

Design and Development of Domestic Cyclone Dust Collector System Using TRIZ And CCD Method

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ABSTRACT

In conventional vacuum cleaners, filter media or filter bags are used to physically separate dust and debris from flowing air streams. However, in such systems, the vacuum cleaner's efficiency diminishes over time as more debris is accumulated on the filter surface. In this study, a two-stage cyclone dust collector system was proposed, which can be attached to existing vacuum cleaners. The system was designed and developed using the integrated Theory of Inventive Problem Solving (TRIZ) and Classical Cyclone Design (CCD) method. The TRIZ method was implemented during the idea generation stage, where specific design solution strategies were reviewed. Theoretical analysis of the selected design was carried out using Classical Cyclone Design (CCD) method. Finally, a full-scale working prototype of the cyclone dust collector was fabricated for evaluation. Based on results, the cyclone dust collector system provides more than 99% fractional efficiency and 96% overall collection efficiency for particles with an average diameter of over 50 μm . The pressure drops and airflow inside the cyclone dust collector were also analysed. The results suggest that the proposed cyclone dust collector system would provide better filtration efficiency and less maintenance compared to the conventional system.

Keywords: Cyclone, collection efficiency, dust collector, Theory of Inventive Problem Solving, Classical Cyclone Design

1. INTRODUCTION

Vacuum cleaners are commonly used in houses and commercial buildings for routine surface cleaning [1]. Dust from floor surface is sucked through the suction nozzle and it is later filtered in the dust collection component inside the vacuum cleaner [2]. However, a common issue with a conventional vacuum cleaner is that it needs regular cleaning due to a clogged air filter or full vacuum bag. A poorly maintained vacuum cleaner would operate at a reduced airflow and thus losing its suction power. Highly efficient low-pressure drop filters using advanced materials have been proposed [3]; however, these filters are expensive and impractical to be used for domestic applications.

In this study, a cyclone dust collector system is proposed to improve the performance of a vacuum cleaner and reduce maintenance. The cyclone dust collector system is designed as an additional tool for a conventional vacuum cleaner that acts via vortex separation to remove dust and debris from flowing air streams. In the early 1950s, Shepherd & Lapple created the first cyclone design, known as the Classical Cyclone Design (CCD) [4]. The working principle of a

cyclone collector system relies on centrifugal forces for particle separation [5]. The airflow forms a centrifugal vortex as it enters a cone-like cyclone (Figure 1). As the vortex spins downward, the centrifugal forces drive large and heavy particles to the first collection outlet at the bottom whilst fine and light particles will be sucked upward into the second outlet [4,5].

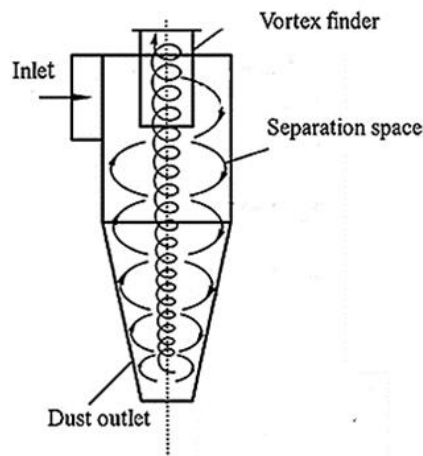


Figure 1. Schematic of airflow inside a typical cyclone dust collector system [6].

There are various cyclone separator models with different configurations and designs. The most commonly used cyclone separator model is called the reversed cyclone model. This model uses a cone-like chamber with a tangential inlet as shown in Figure 1 [7]. CCD is perceived as a standard method in developing cyclone designs [8]. In this study, the design of a new cyclone dust collector system will be developed based on the CCD method. In the CCD method, there are five essential parameters to be considered when developing a cyclone separator system, i.e., the number of effective turns (N_e), cut-point diameter (d_{pc}), fractional efficiency curve (FEC), overall efficiency (η_o), and pressure drop (Δp) [9].

