Mathematical Modelling of Engineering Problems
Vol. 10, No. 2, April, 2023, pp. 597-604
Journal homepage: http://iieta.org/journals/mmep

Simultaneous Fine Particulate Matter Separation and CO_2 Adsorption in a Cyclone Separator with a Fixed Bed Bottom Ash from a Palm Oil Mill Boiler: A Simulation Study

Novi Sylvia[1,2], Rozanna Dewi[2], Bela Aprilia[2], Husni Husin[3], Abrar Muslim[3], Yunardi[3*], Yazid Bindar[4]

[1] Doctoral Program, School of Engineering, Post Graduate Program, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[2] Department of Chemical Engineering, Malikussaleh University, Lhokseumawe 24351, Indonesia
[3] Department of Chemical Engineering, Universitas Syiah Kuala, Banda Aceh 23111, Indonesia
[4] Department of Chemical Engineering, Faculty of Industrial Technology, Institut Teknologi Bandung, Jl. Ganesha 10 Bandung 40132, Indonesia

Corresponding Author Email: yunardi@unsyiah.ac.id

https://doi.org/10.18280/mmep.100229

Received: 16 December 2022
Accepted: 13 March 2023

Keywords:
cyclone, CO_2 adsorbent, simulation, bottom ash

ABSTRACT

At palm oil mills, a cyclone is an integrated piece of equipment in the boiler with the sole purpose of separating air and particles resulting from the shell and fiber combustion process in the boiler unit. Meanwhile, the CO_2 gas emissions produced cannot be reduced simultaneously in the boiler unit. This study aims to minimize the amount of fine particulate matter resulting from the combustion process while reducing CO_2 emissions. By modifying the cyclone separator, namely by placing the adsorbent from bottom ash on the cyclone vortex finder, the research was conducted using the Computational Fluid Dynamics Method. This study was carried out by varying the inlet velocity, namely 10; 15; 20; 25; and 30 m/s, and the bed height at the cyclone separator gas outlet is 0; 0.155; 0.310; and 0.460 meters. The RNG model equation k-ε, capable of supporting device direction simulation flow, is modified with a mass load of 0.1 kg/s and an operating temperature of 573 K to determine particle collection efficiency, CO_2 adsorption percentage, and pressure drop. The results showed that at a bed height of 0.465 m and an inlet velocity of 30 m/s, the cyclone separator achieved the greatest particle collection efficiency of 92.61 percent. At a bed height of 0.465 m and an inlet velocity of 10 m/s, the maximum percentage of CO_2 adsorption is 99.61 percent. Cyclone modification by using bottom ash as an adsorbent is able to reduce CO_2 emissions and minimize fine particulates simultaneously.

1. INTRODUCTION

Palm oil production in Indonesia has expanded annually in tandem with exports [1, 2]. The development of the sector, in particular the usage of boilers as steam generators, will follow the increased production of palm oil. Typically, palm oil mill boilers utilize palm shells and fiber as furnace fuel [3, 4]. Combustion of fuel from shells and fibers produces relatively high particulate matter (PM) which needs to be controlled. Rashid et al. [5] discovered that palm oil mill chimneys produced 3.22 and 12.5% of the average concentration of particles with diameters less than 2.5 and 10 micrometers, respectively.

The fine PM fraction, especially those smaller than 2.5 μm or PM2.5, is harmful to human health, particularly to respiratory and cardiovascular diseases [6]. PM is a major concern for human health, because most of the PM produced by burning biomass is smaller than 10 μm (PM10) or even smaller than 1μm (PM1) [4, 7]. Syahirah et al. [8] reported that the mass concentration of particulate matter with a diameter of 2.5 μm (PM2.5) and 10 μm (PM10) is an emission resulting from 13,600 kg/hour of steam capacity of a palm oil mill boiler, respectively 2.33% and 13.7% of total particulate matter. Several researchers indicated that the total particle size distribution of 50% of particles that a dust arrestor could remove was 40 μm [5]. In addition to PM, the combustion of shells and fiber also produces CO_2 gas and other exhaust gases. Because all the hydrogen and carbon in the biomass will separate and interact with oxygen in the air to form water vapor, carbon dioxide, and heat [5, 9]. Stationary combustion units emit around 38.39% CO_2 [10-12].

Up until now, palm oil mills have utilized cyclone separators in the efforts to reduce particulate matter and emissions. Cyclone is a popular piece of machinery used in palm oil mills to reduce emissions [13]. The purpose of the cyclone machinery in the palm oil mill is to separate the fly ash from the boiler's exhaust gas [14]. The benefit of employing a cyclone as a particle separator is that during the separation process, no portion of the cyclone moves. Cyclones are suitable for continuous long-term operation due to their high separation efficiency, low energy consumption, small structural size, big processing capacity, and ease of operation and maintenance [15]. In addition, its low investment and maintenance costs make it preferable [5]. Consequently, cyclones are widely utilized in particle separation and grading [16], gas purification [17], and atmospheric pollution prevention and treatment [18] in the refining, chemical, environmental protection, food, mining, and textile industries, among others.

