Development of an Axial Cyclone for High-performance: Application of Cycloid Curve and Multi Objective Optimization

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ABSTRACT

Reducing particulate emission is a key factor in improving the air quality as particulate matter cause respiratory diseases. In this study, an axial cyclone was selected from several existing technologies to reduce particulate emissions owing to its outstanding separation performance and low-pressure drop. To enhance the axial cyclone, the fastest descending curve among the lines that pass through two points was selected; it induces faster momentum changes from the axial to the tangential direction. Therefore, the selected cycloid curve was applied to the vanes and body of the axial cyclone. The particle trajectory was simulated using a discrete phase model (DPM) in ANSYS Fluent ver. 2020 R2. Furthermore, the external structure of the axial cyclone was optimized via multi-objective optimization based on response surface methodology. Additionally, experiments were conducted to evaluate the proposed cyclone performance. Without applying the cycloid curve, the separation efficiency and the pressure drop were 73.6% and 1013.3 Pa, respectively. In the case of the cycloid-applied axial cyclone, however, the separation efficiency and pressure drop were 91.6% and 1109.6 Pa, respectively. Thus, the application of the cycloid curve improved the cyclone performance by approximately 24.5%.

Keywords: Axial cyclone, Response surface optimization, Cycloid curve, Swirl number, Pressure drops

1 INTRODUCTION

Atmospheric pollution has become an important issue that needs an urgent resolution on a global scale. Airborne micro-scale particles (PM₁₀) are considered a primary example; they are emitted along with exhaust gases from automobiles or industrial factories and have been reported to trigger respiratory and cardiovascular problems in humans (Choi et al., 2020). In response, the separation technology to remove PM₁₀ from the surrounding air has been developed, which is required to prevent diseases resulting from inhalation of fine dust. There are numerous advanced methods to remove particulate matter from the air, including HEPA filters, electrostatic precipitators, and wet separators (Ali et al., 2018; Lanzerstorfer and Steiner, 2016; Qian et al., 2010).

However, a cyclone is considered superior to the above-mentioned methods. It is an effective separator device that can easily collect micro-scale particles by producing a strong swirling flow in its inner chamber without any external force. Particles entering the interior lose their kinetic momentum and finally settle down due to gravity. Cyclones can be classified into two widely applicable types depending on the flow direction at their outlet compared to that at their inlet: tangential and axial cyclones. The tangential cyclone separator exhibits a clear distinction in performance from the axial and its sudden change in the mainstream direction results in an excellent separation. The strongly induced inertia of fine dust leads to a rapid momentum loss
after friction with the wall or collision between particles. However, this high removal efficiency requires more operational energy owing to a high pressure drop. In contrast, the axial cyclone maintains the flow direction and exhibits a low pressure drop. However, its separator efficiency is low. Nevertheless, the axial cyclone has significant potential for development, whereby its driving merits and, simultaneously, its performance can be improved.

The axial cyclone typically needs a swirl generator installed in the duct to increase the strong interior vortex flow. Several studies have been conducted because the vortex flow can be easily modified depending on the fan or vane shape. For example, Mao et al. (2019) studied the influence of the vane structure in an orthogonal experimental design to determine its separating properties. Gopalakrishnan and Arul Prakash (2019) investigated the parameters of a swirl generator by modifying the number and angle of vanes and the distance between the swirl generator and vortex finer to analyze the pressure drop and separator performance using numerical simulation. Pillei et al. (2019) focused on the angles of the swirl vane and core size ratios to increase the swirl number, which is an important indicator because it directly affects the separation performance. Modifying the swirl vane inlet is sufficient to change the flow pattern of a swirl, indicating that swirl numbers are susceptible to such modifications. In addition, Guangcai et al. (2012) demonstrated the gaseous flow behavior and trajectory of particles in a typical axial cyclone with a guide vane to analyze the effects of the helix angle and leaf margin. The increase in the helix angle improved the separation efficiency owing to the reduced tangential velocity. Gong et al. (2012) focused on optimizing the swirl generator design considering that vane parameters directly affect the efficiency and pressure drop.