Cyclone dust collectors are commonly used in industries due to their advantages such as simple structure, high efficiency, low operating cost, and low maintenance cost. The most efficient cyclone dust collectors are known as the Model 1D3D and Model 2D2D [10]. The first 'D' refers to the cyclone's barrel diameter, and the second 'D' corresponds to the length of the barrel and cone sections, respectively. The 1D2D cyclone and 1D3D are often regarded as better designs than the 2D2D cyclones for flows with high-lint content [11]. Thus, Model 1D2D and Model 1D3D were chosen as the fundamental designs in this study (Figure 2).

In developing a new cyclone dust collector, the use of the CCD method alone is inadequate because the method only describes the parameters and theoretical analysis. Thus, the Theory of Inventive Problem Solving (TRIZ) is adapted in this study to generate ideas and solutions. In 1946, a Russian inventor developed the TRIZ method, which was later summarized to suit all common engineering features and inventive principles [12]. TRIZ can be defined as technical problem-solving, analysis, and tools for generating innovative and creative ideas [13]. Nowadays, the application of TRIZ is very popular among designers and engineers, and it has been widely adapted around the world [14]. The application of the TRIZ method also helps to identify problems, provides direct solutions, and suggests new possible solutions. There are several tools and techniques that are developed in TRIZ [15]. For example, 40 Inventive Principles, which is a conceptual solution to technical and physical contradictions. Next, the contradiction matrix consists of 39 technical parameters that are arranged on the horizontal and vertical axis. It is used to find out the inventive principles that can be utilized to clarify technical contradictions [16].

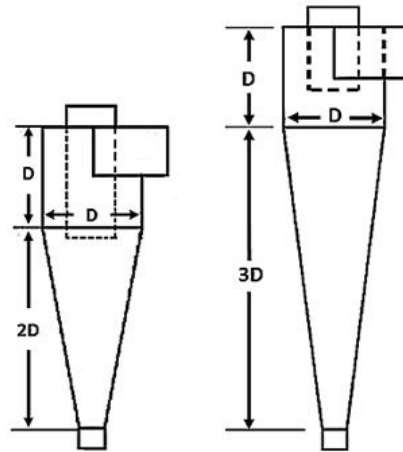


Figure 2. Fundamental design (1D2D and 1D3D).

The objective of this study is to design and develop a domestic cyclone dust collector system using TRIZ and CCD method. The product design's main concern was to make it simple, inexpensive, and easy to produce without the need for advanced manufacturing techniques and materials. Hence, the fundamental cyclone design of Model 1D2D and 1D3D opted, and modifications are made to simplify the design without compromising its performance. At the end of this study, the performance of the cyclone dust collector and the airflow simulation inside the cyclone system will be provided.

2. METHODOLOGY

2.1 Idea Generation

The idea process began with identifying the main product design specifications (PDS) for the cyclone dust collector. Based on market research, there are five main criteria in the cyclone PDS, which are lightweight, manufacturability, recyclability, low cost, and high efficiency. In this study, the design intent is defined based on two considerations; i) the cyclone design that had been proposed should be convenient to use and user friendly; ii) the cyclone design should be easy to manufacture without advanced machinery and equipment.

Using the TRIZ framework, the contradiction was solved by determining the specific problem and converting it into a general problem. Next, the general problem was subsequently converted into a specific solution [17]. In this case, the contradiction matrix is used to generate the potential Inventive Principles based on the improving and worsening parameters from the engineering contradiction. The engineering contradiction is normally stated in the use of the statement, "If manipulate variable changes, then the responding variable will improve/worsen" [18]. This statement helps to clarify what the problem is about and what parameters are needed.

A general problem was determined according to the TRIZ 39 Systems Parameters, which is to fabricate cyclone dust collector with ease manufacturing method (#32 manufacturability) and easy to use (#33 ease of operation) but at the same time, it may reduce the efficiency of the cyclone collector (#24 loss of information). Typically, when the fundamental design of product changes or modified, the performance of the product will either improves or worsen [19]. Once the improving and worsen parameters are identified, the contradiction matrix based on TRIZ 40 Inventive Principles solution was constructed (Table 1) in order to get the best potential solution.

