
L_b	1.20
L_v	0.62
L	0.26
S	0.60
W	0.40
T	0.02

The flow of this study begins with the representation of geometry (pre-processor) on a cyclone separator using the Fusion 360 application. Then, proceed to the processing phase by adding the generated image to the geometry menu of the Workbench R1 ANSYS 2021 application. Before saving the project, the image transferred to the geometry menu will establish the boundary condition and determine the number of subdivisions in the mesh menu. The subsequent stage is the processor stage, which begins with the input of the value variable and the determination of the RSM, followed by the entry of the value for the type of gas fraction injected to fill the porous zone. The solution menu comes next, where variables are initialized and calculations are performed. In the event of an iteration error, the image in the geometry menu must be examined. Nonetheless, the error will be indicated at the conclusion of the iteration if it does not occur (iteration convergent). If the data have converged, they can be included in the report's solution section. Proceed to the result menu stage after collecting animation data on the direction of flow for the adsorbent absorption process (post-processor). Tables 1 and 2 display the parameters utilized in this study, while Table 3 depicts the dimensions of the cyclone.

2.2. Geometric model

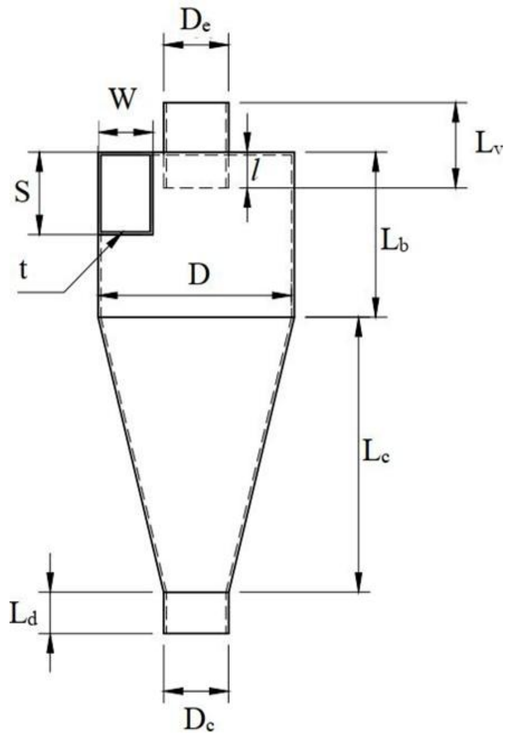


Figure 2. Cyclone dimensions.

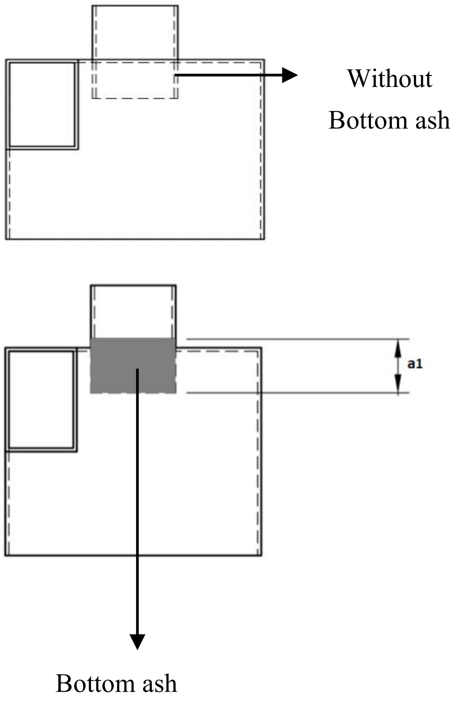


Figure 3. Filter 2D sketch.