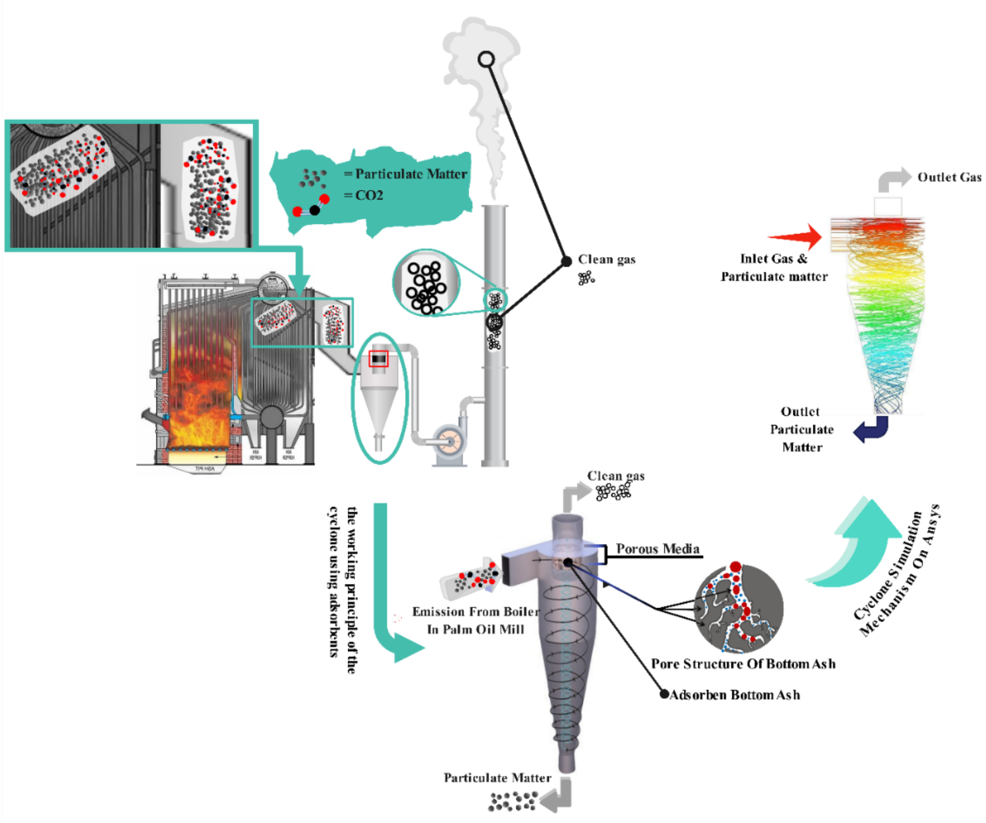

Figure 1. Adsorption mechanism in cyclone

Several research have identified ways to enhance cyclone performance in lowering emissions. Ibhadode et al. [19] designed a cyclone to absorb H_2S gas in biogas by injecting biogas and oxygen, where the process of rotating the gas movement in the cyclone provides a perfect reaction between hydrogen sulfide and oxygen, resulting in sulfur elements that have been separated in the cyclone section. Duran and Caldona [20] redesigned the cyclone separator and employed activated carbon to absorb pollutants as a particle remover. As was done in research [21], activated carbon is added at the cyclone's entrance to absorb volatile organic molecules. Norelyza et al. [22] created MR-deDuster, a multi-cyclone unit using activated carbon as a PM absorber that was able to capture 2.4 m of particulate matter at a purification level of 50% and achieve a total collection of over 95% with a low pressure drop. There are also those who add a filter to the gas exit of the cyclone [23]. Zhang et al. [24] redesigned the vortex finder of a cyclone with corona wires, thereby decreasing submicron-sized PM.

Taking into account studies conducted to date to enhance the performance of cyclones in lowering emissions and particles, such as the addition of activated carbon to the cyclone inlet. Therefore, the purpose of this research is to change the cyclone separation device in order to lower the CO_2 content as well as the fly ash particles that were disseminated in the boiler exhaust flue gas. The vortex finder was modified by installing adsorbents at the gas output, which are anticipated to be able to collect CO_2 and PM. So that the amount of fly ash and carbon dioxide in the boiler's exhaust gas can be decreased. This study was conducted utilizing the Computational Fluid Dynamics (CFD) method and the ANSYS R1 2021 software. The adsorbent utilized as bottom ash [25, 26] is derived from shell and fiber combustion waste in the boiler. This study focuses on the effects of different inlet gas velocity and bed height on the vortex finding of a cyclone. This research seeks to investigate critically the consequences of a cyclone's ability to reduce emissions when equipped with bottom ash. In this instance, the particle collection efficiency, CO_2 and PM removal efficiency, pressure drop, and adsorption capacity were investigated. Several phases of this station's treatment are depicted schematically in Figure 1.

2. METHOD

This study was conducted in a simulation using Autodesk Fusion 360 for the design phase of the cyclone separator equipment and Workbench R1 ANSYS 2021, a simulation application with sophisticated turbulent flow. Computational Fluid Dynamics is a technique used to examine cyclone separator equipment by simulating fluid flow using computational simulations. This pertains to mathematical modeling, which is quite pertinent. Ansys R1 2021 is software that can accurately evaluate dynamic fluid flow in a complicated manner. In addition to more complicated mathematical equation models and boundary conditions, the ANSYS R1 2021 program offers precise meshing levels.