Table 1. Contradiction matrix for cyclone dust collector based on the TRIZ 39 Engineering Parameters.

Improving Feature	Worsening Feature	TRIZ 40 inventive solution principles
#32. Manufacturability	#24. Loss of information	#16. Partial or excessive action. #18. Mechanical vibration #24. Intermediary #32. Colour changes
#33. Ease of operation		#4. Asymmetry #10. Preliminary action #22. Blessing in disguise #27. Cheap disposables

Table 1 stated that there are multiple solutions to solve the contradiction, as suggested in the TRIZ method. Next, each solution will be analysed, and the most suitable solutions were then selected. Based on TRIZ 40 inventive solution, #24 (Intermediary) and #27 (Cheap disposables) were selected as the best general solutions. Then, the specific solution strategy ideas were developed according to the general solution, as shown in Table 2. The process parameters and good understanding of the material structure that meets the performance need to be determined because it will affect the quality of the final build and to make sure the working prototype was fabricated properly [20,21].

Table 2 Specific solution strategy based on the principles of TRIZ solution.

TRIZ 40 inventive solution principles	Solution Description	Specific Solution Strategy
#24 Intermediary	- Merge one object temporarily with another (easy to remove)	- Attach dust bin at the bottom of cyclone dust collector as additional storage for the vacuum cleaner. - Use temporary joint between cyclone dust collector and storage barrel.
#27 Cheap disposables	- Replace an expensive material/object/service with cheap objects.	- Change the manufacturing process of cyclone collector. (Plastic injection molding to self-fabricate) - Use recycle materials to fabricate cyclone collector.

2.2 Theoretical Analysis

In this stage, after a specific solution strategy was identified previously, the next step is to proceed with theoretical studies by applying the Classical Cyclone Design (CCD) method in order to determine the main parameter of the cyclone dust collector. The procedure starts with calculating the number of effective turns (N_e), which is the first step in the CCD method. The number of effective turns is the number of turning points that spin the gas through the outside vortex of the cyclone [22]. Therefore, the collection efficiency would increase when the amount of airflow turns is higher. The calculation of the N_e as follows:

$$N_e = \frac{1}{H_c} \left[L_c + \frac{Z_c}{2} \right] \tag{1}$$

where,

$$\begin{aligned} N_e &= \text{number of effective turns} & L_c &= \text{length of body (m)} \\ H_c &= \text{height of inlet (m)} & Z_c &= \text{vertical length of cone body (m)} \end{aligned}$$

Based on the previous study, the number of effective turns, N_e for Model 1D2D and 1D3D, is 4 and 5 turns, respectively [23]. Hence, the cyclone dust collector should achieve a similar or near the value of effective turns. The second stage of the CCD method is to measure the diameter of the cutting point. With the increased diameter of the cutting point, the collection efficiency will decrease. Lapple's cut-off model was built based on strength equilibrium theory [24]. The Lapple (d_{pc}) cut-off model is as follows:

$$d_{pc} = \left[\frac{9\mu B_C}{2\pi N_e v (\rho_p - \rho_g)} \right]^{1/2} \quad (2)$$

where,

$$\begin{aligned} d_{pc} &= \text{cut-point diameter (m)} & \rho_p &= \text{density of particle (kg/m}^3\text{)} \\ B_C &= \text{width of inlet (m)} & \rho_g &= \text{density of air (kg/m}^3\text{)} \\ N_e &= \text{number of effective turns} & \mu &= \text{viscosity of air (kg/ms)} \\ v &= \text{inlet velocity (m/s)} \end{aligned}$$

Once the cut-point diameter was determined, the next step is to calculate the fractional efficiency curve (FEC). The FEC can be defined as theoretical collection efficiency because it depends on the size of the particles and the formula. The fractional efficiency curve equation as follows:

$$\eta_j = \frac{1}{1 + (d_{pc}/d_p)^2} \quad (3)$$

where,

$$\eta_j = \text{fractional efficiency curve} \quad d_p = \text{actual diameter of the particles (m)}$$