Besides, with an emphasis on the importance of the exterior structure, several studies have been also conducted to investigate the configuration of cyclones. Lim et al. (2004) examined the effect of different vortex finders on the particle collection efficiency, demonstrating that the cone-shaped design affected the collection efficiency rather than the cone length did. In addition, the effect of the vortex finder outlet with a cylindrical body on the flow pattern and collection performance was studied by Balestrin et al. (2017). From this modification, the changed downstream flow made a second chance to separate the particles, improving the performance. The dependence of the pressure drop and cut-off diameter on the vortex finder diameter and length were computationally investigated using a large eddy simulation (Elsayed and Lacor, 2013). Reducing the vortex finder diameter led to the increased pressure drop and removal efficiency. With the importance of structural design factors, recent works have focused on finding the optimized model and investigating the relationship between the pressure drop and collection efficiency in terms of geometrical parameters using mathematical analysis. Response surface methodology (RSM), an evolutionary optimization technique, was employed to enhance the tangential cyclone performance and to determine the optimal vortex finder (Kumar and Jha, 2019). Through RSM analysis, Wei et al. (2020) found out the influence of the inlet dimension and vortex finder diameter on the stagnation of axial velocity, resulting that the inlet dimension is more crucial factor on the stagnation than another. In addition, Qiang et al. (2020) optimized the structure of a two-stage series cyclone using the computational particle fluid dynamics and RSM. However, research related to the structural properties of an axial cyclone are scarce owing to its limited generality in comparison to the tangential cyclone. Therefore, appropriate geometric parameters for the outer configuration of the axial cyclone are required to maximize the separation ability and minimize the pressure drop.

In this study, we present an advanced axial cyclone to achieve a high separation efficiency by applying a cycloid curve and exterior structure optimization. We previously introduced a customized-axial flow cyclone for the air handling of subway stations (Kim et al., 2011). Through experimental and numerical analysis, this cyclone was evaluated as a suitable prefilter owing to its excellent removal efficiency (65.7%) and low pressure drop (20 mmH2O at 2.5 m s⁻¹). However, the removal performance can be further enhanced by re-engineering the swirl generator with the cycloid curve and optimizing the outer configuration. The cycloid curve, also called the brachistochrone curve, is the shortest time drop path passing through two points. It has been widely used to in accelerating and diffusing wind flow effectively owing to its advantageous characteristics (Fangwei et al., 2017; Hashem et al., 2020). This cycloid curve enables the rapid alteration of the direction and velocity of particles along the flow direction. In particular, micro-scale particles following the flow streamline are separated effectively, as the fast shift in flow direction generates an increased swirl number and tangential velocity directly. Four homemade case models (OO, CO, OC, and CC)
of the current study in which cycloid curves are applied to the vane or body were prepared to determine the inner flow depending on the applied cycloid curve. The OO model is identical to the model presented in our previous study. Therefore, the introduction of a cycloid curve on vanes considerably enhances the separation efficiency due to the increase in swirl numbers. Furthermore, the external structure of the axial cyclone was optimized using a multi-objective optimization process based on the RSM. The geometric factors that influence the pressure drop and separator efficiency were designated as input parameters: the length of the duct, length of the vortex finder, outlet diameter, and width of the dust collector. Finally, a mathematical method was applied to optimize the cycloid-applied axial cyclone for high performance.

**2 EXPERIMENTAL METHODS**

**2.1 Grid Independence Test**

The numerical methods are described in detail in the Supplementary Materials. To accurately describe the flow expression in the separator, a grid independence test was performed on the grid division of the physical model before proceeding to the computational fluid dynamics (CFD) simulation. The polyhedral mesh was constructed using Fluent meshing software, as shown in Fig. S1. The cyclone separator mesh regions were divided into vane areas to improve the grid quality. For the polyhedral grid, the grid calculation in a combined form from the tetrahedral grid is faster than that of a hexahedral grid. In addition, the accuracy was higher than that of the tetrahedral grid (Wang et al., 2021). The results of the grid independence test verified that the error rate from approximately 4,000,000 elements was smaller than 1%, as presented in Table S1. Therefore, a numerical analysis was performed on approximately 4,000,000 elements of all four models.