The cyclone proportions utilized at the palm oil facility of PT Syaukat Sejahtera Aceh are those of cyclones with geometry. The dimensions of the cyclone are listed in Table 3. As shown in Figure 2, the cyclone geometry comprises the two-phase mixed inlet (defined by height S and width W), the vortex finder diameter (D_e) and length (L_v), the height of the cylindrical cross section (L_b), the height of the cone cross section (L_c) and the cyclone diameter (D). Figure 3 depicts the positioning of bottom ash with a bed height of 0.310 m in the vortex finder. Using the "hex-dominant method" mesh type, Figure 4 depicts the cyclone grid as a domain on the CFD. There are 339,261 nodes and 397,836 elements in the network. The boundary conditions for numerical analysis in this investigation are shown in Table 1 and Figure 5. During the run phase, the inlet velocity and pressure are equal to zero in the initialized simulation. While the filter section data in the form of bottom ash is thought to represent a porous zone, as shown in Table 2, the SIMPLE algorithm was used to calculate pressure and velocity. We use PRESTO on interpolation techniques for pressure discretization. For a turbulent kinetic energy dissipation rate, the momentum equation is discretized with the QUICK scheme using a second-order upwind approach. The convergence rate is set to be between 10^{-1} and 10^{-4}. The parameters of the bottom ash filter are shown in Table 2. Figure 6 depicts the order of the investigation's phases; Figure 7 depicts the cyclone process.

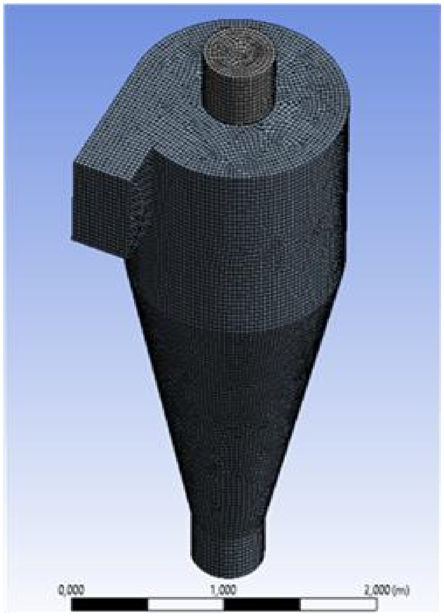


Figure 4. Computational grid.

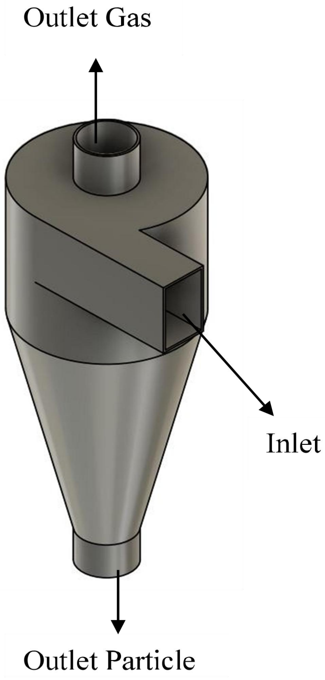


Figure 5. Boundary condition.

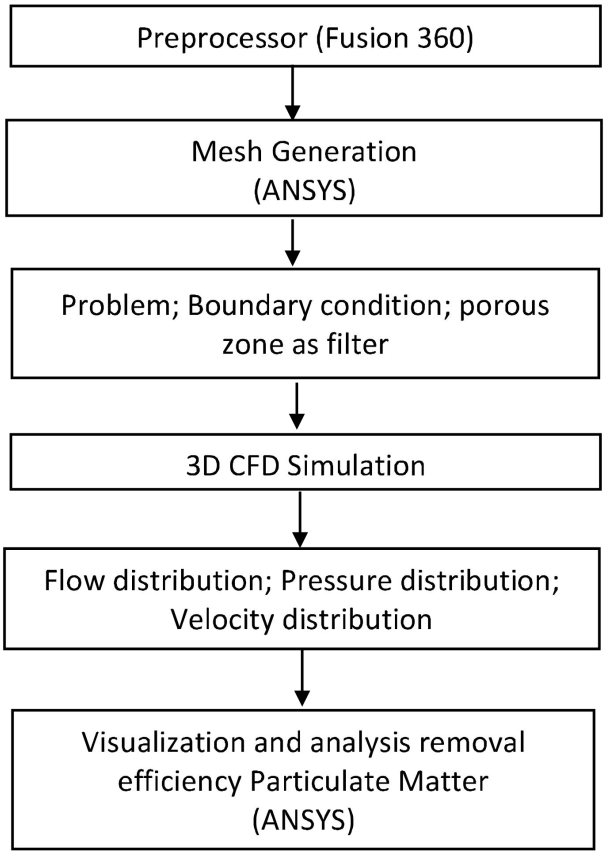


Figure 6. CFD simulation process block diagram.