The cyclone fractional efficiency can determine the overall collection efficiency if a size distribution of the inlet particles is known [25]. The overall collection efficiency is the actual collection efficiency of a cyclone dust collector. It is given by:

$$\eta_o = 1 - \frac{m_{esc}}{m_{inj}} \quad (4)$$

where,

$$\begin{aligned} m_{esc} &= \text{mass of particle escaping in the vortex} \\ m_{inj} &= \text{mass of particle injected at the barrel} \end{aligned}$$

A significant factor in the creation of a cyclone system is the cyclone pressure drop. The Lapple technique requires two steps, first is to estimate the cyclone pressure drop using the number of inlet speed heads (H_v) Equation 5. The second step is to transform the number of velocity heads (ΔP) in Equation 6 into a constant pressure drop:

$$H_v = K \frac{H_C B_C}{D_e^2} \quad (5)$$

$$\Delta P = \frac{1}{2} \rho_g v^2 H_v \quad (6)$$

where,

H_v = pressure drop in terms of the number of inlet velocity heads
 K = constant ($K = 12$ to 18 for a standard tangential-entry cyclone)
 ΔP = pressure drop (Pa)
 v = inlet velocity (m/s)

However, there is one problem with this approach, where the Lapple pressure drop equation does not deal with any vertical dimensions [25]. This will affect the cyclone design structure; for instance, the tall cyclone could have the same pressure drop as the short cyclone if the inlet velocities and inlets and outlets dimensions are the same. Due to the inaccurate calculation by the Lapple pressure drop model, thus in this case study, the pressure drop will be analysed by using simulation software (Ansys R16) to determine the pressure inside the cyclone dust collector. Typically, the pressure drop occurs when the full vacuum bag or velocities at the inlet hose slightly drop [26].

2.3 Performance Evaluation

In order to determine the collection efficiency of the new cyclone dust collector system, the weight of particles in primary and secondary storage was measured using an analytical balance (Mettler Toledo – ML204). There were three particulate matter samples used, i.e., pebble, coarse sand, and sawdust, with different densities and size particles. The same mass of each sample was used, which was 100 grams per sample. The samples were put on a flat surface, then the vacuum cleaner with cyclone dust collector system was turned on. The cyclone is considered efficient if the weight of the particulate matter in the primary container is heavier than secondary container.

Next, the average diameter of the samples which were collected during vortex separation were measured using Optical Image Analyzer (Axioskop 2 Plus). However, for samples that has a larger particle size of more than 1 millimetre, especially pebbles, a vernier calliper was used to measure the diameter of the particles. To determine the effectiveness of the cyclone dust collector to filter small particles, the size of the particles that were trapped inside secondary container were also measured.

3. RESULTS AND DISCUSSION

3.1 Conceptual Design and Fabrication

After the appropriate TRIZ solution principles have been determined (Table 2), the conceptual design was developed based on morphological chart method. The generated ideas were then structured to understand the solutions better and then each element was matched with different functions to form new design solutions. The morphological chart matrix and the functional features relevant to the solution principles for the TRIZ solution principles are shown in Figure 3. At the end of the analysis, the best solution was chosen.

Next, detail design is a phase of refining design, fabrication plans, and specifications of the products. The cyclone 3D model was developed using software CATIA Version 5 after analysing all the specific solution strategies. According to the proposed conceptual design, the cylindrical body of the cyclone dust collector was removed (Figure 4). This is against the fundamental cyclone design. However, the cyclone structure can be simplified and easy to fabricate as long as

the performance of the cyclone remains the same. Next, the working prototype was fabricated using recycled materials such as skittle cone, plywood, PVC pipe, coupling, reducer, and storage barrel as primary storage.

There are several steps that need to be followed in order to develop a working prototype of the cyclone dust collector. Firstly, the upper part of the skittle cone was cut to make the cyclone outlet. Then, inlet and outlet components were developed using PVC pipe, coupling, and reducer. Later, the inlet components were installed tangentially to the cone surface. Finally, a dust bin that act as a primary storage barrel was installed at the bottom of the cyclone collector.