2.1 Model simulation

In this simulation, the RNG k- ε model is used. Model RNG k- ε is nearly identical to the regular k-. However, the Model RNG k- model is loaded with features that make it more accurate and dependable for a broad range of flow models than conventional k- ε. Model RNG k-ε is generated from RANS (Reynolds Averaged Navier Stokes) Eqns. (1-5) [27] based on the RNG turbulence model. The described cyclone separator in Fusion 360 is subsequently simulated using the boundary conditions shown in Table 1.

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{1}$$

$$\rho\frac{\partial u_i}{\partial t} + \rho u_j\frac{\partial u_i}{\partial x_j} = -\frac{\partial P}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\left[2\mu S_{ij} - \rho\overline{u_i^{'}u_j^{'}}\right] \tag{2}$$

$$S_{ij} = \frac{1}{2}\left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right] \tag{3}$$

where, u_i=the mean velocity, x_i=the coordinat system, P=mean pressure, ρ=density of gas, μ=dynamic viscocity of continuous phase, the Reynold stress strenght $\tau_{ij} = -\rho\overline{u_i^{'}u_j^{'}}$.

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left(a_k\mu_{eff}\frac{\partial_k}{\partial x_j}\right) + G_k + G_b - \rho\varepsilon - Y_M + S_k \tag{4}$$

$$\frac{\partial}{\partial t}(\rho\varepsilon) + \frac{\partial}{\partial x_i}(\rho\varepsilon u_i) = \frac{\partial}{\partial x_j}\left(a_\varepsilon u_{eff}\frac{\partial_\varepsilon}{\partial x_j}\right) + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon \tag{5}$$

G_k represent the generation turbulence kinetic, G_b is the generation of turbulence kinetic energy due to buoyancy, Y_M represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate, α_k and α_ε are the inverse effective Prandtl numbers for k and ε. S_k and S_ε are user-defined source terms. The constans in Eq. (5); $C_{1\varepsilon}$=1.42, $C_{2\varepsilon}$=1.68.

For the calculation of collection efficiency and CO_2 removal efficiency shown in the Eqns. (6) and (7).

$$Particle\ Collection\ Efficiency = \frac{particles\ trapped}{total\ tracked\ particles} \tag{6}$$

$$CO_2\ Removal Efficiency = \frac{C_{CO_2\,in} - C_{CO_2\,out}}{C_{CO_2\,in}} \tag{7}$$

2.2 Geometry model

The dimensions of the cyclone described are based on the proportion of one of the palm oil mills in Aceh, PT. Syaukat Sejahtera. The geometry of the 2D and 3D sketches of the simulated cyclone separator is shown in Figure 2 (a), 2(b) and Table 1. Drawing geometry is done with Fusion. After the drawing, the grid is divided into 52397 nodes and 113337, which is shown in Figure 2 (d). This study varied the inlet velocity, namely 10, 15, 20, 25, and 30 m/s, and also the height of the adsorbent bed was 0, 0.155 m, 0.310 m, and 0.465 m on the vortex finder cyclone as shown in Figure 2(c).

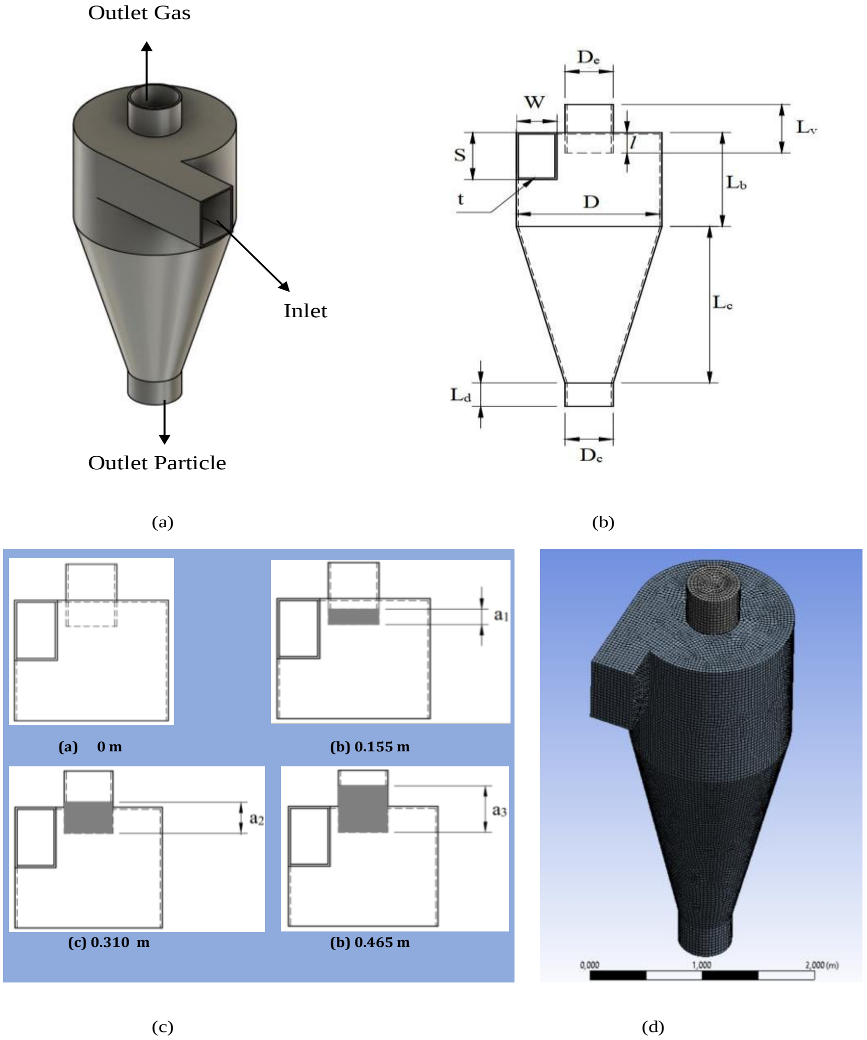

Figure 2. (a) The geometry of the 3D sketches and boundary condition; (b) The geometry of the 2D sketches; (c) Adsorbent bed height 2D sketch; (d) Computational grid