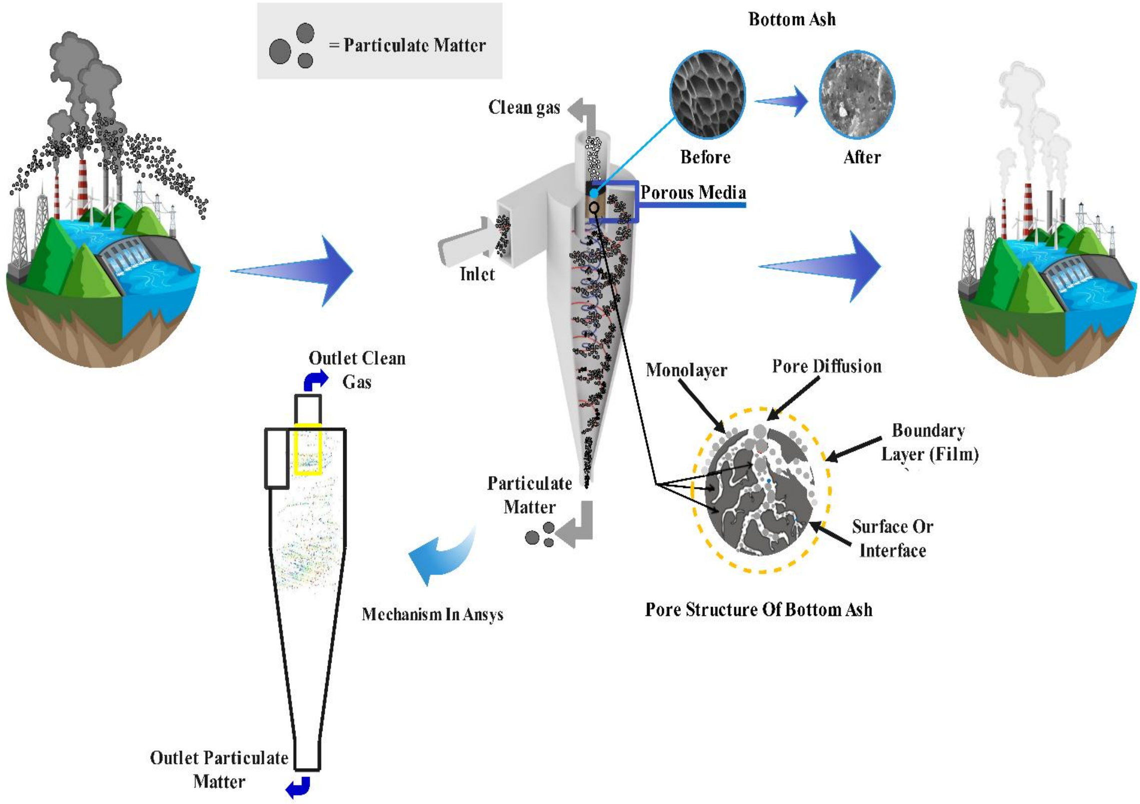


Figure 7. Filtration process in the cyclone.

3. **Results**

3.1. Analysis of removal efficiency

The primary function of cyclones is to separate particles from gases; the separation ability of cyclones is defined by the ratio of the number of particles separated by the cyclone separator to the number of particles entering the cyclone, as shown in Eq 3 [11]. Particle size determines removal efficacy. And, vice versa, the larger the particulate size, the more efficient the removal. Calculations and experiments imply that it is difficult to achieve particle separation below 10 µm [24]. Figure 8 illustratively demonstrates this. At a particle size of 2.5 µm, cyclones without a filter have a 70% removal rate, while cyclones with bottom ash as a filter can attain a 98% removal rate. The addition of bottom ash significantly improves the efficacy of removal. A comparison of particle paths in cyclones with and without bottom ash is illustrated in Figure 9. Several particles appear to be dispersing into the air in Figure 9(a). Bottom ash can filter out fine particles after being inserted as a filter in the vortex detector, as shown in Figure 9(b). Fine particles tend to migrate out of the gas outlet more rapidly than larger particles, so the percentage of fine particle removal efficiency is lower than that of larger particles. This is illustrated in Figure 10. Figure 11 depicts particle trails in cyclones lacking bottom ash filters. Still, the path of particulates between 0.5 and 2.5 µm in size escapes into the air.