**2.2 Measurement System Description**

Figs. S2 and S3 show a schematic of the experimental setup. The detailed configuration of the separation system is presented in Table S2. A dust generator (Topas SAG 410, Dresden, Germany) was used to release a certain amount of dust using defined segments at the inlet. A mass flow controller was used to effectively reduce the concentration of fine dust in the atmosphere. In addition, the velocity magnitude at the inlet and outlet was measured using a hot-wire anemometer. With a honeycomb installed in the duct, the turbulent flow generated by the main blower was converted to laminar flow. A dust monitor (11-A, GRIMM, Germany) was employed to measure the number of fine dust particles in front of and behind the cyclone. As shown in Fig. 1, the four homemade models in this experiment were classified into original guide vane + original guiding cone (OO), cycloid guide vane + original guiding cone (CO), original guide vane + cycloid guiding cone (OC), and cycloid guide vane + cycloid guiding cone (CC). Both separation and pressure drop evaluations were conducted by controlling the velocity of several levels to range from 2 m s⁻¹ to 8 m s⁻¹ using a primary blower. The pressure drop between the front and rear of the cyclone was measured using a differential pressure gauge (Testo-400, Testo, Germany). Moreover, Arizona A4 coarse dust was used in the experiment. Fig. 2 illustrates the cumulative size rate of (black) Arizona dust for the experiment and (red) simulated dust for numerical analysis, showing that the mean particle diameter was 3 µm and the particles constituting the maximum fraction had a size of 4 µm. Thus, the simulated particle size distribution for CFD simulation was comparable to

![Fig. 1. Four types of swirl generators used in the experiment: (a) original guide vane + original guiding cone (OO), (b) cycloid guide vane + original guiding cone (CO), (c) cycloid guide vane + cycloid guiding cone (CC), and (d) original guide vane + cycloid guiding cone (OC).](figure)
Fig. 2. Cumulative particle distribution of (black) Arizona dust and (red) dust simulated using Rammler method.

that of Arizona A4 dust. The separation performance was estimated by calculating the number of injected dust particles and dust separated after passing through the cyclone.

2.3 Optimization Process

The entire optimization process is briefly presented in Fig. 3. RSM is an effective analytical tool for optimizing, improving, and developing processes in several different fields (Brar, 2018; Marichamy et al., 2020; Yıldız, 2020). In this study, the Kriging method was applied to construct an approximation function between the structural parameters and the performance of the axial cyclone. The Kriging model proceeds without adopting a mathematical model, making it accurate and flexible (Xiaobo, 2017). Moreover, using this model provides a more appropriate function than utilizing the second-order model, even in the case of high-order nonlinear forms. As the empirical RSM modeling is formed by fitting with the input parameter, the design of experiments has been established with four independent structural parameters using Latin hypercube sampling (LHS) based on central composite design (CCD). LHS is a statistical method with a high accuracy and reasonable space-filling property for response surfaces with a uniform and independent random sampling (Wang, 2003). Moreover, 24 sample design points, derived by filling the entire design surface without overlap, were extracted. The samples of the design points and corresponding calculated results are presented in Table S3. To optimize the design of a point, a multi-objective
genetic algorithm was employed considering its advantages such as rapid convergence and satisfactory search capability (Deng et al., 2020). The multi objective optimization was proceeded to minimize the pressure drop and maximize the separation efficiency based on the design of points and calculated results. However, it is impossible to find the design of a point that meets the constraints simultaneously. Since a better solution does not exist, the Pareto optimal solution is regarded as the best solution. A Pareto front presents a set of several feasible solutions satisfying the required conditions without conflicting multi objectives. Therefore, an approximately optimized point for geometric configuration can be obtained using the Pareto front (approximation).