In this study, the cyclone was equipped with an adsorbent made from bottom ash and placed in a cyclone vortex finder to reduce CO_2 emissions from the cyclone exhaust gas. Bottom ash is derived from the byproducts of shell and fiber combustion in the boiler unit of the palm oil mill. In the boiler unit of the palm oil mill, shells and fiber are burned to produce bottom ash. Table 2 [26] lists the parameters of the bottom ash adsorbent. The integrated CFD model is used to simulate the dynamic behavior of the fixed bed adsorption column. In this investigation, the CO_2/N_2 ratio at the inlet was fixed to (95/5) percent.

The following assumptions are made in order to formulate the gas adsorption mechanism in this system: (1). The adsorption that occurs between CO_2 and N_2 is assumed to be competitive, (2). Heat transfer in the bed can be neglected, (3) Mass transfer is represented by a linear driving force (LDF) model, (4) The porosity of the adsorbent is assumed to be uniform throughout the bed, (5). The Navier-Stokes equation model is used to describe flow dynamics [27].

Discrete Phase Model-based simulation of particle transport (DPM). Escape, trap, and reflect are solid inert particle boundary conditions. For a solid inert particle, escape and trap are identical, hence the particle's route comes to an end when it contacts the wall. Reflect indicates that the wall is reflecting the particle's path. All numerical calculations employed the higher upwind interpolation method and the pressure-velocity coupling algorithm COUPLED. The Boundary condition were set:

•Inlet: velocity inlet
•outlet: pressure outlet
•wall: standard wall function

Complete boundary conditions are shown in Table 3.

Table 1. Section size 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

Table 2. Parameter adsorbent

Parameter	Value
Porosity	0.881
Bulk Density	108.9 kg/m^3
Adsorbent Particle Diameter (d_p)	46,51 µm
Adsorbent Type	Bottom ash from POM
Bed Height	0; 0.155 m; 0.310 m; 0.465 m

Table 3. Boundary condition

Parameter	Value
Velocity Inlet	10; 15; 20; 25; 30 m/s
Temperature Operational	573 K
Mass loading particle	0.1 kg/s
Pressure	1 atm
Fluid	CO_2 and N_2 ideal gas
Diameter particle	0.5-2.5 µm

3. RESULTS AND DISCUSSION

Simulation of cyclone fitted with bottom ash adsorbent to the process of CO_2 gas emissions adsorption using CFD by altering bed height and inlet velocity. The simulation experiment yielded data regarding the performance of a cyclone outfitted with an adsorbent, including pressure drop, particle collecting efficiency, CO_2 removal, and isotherm adsorption.

3.1 Effect of inlet velocity and bed height on particle collection efficiency and pressure drop

The height of the bed is one of the parameters influencing the efficiency of particle collection. Figure 3 demonstrates that the higher the bed, the greater the efficiency of particle collection as a result of the action of the adsorbent that will block the particles from exiting through the vortex finder cyclone. Particulates absorbed by the adsorbent will descend, and the flow will be directed to the dust collector. Additionally, particle velocity influences the collection efficiency, 81.36% is the lowest particle collection efficiency value for a bed height of 0 m (no bed height) at a velocity of 10 m/s. At a bed height of 0.465 m and an inlet velocity of 30 m/s, particle collection efficiency reaches a maximum of 92.68 percent [17]. Furthermore, inlet velocity and bed height, cyclone geometry also affects cyclone performance, as demonstrated by this study's use of high-performance cyclone geometry [28, 29].

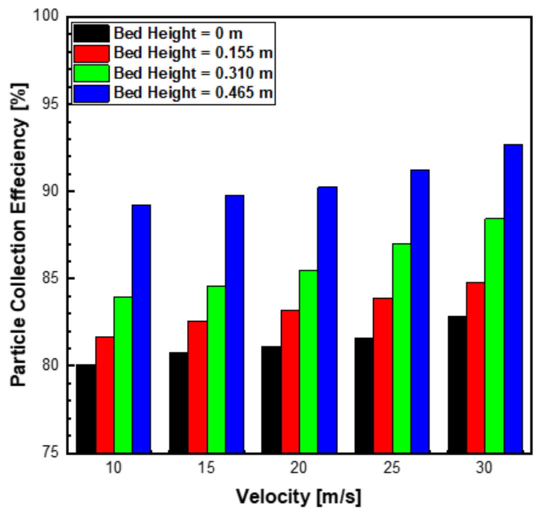

Figure 3. Effect of bed height and inlet velocity on collection efficiency

The lowest pressure drop at bed height 0 mm (without bed height) is 141 Pascal at a velocity inlet of 10 m/s, while the largest pressure drop occurs at bed height 0.465 m, which is 6500 Pascal at an inlet velocity of 30 m/s (Figure 4). The lowest pressure drop happens in the cyclone's center. After experiencing centrifugal force, particles will descend according to the flow pattern in the cyclone's core. According to Demir (2014), the pressure drop in the cyclone separator may be calculated from the gas and particle entrance area and the gas and particle output area [30]. This can be determined by observing the effect of particles' inlet velocity on the cyclone. The higher the inlet particle velocity, the greater the pressure decrease. The effect of the height of the vortex finder also performs a very important role, in this case the height of the bed at the vortex finder affects the pressure drop [29].