The relationship between inlet velocity and particle size variation removal efficacy is especially significant for cyclones without bottom ash, which rely solely on centrifugal force to separate particles according to their size and density. In a cyclone without bottom ash, particulates are introduced at a high velocity through the cyclone's inlet, causing them to spiral along the cyclone's walls. As the particles move toward the cyclone's bottom, they encounter a diminished velocity and are thrown toward the cyclone's outer wall, where they are collected and removed.

However, the size and density of the particles, as well as the inlet velocity, affect the efficiency of particle separation in a cyclone. Smaller particles may not be effectively separated at higher inlet velocities due to their lower momentum and increased likelihood of being carried along with the gas stream. Therefore, cyclones without bottom debris may have difficulty separating fine particles from the gas stream, resulting in a lower separation efficiency overall.

$$\mathrm{Re}\,moval\ Efficiency = \frac{total\ \ tracked\ particles - particles\ escaped}{total\ \ tracked\ particles} \tag{3}$$

In contrast, particle size variation has no effect on the removal efficiency of cyclones equipped with bottom ash because the bottom ash layer functions as a filtering medium. Regardless of the inlet velocity or particle size variation, the bottom ash layer can capture and eliminate fine particles that the cyclone alone may not be able to effectively separate. Consequently, the use of bottom ash as a filtering medium can improve the performance of cyclone separators and increase the efficacy of particle separation, even at higher inlet velocities.

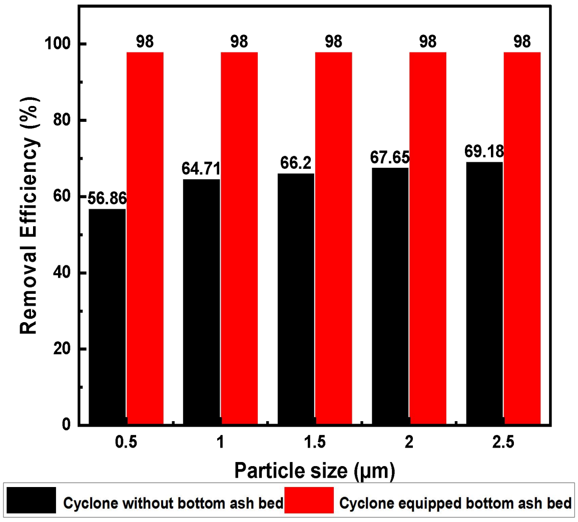
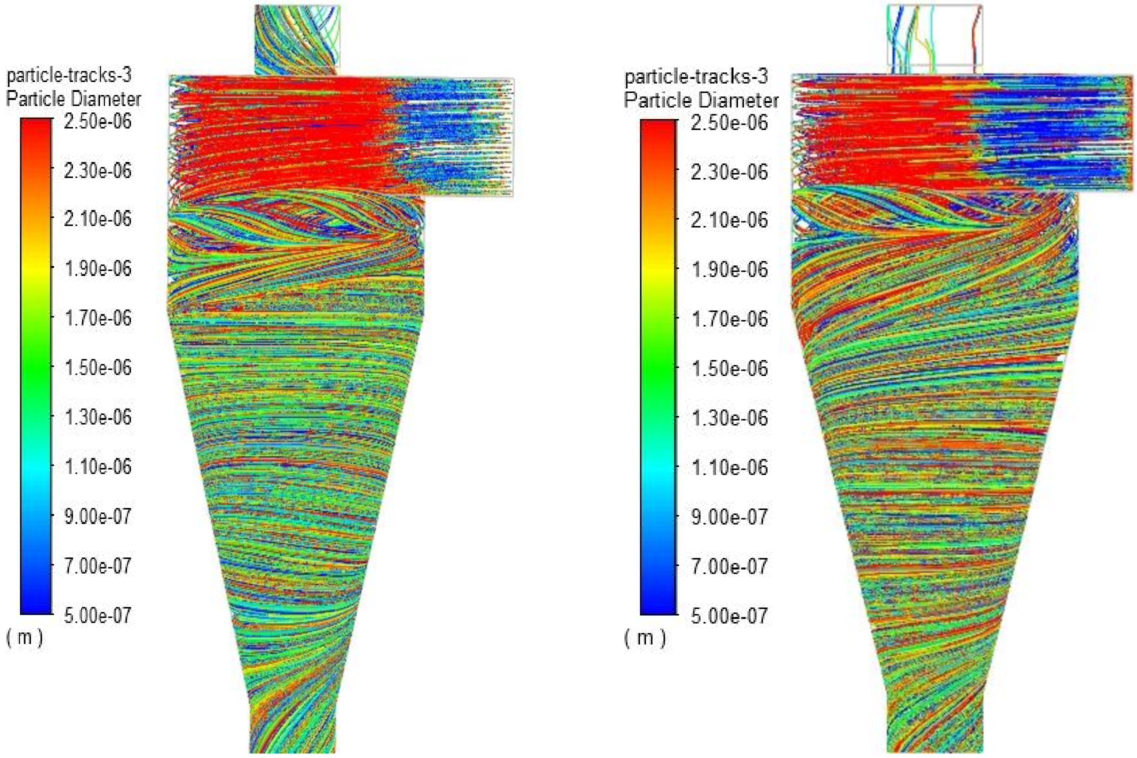