3 RESULTS AND DISCUSSION

3.1 Numerical Analysis

The separation in the axial cyclone primarily proceeds due to the changing axial momentum of the particles with respect to their tangential momentum. Moreover, a sufficiently large tangential momentum is required to obtain a large centrifugal force for effective separation; a high swirl number leads to high separation efficiency. The mean axial and tangential velocity of all the models are illustrated in Fig. S4. The black and red colors indicate the average value of the axial and tangential velocity, respectively. While there was little difference in the mean axial velocity, the CO model exhibited the highest mean tangential velocity. The axial velocity contours of all models are presented in Fig. 4. This indicates that the dominant factor determining the swirl number is the tangential velocity across all models, whereas the axial velocity remains unchanged regardless of the shape of the vane or body. The tangential velocity contours of all cyclones at regular intervals in the axial direction are shown in Fig. 5. It was confirmed that the difference in the tangential velocity range for each model was greater than that of the axial velocity. The swirl number is calculated at the end of the cyclone vane, resulting in an increase in the swirl number to 1.21 and 2.02 when applying the cycloid curve to the vane in Figs. 5(b) and 5(c). In the cases where the cycloid curve was applied to the body, the swirl number was reduced, as shown in Figs. 5(c) and 5(d). It can be observed that the application of the cycloid curve to the vane affects the swirl number more strongly than the cone. Fig. 6 displays the contours of the pressure drops for all the models. Compared to the original curve in Figs. 6(a) and 6(d), the pressure drop increases when only the vane has a cycloid curve, as shown in Figs. 6(b) and 6(c). In contrast, for the axial cyclone, in which the cycloid curve is applied to the shape of the body, the pressure drop decreases.

The particle trajectory in the axial cyclone was visually confirmed using DPM in the numerical simulation. This analysis was conducted to determine the number of sub-10\(\mu\)m particles that were separated out and the relationship between the swirl number and separation efficiency. The swirl number was previously determined to be proportional to the separation performance (Liu et al., 2012), which was validated by this study. Fig. 7 illustrates the trajectory and separation efficiency of the 10 \(\mu\)m particles for all models, indicating the same trend as both the swirl number and pressure drop. Overall, the CO model with the largest swirl number exhibited excellent performance, in contrast to the OC model with the smallest swirl number, as shown in Figs. 7(b) and 7(d). The separation efficiency of the OO and OC models are 68.0% and 88.6%, respectively, as shown in Figs. 7(a) and 7(c). The cycloid curve applied to the vane enhanced the separation efficiency.
Fig. 5. Tangential velocity contours of cyclone cone by regular interval positions for the (a) OO model, (b) CO model, (c) CC model, and (d) OC model.

Fig. 6. Pressure drop contours of the separator system: (a) OO model, (b) CO model, (c) CC model, and (d) OC model.

Fig. 7. Separation efficiency of the models using DPM: (a) OO model, (b) CO model, (c) CC model, and (d) OC model.

efficiency of the axial cyclone by strengthening the tangential momentum. Fig. 8(a) shows the projections of the particle distributions onto the cross sections, which are located at the swirl generator, middle of the cyclone, dust collector, and outlet to present the particle trajectories depending on the particle size from 1 µm to 100 µm. As shown in Fig. 8(b), the particle concentration decreases gradually from Location 1 to Location 2 and Location 3 due to effective separation. However, at Location 1, the CO model, which had the largest swirl number, has the largest tangential velocity, resulting in particles gathered near the edge and wall. In contrast, in the case of the OC model, which had the lowest swirl number, the low tangential velocity produces an extremely
weak centrifugal force, resulting in broader particle distribution. The particle distribution at Location 3 indicates that only the CO model effectively separated the particle corresponding to the size of 1 µm, although the particles larger than 25 µm were completely captured in other models. At Location 4, models that exhibited better separation than the OO model were performed better than models with lower swirl number. Overall, in all models, separation was better when the particles were larger. However, small particles required stronger swirl flow.