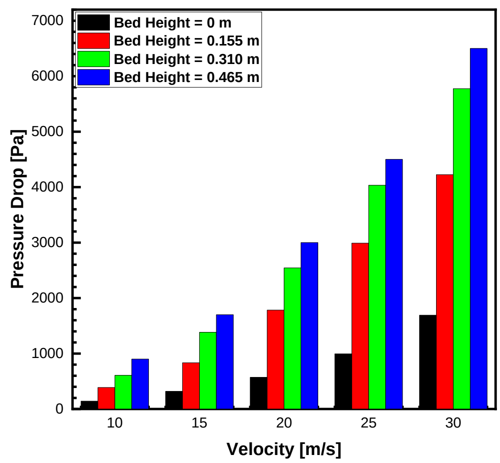

Figure 4. Effect of bed height and inlet velocity on pressure drop

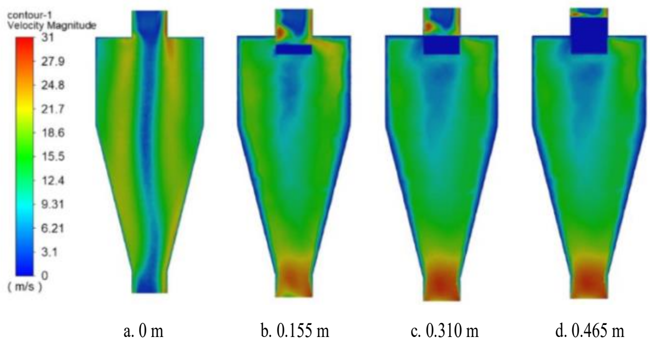

Figure 5. Effect of bed height in contour velocity magnitude

The velocity contour is shown in Figure 5. The figure shows that the higher of bed height, the smaller the velocity of the particles in the vortex finder so that the particles do not escape into the air. The magnitude of the velocity and the changes that occur in the 0.310 m bed height do not cause a significant change in the distribution of particles, so that there are still fine particles that escape at the outlet. while a bed height of 0.465 m can increase particle collection by up to 15% over a bed height of 0.310 m.

3.2 Effect of bed height and velocity inlet on CO_2 adsorption efficiency

Figure 6 depicts the influence of incoming gas inlet velocity on the adsorption percentage; the higher the incoming gas inlet velocity, the greater the CO_2 gas adsorption percentage. At 0 m bed height, there is no CO_2 removal efficiency because the cyclone separator in the vortex finder is not changed with adsorbent. With a value of 76.30% with an inlet velocity of 30 m/s, the 0.155 m bed height has the lowest CO_2 removal percentage. At an inlet velocity of 10 m/s, 99.61% of CO_2 is absorbed at a bed height of 0.465 m.

The higher the bed height, the greater the CO_2 removal effectiveness, but only at the lowest incoming velocity. Bottom ash from palm oil mills is used for this investigation. Characteristic tests and CO_2 adsorption processes have been conducted [26, 31, 32], and bottom ash is acceptable for the CO_2 adsorption method [33].

This is due to the lowest inlet velocity, the longer the contact time between the adsorbent and CO_2. The contour in Figure 7 also shows the dispersed CO_2 fraction.

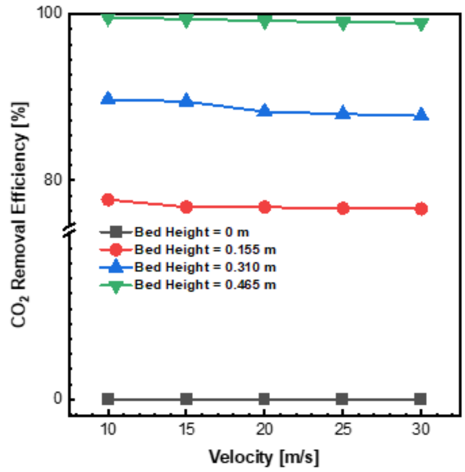

Figure 6. Effect of bed height and inlet velocity on CO_2 Removal efficiency

Figure 7 shows the flow of CO_2 which is dispersed. The CO_2 gas fraction that is injected into the cyclone separator without a bed does not have a separation process (without the addition of an adsorbent) so a lot of the injected CO_2 gas is out through the vortex finder [24, 29].