Figure 8. Effects of particle diameter on removal efficiency in cyclones without bottom ash and cyclones equipped bottom ash.

The vortex finder's bottom ash can absorb fine particles ranging from 0.5 to 2.5 μm, resulting in a removal efficacy of 98%. As shown in Figure 10, the relationship between inlet velocity and particle size variation removal efficacy is especially significant for cyclones without bottom ash. In contrast, particle size variation has no influence on the removal effectiveness of cyclones equipped with bottom ash. Bottom ash on the vortex finder can increase the efficacy of removal.

The bottom ash layer can function as a filter, capturing and removing fine particles that the cyclone may not be able to effectively separate. This can result in increased separation efficiency and enhanced overall system performance. Using bottom ash as a filtering medium is a cost-effective and eco-friendly solution. The abundant and inexpensive byproduct of palm oil production is bottom ash. By employing this material as a filtering medium, the system's price can be reduced, making it more accessible and practical for use in industries such as palm oil processing.



a. Without bottom ash

b. With bottom ash

Figure 9. Particle trajectory in cyclones.

3.2. Pressure drop

Using the average difference in total pressure between the intake and exhaust surfaces, which, in this case, involves the gas outlet and particle outflow, the pressure drop is calculated. This factor is proportional to the quantity of energy a cyclone requires to function. A greater pressure drop indicates a substantial loss of energy, as fluid must be moved across the cyclone's volume with effort [11,12]. Continuous operation of cyclones necessitates that the design of the cyclones ensures minimal pressure loss, which, in some applications, can be prolonged. Low pressure loss should be guaranteed by the proposed design because this device operates indefinitely. The contour of static pressure in Figure 11 illustrates the pressure decrease that occurs in cyclones. Figure 12(a) depicts a cyclone with a maximum pressure drop of 1111.8 Pa and no bottom ash, while Figure 12(b) depicts a cyclone with bottom ash and a maximum pressure drop of 1205 Pa. It indicates that the variation in pressure is merely 93 Pa.

Figure 13 depicts the static pressure decrease at different heights beneath the vortex finder. It is possible to explain why the decrease in pressure at various heights has no significant effect on cyclones with or without bottom debris. Consequently, it is evident that using bottom ash as a filter in cyclones does not significantly increase pressure loss [14].