3.2 Experimental Analysis

The four homemade models were evaluated experimentally to compare the separation performance and pressure drop at different inlet velocity. Fig. 9 presents the separation efficiencies with particle diameter depending on the inlet velocity (2.4 m s⁻¹, 4.8 m s⁻¹, and 7.7 m s⁻¹). The cutoff size was defined as the particle size at which the separation efficiency was 50%. To be precise, a lower cutoff size represents a better separation performance. Figs. 9 and 10 show that increasing velocity generally increases the separation performance and pressure drop owing to the formation of a strong swirl flow. It is noteworthy that despite nearly identical particle separation efficiencies of the OO and CO models at an inlet velocity of 2.4 m s⁻¹, the axial cyclones with cycloid-curve vanes exhibited better performances than the OO model, as shown in Figs. 9(a), 9(b), and 9(d). Fig. 9(c) shows the cutoff sizes of the OC model, which were determined to be 2.7 µm, 2.3 µm, and 2.0 µm by increasing flow velocity. Among all the models, the CO model exhibited the best filtration performance, resulting in cut-off sizes of 2.5 µm, 2.1 µm, and 0.87 µm. The separation efficiency and pressure drop for several inlet flow velocities are plotted in Fig. 10. Similarly, it was observed that the CO model performed better than the OO models, as shown in Figs. 10(a) and 10(b). Among the axial cyclones with a cycloid curve body, the OC model obtained the lowest efficiency and lowest pressure drop, as shown in Fig. 10(c). However, applying the cycloid curve to both the vane and body promoted the separation efficiency and pressure drop unlike OC model shown in Fig. 10(d). Through experimental and numerical analyses, it can be
Fig. 9. Separation efficiency with respect to the particle size for the (a) OO model (b) CO model, (c) CC model, and (d) OC model.

Fig. 10. (black) Separation efficiency and (red) pressure drop as a function of velocity for (a) OO model, (b) CO model, (c) OC model, and (d) CC model.
concluded that when a cycloid curve is applied only to the vane, the separation efficiency increases. This ability of the CO model to separate smaller particles can be attributed to the cycloid curve design, which induces airborne dust to increase the tangential momentum. Moreover, the original body shape is convex compared to the cycloid curve body, which is concave. Concavity results in a reduction in the differential pressure but does not significantly affect the swirl formation, which is the primary key to enhancing the separation performance. The rankings for all models are as follows. Separation efficiency: CO > CC > OO > OC, and pressure drop: CO > CC > OO > OC. The normalized values of the separation efficiency for differential pressure are as follows: CO (1.00) > CC (0.98) > OO (0.94) > OC (0.80). Eventually, although the pressure drop increased by 5%, the separation efficiency of the CO model was significantly improved by approximately 25% compared to the original model.

3.3 ANOVA Analysis

In this study, ANOVA analysis was conducted to evaluate the importance of the cycloid curve as a variable. To determine whether a factor is suitable as a variable, the influence can be identified after decomposing the sum of squares of the dispersion over the characteristics into the sum of squares of the factor (Kim, 2014). The experimental and numerical results are based on an empirical ANOVA analysis. Figs. 11(c) and 11(d) indicate that the trends of the numerical analysis and experimental results are similar. However, compared to other models, the numerical analysis and experimental exhibited disparity in the results of the separation efficiency of the OO model and the pressure drop of the OC model. Apart from these exceptions, the numerical analysis performed with DPM can be considered reliable because of the minimal error. In addition, the mean value of the pressure drop and efficiency were calculated to determine whether the shape

![Graphs showing separation efficiency and pressure drop for all models](https://example.com/fig11)

Fig. 11. (a) Separation efficiency and (b) pressure drop as a function of velocity for all models. (c) separation efficiency and (d) pressure drop results from the experimental and simulation analyses for all models.
Table 1. Mean values of the separation efficiency and pressure drop.