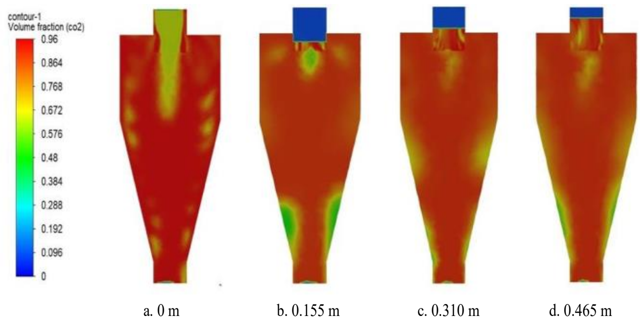

Figure 7. Volume fraction CO_2

The centrifugal force that happens in the cyclone separator flow also influences the carbon dioxide that generates an irregular flow pattern in the cyclone separator body. When particles and air enter and strike the wall of the cyclone separator, centrifugal force causes a separation process in which particles with a high density fall into the dust collector and CO_2 gas follows the properties of the real gas and is easily released into the air. With the inclusion of the adsorbent, the CO_2 must pass through the adsorbent introduced to the vortex finder before being released. This causes the adsorption process depicted in Figure 7 The CO_2 fraction that escapes through the bottom ash adsorbent is decreased in (a), (b), (c), and (d). Where the blue contour represents the lowest $_2$fraction discharged into the atmosphere and the red color represents the highest CO_2 fraction in the cyclone separator.

3.3 Effect of bed height and velocity inlet on adsorption capacity

Figure 8 demonstrates that the maximum CO_2 absorption capability occurs at a bed height of 0.465 meters with an inlet velocity of 10 meters per second, while the minimum absorption capability occurs at a bed height of 0.155 meters with a velocity of 30 meters per second. Based on observed effects, the proportion of CO_2 absorbed is inversely related to absorption capacity. Where CO_2 absorption capacity diminishes as inlet velocity increases. And the potential for CO_2 absorption increases with the quality of the adsorption bed. The intake velocity influences the contact time for CO_2 absorption in the adsorbent. The influence of the inlet velocity and the contact time are simultaneously proportional, so that if the inlet velocity is high, the contact time that happens during this absorption method may be shorter. Conversely, if the inflow velocity is low, the absorption system's contact duration could be prolonged.

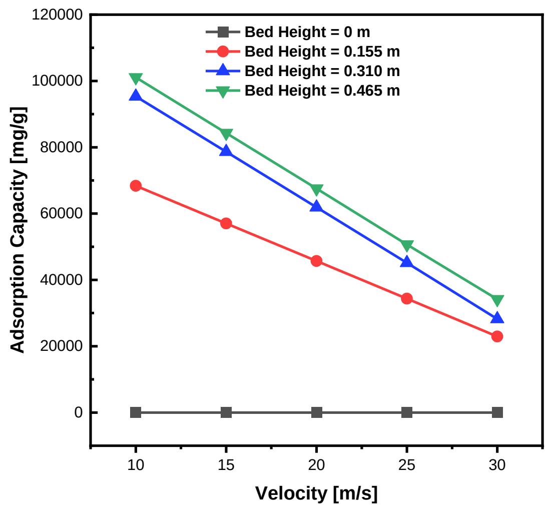

Figure 8. Effect of bed height and inlet velocity on adsorption capacity of CO_2.

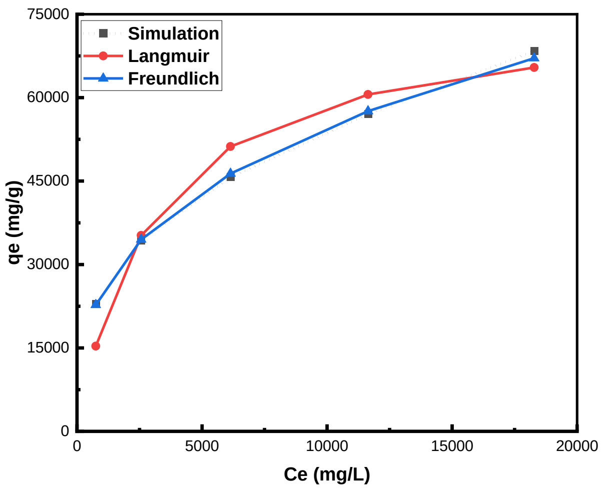

Figure 9. Isothermal adsorption

3.4 Isotherm adsorption

In this investigation, absorption was performed using an adsorption method, which is essential for understanding the adsorption process and determining the number of adsorbate molecules that can be absorbed by porous materials. The Langmuir and Freundlich model were utilized to represent the equilibrium adsorption data. To interpret the adsorption process on a heterogeneous or heterogeneous surface, the Freundlich model was applied. The Langmuir model implies that the adsorbent surface is homogeneous and that the adsorption energy is constant over the whole adsorbent surface [32, 34]. This model also assumes that adsorption is confined and that each location can accommodate only one molecule or atom. The Freundlich and Langmuir isotherms for CO_2 adsorption are depicted in Table 4 and Figure 9. To improve the design of the sorption system for CO_2 uptake in bottom ash, an appropriate isotherm model must be constructed for the curve.

Table 4. Isothermal adsorption

Type	Parameter	Unit	Equation non-linear
Langmuir			
q_m	76071.6595	mg/g	$q=\frac{q_m . k_L . C_e}{1+k_L .}$
k_L	0.000335	-	
R^2	0.97	-	
Freundlich			
k_F	2409,8499	-	$q=k_F . C_e^{1/n}$
n	2.95	-	
R^2	0.99	-	

Notes: q is the amount of adsorbed CO_2 per unit weight of bottom ash at equilibrium, and C_e is the unadsorbed CO_2 concentration in effluent at equilibrium (mg/L). k_L is the Langmuir equilibrium constant, q_m is the amount of CO_2 adsorbed with monolayer coverage, k_F is the Freundlich constant, and n is the Freundlich exponent.