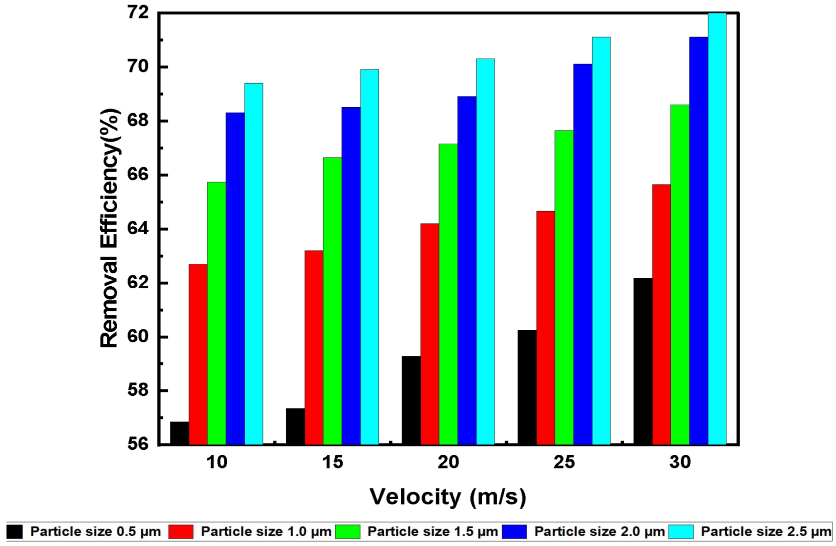
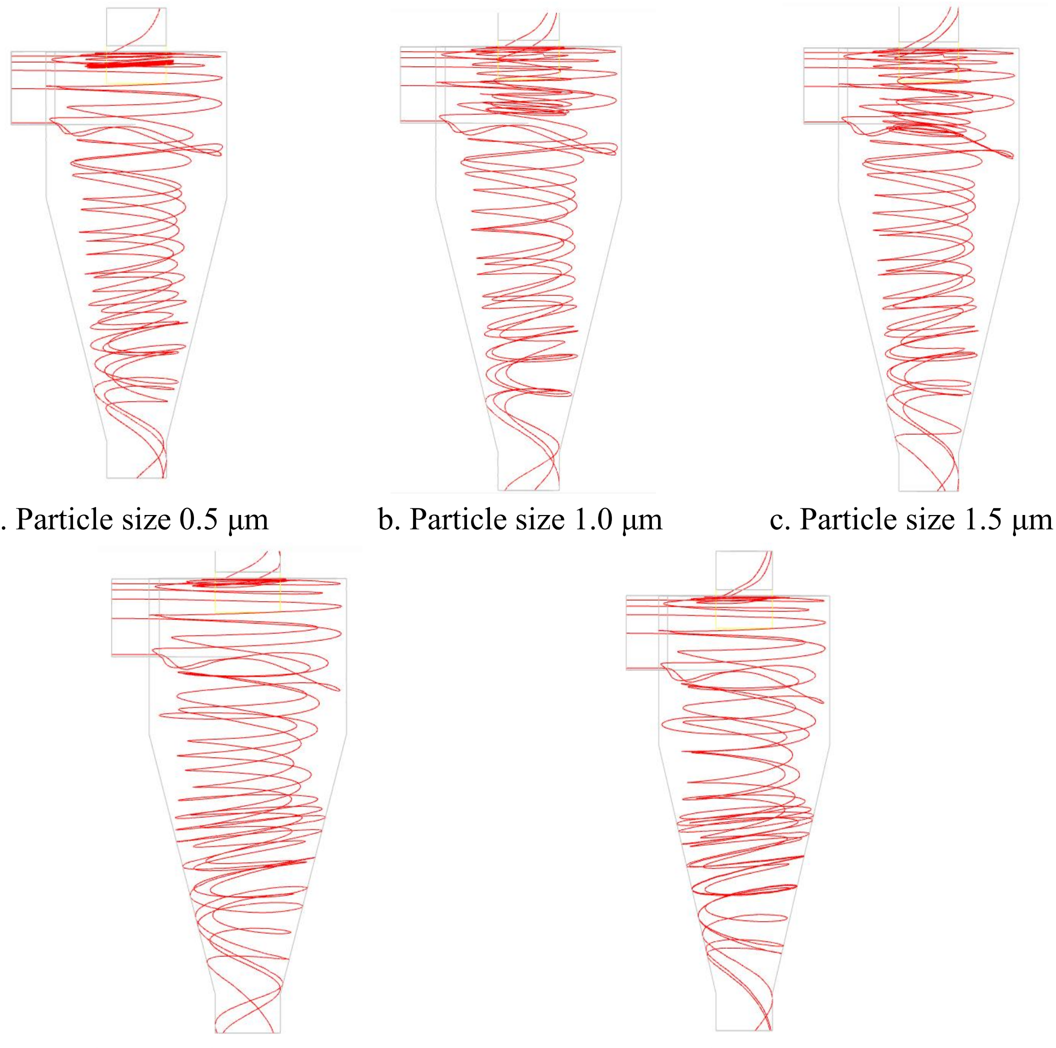