TRIZ solution and specific strategy	Feature	Solution		
		1	2	3
#27 Cheap disposable - Self-fabricate of cyclone dust collector.	Material	Street Cone	Skittle Cone	-
	Storage size	Small	Medium	Large
	Weight	Lighter	Medium	Heavy
	Painting	Yes	No	
#24 Intermediary - Merge cyclone dust collector temporarily with the storage barrel, which can be easily removed.	Joint	Bolt and nut	Screw	Press fit

Figure 3. Morphological chart of the cyclone dust collector.

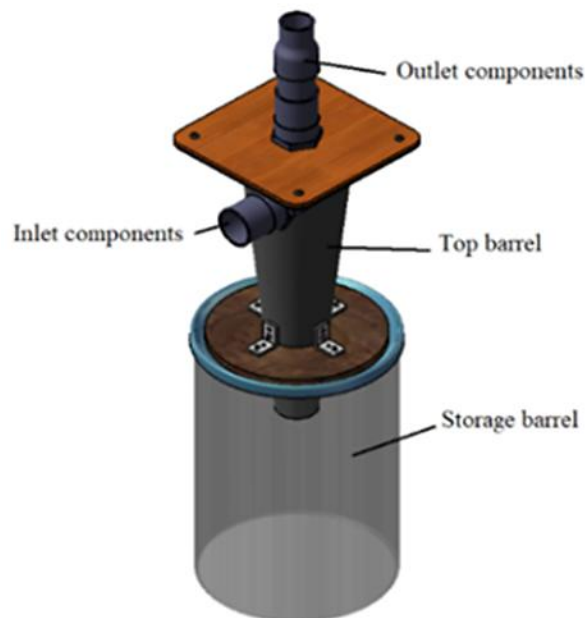


Figure 4. 3D model of cyclone dust collector using CATIA Version 5 software.

3.2 Design Evaluation

The collection efficiency tests were performed using a vacuum cleaner that was attached to the cyclone dust collector. The dimension and ratio of the cyclone are shown in Table 3 and Figure 5, respectively. Based on the CCD method, the number of effective turns was calculated using Equation (1). There were approximately 3.9 effective turns in the cyclone prototype. Based on the dimension ratio in Table 3, this cyclone dust collector can be categorized as a 1D2D cyclone model instead of a 1D3D model.

The comparison of the number of turns, N_e , by different models is shown in Table 4. As stated in Table 4, the difference between the predicted number of turns in the CCD model and this study was very close. Furthermore, cut-point diameter and fractional efficiency curves, FEC of particles were calculated using Equations (2) and (3), the results shown in Table 5. The average particle diameter of pebble, coarse sand, and sawdust were 22.36, 40.420, and 31.968 μm , respectively.

The fractional efficiency, FEC of the cyclone system was more than 98% for pebble and coarse sand. However, the fractional efficiency will drop to 86% when using sawdust (Table 5). Besides, the average collection efficiency, η_o for pebble, coarse sand, and sawdust were 96.019%, 80.362%, and 67.715%, respectively, as shown in Table 6. The cyclone dust collector's collection efficiency will be affected by the diameter and density of the sample. The smaller the particles' density, the more the particles will escape through the vortex. Meanwhile, the large particle will fall into the primary storage (dust bin) because of the lost momentum during vortex separation.