4. CONCLUSIONS

The cyclone fitted with an adsorbent at 0.465 m bed height and 30 m/s inlet velocity has a particle collection efficiency of 92.61%. The lowest particle collection efficiency is 81.65% in a cyclone with an adsorbent in a 0.155 mm bed moving at 30 m/s. At a bed height of 0.4658 meters and inlet velocity of 10 meters per second, 99.618% of CO_2 was adsorbed using bottom ash. At a bed height of 0.155 m and a velocity of 30 m/s, 76.30 percent of CO_2 was adsorbed by bottom ash.

The higher the inlet velocity and bed height, the greater the particle collection efficiency will be. However, this is not the case for adsorption capacity, which shows that the higher the bed and the lower the inlet velocity, the higher the adsorption capacity.

The maximum pressure drop value in a cyclone separator with a bed height of 0.465 m and an inlet velocity of 30 m/s is 6500 Pascal, while the lowest pressure drop value is 141 Pascal in a cyclone separator with no adsorbent and an inlet velocity of 10 m/s. Based on the derived graph and linearity, the adsorption process is linear. The CO_2 process follows the Freundlich isotherm.

Suggestions for future research are that the research is also done experimentally and is more focused on adsorption isotherm studies.

ACKNOWLEDGMENT

The authors are grateful to LPPM of Malikussaleh University for financial support through the research project PNBP, No. 344/UN45/KPT/2022.

REFERENCES

[1] Aprina, H. (2014). The impact of crude palm oil price on rupiah's rate. Bulletin of Monetary Economics and Banking, 16(4): 295-314. https://doi.org/10.21098/bemp.v16i4.448

[2] Rifin, A., Feryanto, Herawati, Harianto. (2020). Assessing the impact of limiting Indonesian palm oil exports to the European Union. Journal of Economic Structures, 9(1): 1-13. https://doi.org/10.1186/s40008-020-00202-8
[3] Kun, Y.C., Abdullah, A.M.H. (2013). Simulation of total dust emission from palm oil mills in Malaysia using biomass fuel composition and dust collector efficiency models. International Journal of Energy and Environmental Engineering, 4: 1-13. https://doi.org/10.1186/2251-6832-4-19
[4] Matseh, I. (2018). Processing of palm oil mill wastes based on zero waste technology. IOP Conference Series: Materials Science and Engineering, 309: 012136.
[5] Rashid, M., Syahirah, M.M., NorRuwaida, J., Huda, N. (2014). Characteristics of particulate emission from a biomass fired boiler. Agriculture and Agricultural Science Procedia, 2: 265-271. https://doi.org/10.1016/j.aaspro.2014.11.038
[6] Chong, W.C., Rashid, M., Ramli, M., Ruwaida, J., Noor, Z.Z. (2014). Effect of flue gas recirculation on multi-cyclones performance in reducing particulate emission from palm oil mill boiler. Particulate Science and Technology, 32(3): 291-297. https://doi.org/10.1080/02726351.2013.856360
[7] Shukri, N.S., Kuntom, A., Jamaluddin, M.F., Mohamed, M.N., Menon, N.R. (2020). Code of good milling practice in enhancing sustainable palm oil production. Journal of Oil Palm Research, 32(4): 688-695. https://doi.org/10.21894/jopr.2020.0055
[8] Syahirah, M. M., Rashid, M., Nor Ruwaida, J. (2016). Total particulate matter, PM10, PM2.5 emissions from palm oil mill boiler. Jurnal Teknologi, 78(6-11). http://dx.doi.org/10.11113/jt.v78.9184
[9] Abdullah, I., Napitupulu, F.H., Tulus, Yudanto, B.G. (2013). Improvement of combustion process of oil palm fruit fiber (mesocarp) by adjusting of combustion air ratio between primary and secondary air. Journal of Engineering Research and Education, 7: 45-57.
[10] Moreno, J.E., Martinez Vallejo, L.A., Belalcazar Ceron, L.C., Rojas, N.Y. (2018). Corporate carbon footprint of a palm oil mill, a case study in Colombia. TECCIENCIA, 13(24): 1-10. https://doi.org/10.18180/tecciencia.2018.24.2
[11] Ayo, S., Reza, M. (2019). Prediction of carbondioxide emissions from crude palm oil industry case study: Palm oil mill X in Kampar regency of Riau province. IOP Conference Series: Materials Science and Engineering, 620: 012033. http://dx.doi.org/10.1088/1757-899X/620/1/012033
[12] Dashti, A.F., Fatehah, M.O., Zahed, M.A. (2022). Waste management of the palm oil industry: Present status and future perspective. Journal of Environmental Engineering and Science, 17(2): 75-88. https://doi.org/10.1680/jenes.20.00059
[13] Pratiwi, I.A., Ardiansyah, H.D. (2019). Pressure drop investigation of industrial scale cyclone for palm oil fiber boiler. IOP Conference Series: Earth and Environmental Science, 259: 012018. http://dx.doi.org/10.1088/1755-1315/259/1/012018
[14] Oh, J., Choi, S., Kim, J. (2015). Numerical simulation of an internal flow field in a uniflow cyclone separator. Powder Technology, 274: 135-145. https://doi.org/10.1016/j.powtec.2015.01.015
[15] Bhasker, C. (2010). Flow simulation in industrial cyclone separator. Advances in Engineering Software, 41(2): 220-228. https://doi.org/10.1016/j.advengsoft.2009.08.004
[16] Elsayed, K., Lacor, C. (2011). Numerical modeling of the flow field and performance in cyclones of different cone-tip diameters. Computers & Fluids, 51(1): 48-59. http://dx.doi.org/10.1016/j.compfluid.2011.07.010
[17] Yang, J., Sun, G., Zhan, M. (2015). Prediction of the maximum-efficiency inlet velocity in cyclones. Powder Technology, 286: 124-131. https://doi.org/10.1016/j.powtec.2015.07.024
[18] Li, H.X., Gao, B.G., Li, B. (2015). Numerical analysis of flow dynamics of cyclone separator used for circulating fluidized bed boiler. Chemical Engineering Transactions, 46: 991-996. https://doi.org/10.3303/CET1546166
[19] Ibhadode, O.O., Ogedengbe, E.O.B., Rosen, M.A. (2017). Performance characterization of gas-solid cyclone for separation of particle from syngas produced from food waste gasifier plant. European Journal of Sustainable Development Research, 1(2): 1-14. https://doi.org/10.20897/ejosdr.201713
[20] Duran, J.Z., Caldona, E.B. (2020). Design of an activated carbon equipped-cyclone separator and its performance on particulate matter removal. Particulate Science and Technology, 38(6): 694-702. https://doi.org/10.1080/02726351.2019.1607637
[21] Ma, L., He, M., Fu, P., Jiang, X., Lv, W., Huang, Y., Liu, Y., Wang, H.L. (2020). Adsorption of volatile organic compounds on modified spherical activated carbon in a new cyclonic fluidized bed. Separation and Purification Technology, 235: 116146. https://doi.org/10.1016/j.seppur.2019.116146
[22] Norelyza, H., Rashid, M., Hajar, S., Nurnadia, A. (2014). MR-deDuster: A dust emission separator in air pollution control. Jurnal Teknologi, 68(5): 21-24. https://doi.org/10.11113/jt.v68.3025
[23] Jeon, H., Park, S. (2019). Separation of fine particles with electrostatically enhanced cyclone. Separation Science and Technology, 55(3): 575-582. https://doi.org/10.1080/01496395.2019.1567553
[24] Zhang, J., Zha, Z., Che, P., Ding, H., Pan, W. (2019). Charging effect on separation performance of outer vortex type cyclone for submicron particles at different operating parameters. Particulate Science and Technology, 38(5): 596-604. https://doi.org/10.1080/02726351.2019.1571542
[25] Hamzah, M.H., Ahmad Asri, M.F., Che Man, H., Mohammed, A. (2019). Prospective application of palm oil mill boiler ash as a biosorbent: Effect of microwave irradiation and palm oil mill effluent decolorization by adsorption. International Journal of Environmental Research and Public Health, 16(18): 3453. http://dx.doi.org/10.3390/ijerph16183453
[26] Sylvia, N., Fitriani, F., Dewi, R., Mulyawan, R., Muslim, A., Husin, H., Yunardi, Y., Mutia, R. (2021). Characterization of bottom ash waste adsorbent from palm oil plant boiler burning process to adsorb carbon dioxide in a fixed bed column. Indonesian Journal of Chemistry, 21(6): 1454-1462. https://doi.org/10.22146/ijc.66509
[27] Fluent Theory Guide. (2016). Fluent Inc.: Canonsburg, PA, USA.
[28] Brar, L.S., Sharma, R.P., Elsayed, K. (2015). The effect