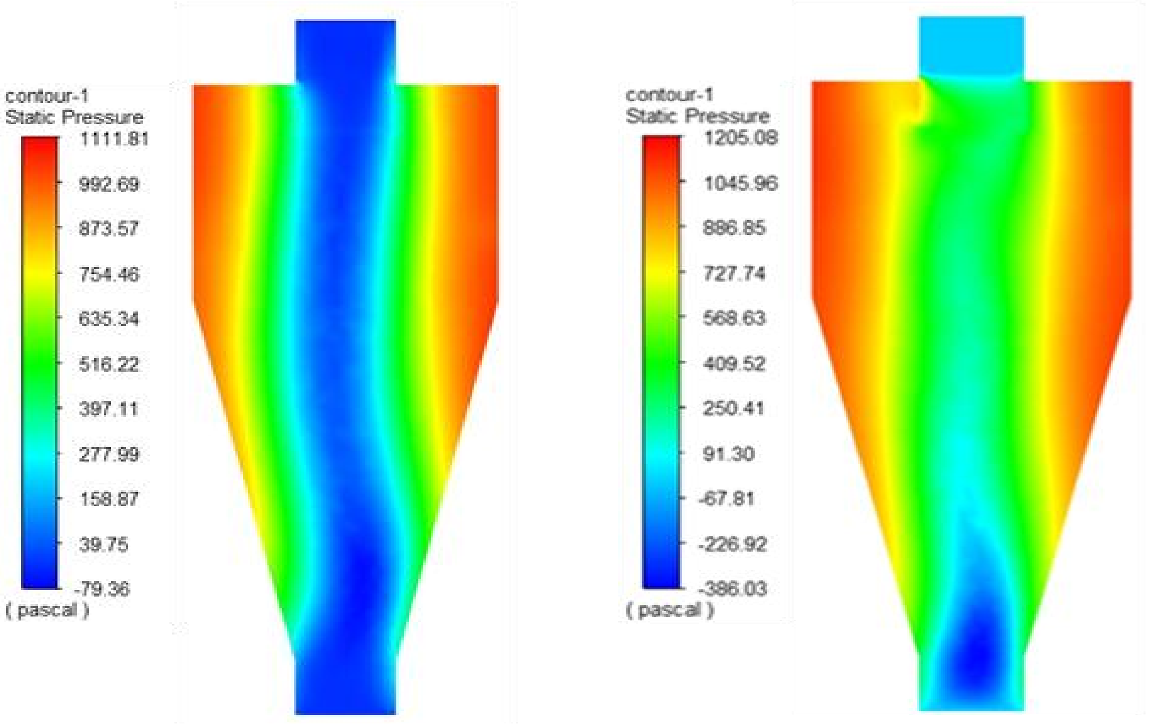
Figure 10. Effects of inlet velocity with various particle diameters on removal efficiency.