Table 3 Dimension ratio of the cyclone dust collector

Cyclone Dust Collector Dimension			
	Symbol	Value (m)	Ratio (with respect to body diameter, D)
Body Diameter	D	0.160	1.00
Length of the Cone	Zc	0.390	2.44
Height of the Inlet	Hc	0.050	0.31
Width of the Inlet	Bc	0.050	0.31
Diameter of Outlet	De	0.050	0.31
Diameter of Gas Exit	Dd	0.055	0.31
Diameter of Inlet	d	0.050	0.31
Length of vortex Funder	Sc	0.100	0.63

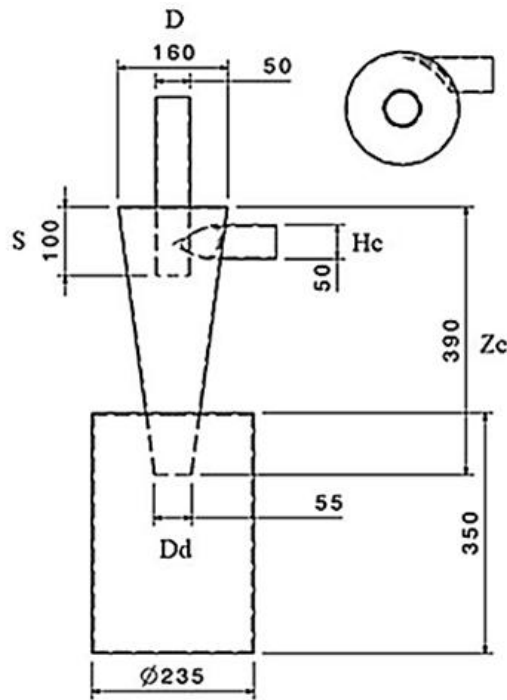


Figure 5. Dimensions of the cyclone dust collector (unit mm).

Table 4 Comparison of the number of turns (N_e) predicted by different models

Cyclone Design	CCD	Rosin et al. (1932)	Shepherd and Lapple (1940)	Lapple (1951)	This Study
1D2D	4.0	0.51	0.84	1.92	3.9

Table 5. Results of fractional efficiency curve (FEC), η_j .

Particle	Density (kg/m^3)	Average diameter of the particle, d_p (μm)	Cut-Point Diameter, d_{pc} (μm)	Fractional efficiency curve, η_j (%)
Pebble	1961.928	2236	2.571	99.995
Coarse Sand	1604.540	40.420	2.843	98.407
Sawdust	259.326	31.968	7.087	86.146

Next, Table 6 also suggest that around 7 grams of sawdust particles loss to the surrounding during operation. Fractional efficiency (FEC) was calculated using a theoretical formula. Meanwhile, overall collection efficiency was the cyclone's actual results. As shown in Figure 6, FEC was higher than overall collection efficiency by approximately 10%. Both results have the same similarity, which suggest that the cyclone dust collector's efficiency will decrease if the particle diameter was less than 40-50 μm .

Table 6 Overall collection efficiency, η_o

Particle	Primary Storage, Dust Bin (g)	Secondary Storage, Vacuum Bin (g)	Loss to surrounding, (g)	Collection efficiency, η_o (%)	Average collection efficiency, η_o (%)
Pebble	94.236	4.332	1.432	95.403	94.861
	95.547	3.643	1.210	96.605	
	95.580	3.891	1.429	96.870	
	94.853	3.458	1.689	96.354	
	93.867	4.230	1.310	94.861	

					96.019
Coarse Sand	82.753	15.206	2.041	81.625	
	81.721	15.734	2.545	80.747	
	81.086	15.991	2.923	80.279	
	82.193	15.953	1.854	80.590	
	80.326	17.213	2.461	78.571	
					80.362
Sawdust	68.186	25.523	6.291	62.569	
	68.647	24.326	7.027	64.564	
	71.342	21.403	7.255	69.999	
	73.220	21.991	4.789	69.969	
	73.143	20.861	5.996	71.479	
					67.715

Since the pebble diameter was more than 1 millimetre, it was unlikely to escape the vortex separation. The particles with smaller diameters almost invisible to human eyes. As stated in Figure 7, the average diameter of coarse sand and sawdust that escaped the vortex separation were 17.383 μm and 25.073 μm , respectively. The diameter of sawdust and coarse sand were very small and might affect indoor environmental quality after vacuum cleaning. Hence, the results show that the cyclone dust collector was suitable for use when the particle sizes were more than 50 μm .