of the cyclone length on the performance of Stairmand high-efficiency cyclone. Powder Technology, 286: 668-677. https://doi.org/10.1016/j.powtec.2015.09.003
[29] Kumar, V., Jha, K. (2019). Multi-objective shape optimization of vortex finders in cyclone separators using response surface methodology and genetic algorithms. Separation and Purification Technology, 215: 25-31. https://doi.org/10.1016/j.seppur.2018.12.083
[30] Demir, S. (2014). A practical model for estimating pressure drop in cyclone separators: an experimental study. Powder Technology, 268: 329-338. https://doi.org/10.1016/j.powtec.2014.08.024
[31] Trinh, T.T., Tran, K.Q., Bach, Q.V., Trinh, D.Q.A. (2016). A Molecular dynamics simulation study on separation selectivity of CO_2/CH_4 mixture in mesoporous carbons. Energy Procedia, 86: 144-149. https://doi.org/10.1016/j.egypro.2016.01.015
[32] Zhang, X.Q., Li, W.C., Lu, A.H. (2015). Designed porous carbon materials for efficient CO_2 adsorption and separation. New Carbon Material, 30(6): 481-501. https://doi.org/10.1016/S1872-5805(15)60203-7
[33] Singh, G., Lakhi, K.S., Sil, S., Bhosale, S.V., Kim, I., Albahily, K., Vinu., A. (2019). Biomass derived porous carbon for CO_2 capture. Carbon, 148: 164-186. https://doi.org/10.1016/j.carbon.2019.03.050
[34] Al Mesfer, M.K., Amari, A., Danish, M., Al Alwan, B.A., Shah, M. (2020). Simulation study of fixed-bed CO_2 adsorption from CO_2/N_2 mixture using activated carbon. Chemical Engineering Communications, 208(9): 1358-1367. https://doi.org/10.1080/00986445.2020.1777111