<table>
<thead>
<tr>
<th>Level</th>
<th>Separation efficiency</th>
<th>Pressure drop</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vane</td>
<td>Body</td>
</tr>
<tr>
<td>1</td>
<td>0.653</td>
<td>0.811</td>
</tr>
<tr>
<td>2</td>
<td>0.817</td>
<td>0.735</td>
</tr>
<tr>
<td>Delta</td>
<td>0.164</td>
<td>0.076</td>
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<tr>
<td>Rank</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 2. Variance analysis of the separation efficiency and pressure drop.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Ads SS</th>
<th>F</th>
<th>P</th>
<th>Seq SS</th>
<th>Adj SS</th>
<th>Ads SS</th>
<th>F</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vane</td>
<td>1</td>
<td>0.1147</td>
<td>0.1147</td>
<td>0.1147</td>
<td>125.58</td>
<td>0.000</td>
<td>66033</td>
<td>66033</td>
<td>66033</td>
<td>15.56</td>
<td>0.011*</td>
</tr>
<tr>
<td>Body</td>
<td>1</td>
<td>0.0116</td>
<td>0.0116</td>
<td>0.0116</td>
<td>12.65</td>
<td>0.016*</td>
<td>20542</td>
<td>20542</td>
<td>20542</td>
<td>4.84</td>
<td>0.079</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td>0.0046</td>
<td>0.0046</td>
<td>0.0010</td>
<td>12.65</td>
<td>0.016*</td>
<td>21223</td>
<td>21223</td>
<td>4245</td>
<td>107798</td>
<td></td>
</tr>
</tbody>
</table>

of the vane and cone are significant variables, as presented in Table 1. The variance analysis of the pressure drop and efficiency is presented in Table 2. Using the cycloid curve in the vane and the body was confirmed to induce a significant distinction in the pressure drop. In addition, there is a notable difference between the original models and those in which the cycloid curve is applied. The variance analysis confirmed that the p value in the vane was very low and is a meaningful variable. There is also a difference in the separation efficiency when the cycloid curve is used for the shape of the vane and body. Moreover, the use of the cycloid curve in the vane affects the separation efficiency more strongly than the pressure drop. In conclusion, the cycloid curve is a significant variable for both vane and cone in terms of separation efficiency. In contrast, the pressure drop varies significantly depending on whether the cycloid curve is applied.

The separation efficiency and pressure drop for all models are summarized in Fig. 12. A comparison of the black (CO) and red line (OO) in Fig. 11(a) shows that the separation efficiency is significantly increased by the cycloid-applied vane. The difference between the solid and dotted lines reveals that the separation efficiency decreases if the cycloid curve is applied to the body. The variation in the pressure drop also displays the same trend as that for the separation efficiency, as shown in Fig. 11(b). In Figs. 11(c) and 11(d), the error of the experimental and numerical results of the separation efficiency is lower than 1%, while the error of the pressure drop is approximately 7%. This error rate occurs due to the numerical instability, which increases the error by the high complexity of flow in high flow rate, and the experimental factors such as head loss (Raoufi et al., 2008). Fortunately, both the separation efficiency and pressure drop were similar in the simulation results.

3.4 Optimization Results

The CO model was selected as the best separator among the suggested axial cyclone models after evaluating the pressure drop and collection efficiency of all the models. However, to surpass the performance of the CO model, the optimized design point of the external structure was obtained using a multi-objective genetic algorithm based on the RSM. As presented in Table 3, the CO model can be optimized to a pressure drop of 1150 Pa and separation performance of 63.7% by injecting particles with a diameter of 0.87 µm corresponding to the cutoff size at the inlet velocity of 7.7 m s⁻¹. The RSM method generates one case of the design point that meets the two objective constraints, exhibiting a pressure drop of 1142 Pa and a separation efficiency of 64.1%. The predicted results from RSM have a low relative error compared to those calculated from CFD regarding the derived point because the designed response surfaces based on the Kriging model exhibit high accuracy and good predictability. Moreover, it exhibited improved performance compared to that of the original model. In addition, the optimized conditions shorten the length of the duct and vortex finder, narrow the width of the dust collector, and expand the diameter
Table 3. Comparison between the original and optimized CO models.