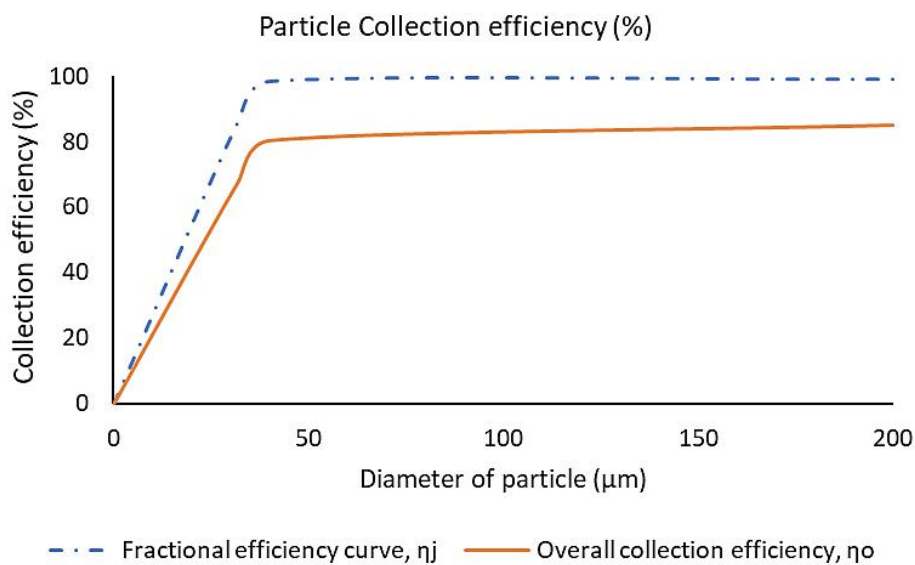


Figure 6. Particle collection efficiency with respect to diameter of particles.

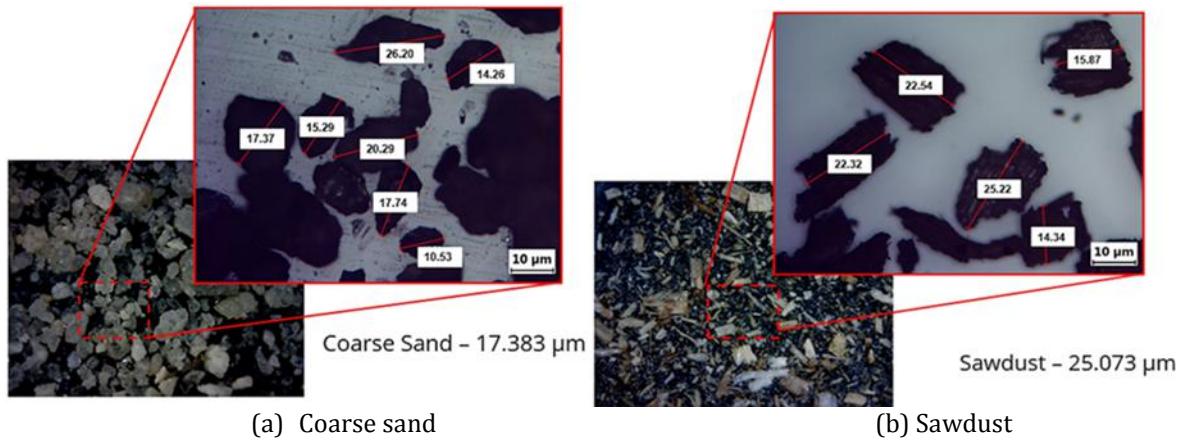


Figure 7. The average diameter of particles escaped the vortex separation.

3.3 Computer Simulation

The airflow simulation inside the cyclone dust collector was examined using Ansys R16. The major factor affecting the swirl in the cyclone collector was the inlet velocity. The pressure gradient in the particle was affected by the amount of swirl. The pressure gradient was a significant factor which influence the particle force balance and the cyclone separator's collection performance. Hence, the main parameter of cyclone collection efficiency depends on inlet velocity. Based on this study, particles size was kept constant at 5×10^{-6} m, and the inlet velocity varied from 4 m/s to 12 m/s. The effect of increasing velocity was observed on pressure drop and the flow field of particles.