a. Particle size 0.5 μm b. Particle size 1.0 μm c. Particle size 1.5 μm

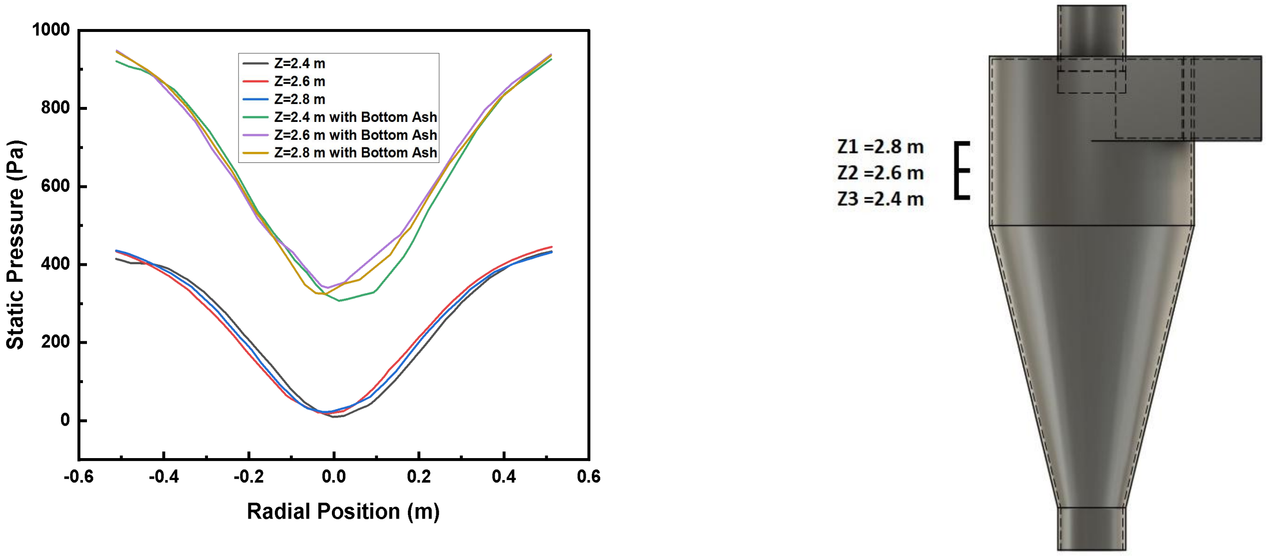
d. Particle size 2.0 μm e. Particle size 2.5 μm

Figure 11. Particle tracks with a particle diameter range of 0.5–2.5 μm.



a. Without bottom ash b. With bottom ash

Figure 12. Contour static pressure on a cyclone.



a. Static pressure at various heights b. Position static pressure

Figure 13. Contour static pressure on a cyclone.

4. Conclusions

The research on bottom ash as an integrated filter in a cyclone indicates that it can be used effectively as a filter medium to remove fine particles, particularly dust and ash particles. The following conclusions can be derived from this study:

- Utilizing bottom ash as a filter in cyclones has a significant impact on PM reduction. The addition of bottom ash to the vortex finder of the cyclone resulted in a pressure decrease difference of 93 Pa and a removal efficiency of 98%. This indicates that bottom ash can be used to power cyclones, especially in palm oil mills.
- Integrating cyclone separators with a bottom ash layer is a novel method for enhancing the performance of cyclone separators. In the palm oil industry, where the separation of fine particulates is essential for efficient waste and material processing, this method can be particularly useful.
- Using simulation as a research method has several advantages, including cost and time savings and the ability to test and optimize the design and performance of the cyclone separator in a virtual environment prior to conducting actual testing. Before committing resources to physical testing, this strategy can assist researchers in identifying potential design flaws or inefficiencies.
- Additional research can be conducted to validate the results with experimental methodologies and investigate the performance of the cyclone separator with a bottom ash layer under different operating conditions.
- By providing new contributions to waste and material processing in the palm oil industry, this research may result in more efficient and cost-effective processing methods, thereby minimizing waste and increasing the yield of useful materials. In addition, this technique may have applications in other industries requiring the separation of fine particulates, such as mining, chemical processing and food production.

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Conflict of interest

We have no conflict of interest to declare.

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