<table>
<thead>
<tr>
<th>Model</th>
<th>Input parameter (m)</th>
<th>Output parameter</th>
<th>η (%)</th>
<th>Δp (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original CO</td>
<td>0.13 0.04 0.024 0.018</td>
<td>CFD 56.2 1195.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimized CO</td>
<td>0.125 0.043 0.023 0.019</td>
<td>RSM 64.1 1142</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Rate of change
-3.8% +7.5% -4.2% +5.5%

Fig. 12. Contour images of the (a) pressure, (b) axial velocity, and (c) tangential velocity in the y-z plane for a velocity of 7.7 m s⁻¹.

of the outlet. The contour images in Fig. 12 were analyzed to determine the pressure and velocity distributions at the three-coordinate plane x = 0. Considering that the tangential velocity to be a critical factor for particle collection, the optimized model improved separation efficiency not by enhancing the swirl number, but by reducing the length of the duct and increasing the diameter of the outlet. Consequently, this modification of geometrical factors decreases the pressure drop by approximately 44.5 Pa compared to that of the original model, as shown in Fig. 12(a), probably because the optimized design enables the rapid escape of the inner flow to the outlet. Figs. 12(b) and 12(c) show that the axial and tangential velocity can be expected to remain unchanged when the same swirl generator is utilized in the two models. Among the structural factors, the parameters P1, the length of the duct, and P2 as the diameter of the outlet, are modified according to the calculated rate of change, which indicates the increase or decrease of each parameter. In addition, response surface diagrams were constructed, as shown in Fig. 13, to determine the sensitivity of the output parameters to the input variables. The performance effect of the four geometrical factors on the static pressure drop and separation is confirmed by Figs. 13(a–c) and Figs. 13(d–f), respectively. Based on the above results, it can be speculated that P1 and P2 parameters are significant factors for the variance of the output parameters owing to their high responsivity, as shown in Figs. 13(a) and 13(b). Specifically, the relationship between P1 and P2 indicates that the output results are more susceptible to the change in P2. This is illustrated by an abrupt decrease in the pressure drop and efficiency under constant P1. In comparison to other parameters in Figs. 13(b), 13(c), and 13(e), there are a few variations despite changing the length of the vortex finder and the width of the dust collector. However, as shown in Fig. 13(f), the response surface for the separation efficiency by P1 has an apex, which indicates that the maximum value is 15% higher than the minimum value. Hence, the input parameters P1 and P2 are considered crucial points for designing the optimized CO model.

4 CONCLUSIONS

The cycloid curve was applied to axial cyclones, and these were tested to evaluate the separation performance and pressure drop through numerical and experimental analyses. When the cycloid curve was applied to the vane, the separation efficiency and pressure drop increased. However, when it was applied to the body, both the separation efficiency and differential pressure decreased considerably. The application of the cycloid curve enabled a transition from axial to tangential momentum in the cyclones, thereby resulting in an increase in the swirl number. Consequently,
the CO model was found to be the most efficient at separation with an improvement of 24.5% in separation efficiency compared to that of the original model. Although there was no notable difference in the pressure drop between models, the separation efficiency showed significant variation. The ANOVA analysis confirmed that modifying the vane resulted in more significant improvement compared to modifying the body. Subsequently, the CO cyclone was optimized using the multi-objective optimization based on RSM. The optimized CO cyclone exhibited the greatest performance with a pressure drop of 1150 Pa and a separator efficiency of 64.1%. Finally, it can be concluded that the introduced cycloid curve and optimization method effectively improved the separation efficiency of the axial cyclone. Such a cycloid curve paves a new way for enhancing swirl number or easily modifying the momentum flow in various areas such as aerodynamics, fluid machine, and continuum mechanics.

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**SUPPLEMENTARY MATERIAL**

Supplementary material for this article can be found in the online version at https://doi.org/10.4209/aaqr.220041

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