Figure 8 and Figure 9 show the pressure contours at the cyclone dust collector's top and side sections according to increasing velocities from 4 m/s to 12m/s. The negative pressure was seen at the cyclone centre, where a forced vortex occurred directly related to the high swirling flow profile. Besides, for inlet velocity of 4 m/s there was an almost uniform pressure gradient. When the velocity increased, the pressure gradient also increased. Furthermore, a pressure drop occurs at outlet components due to pressure loss as rotational kinetic energy and wall friction.

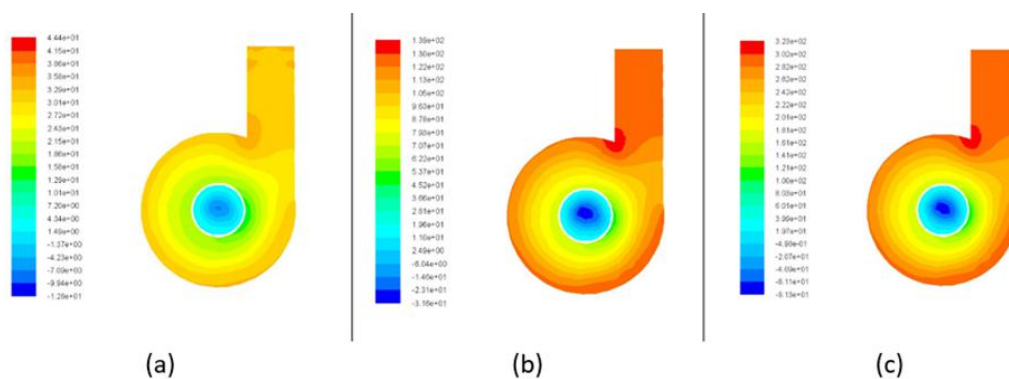


Figure 8. Pressure contours cross section at top view of cyclone for (a) $v = 4$ m/s, (b) $v = 8$ m/s, (c) $v = 12$ m/s.

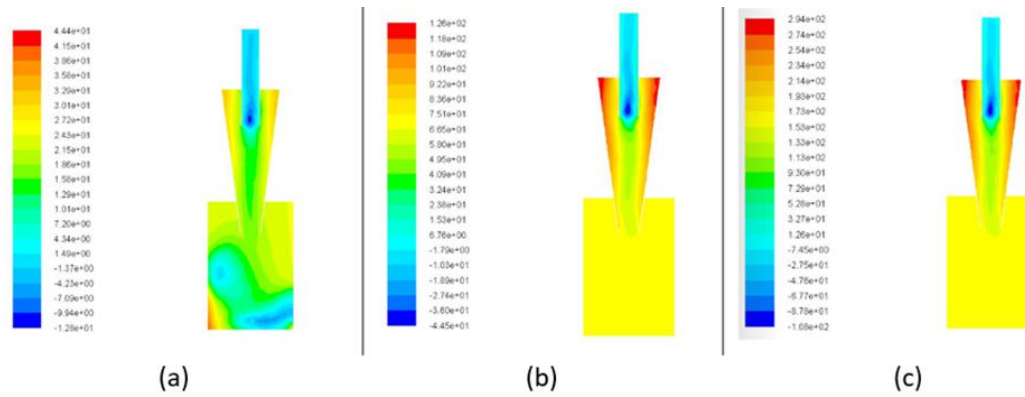


Figure 9. Pressure contours cross section at side view of cyclone for (a) $v= 4$ m/s, (b) $v = 8$ m/s, (c) $v= 12$ m/s.

Figure 10 displays the airflow series in the cyclone dust collector. The airflow reached the top of the barrel and descended to the cone to create an outer vortex. As air enters the cyclone's bottom part, the inner vortex reverses the path, the lighter particles leaving the top parts. Simultaneously, the heavy particles fell into the primary storage at the cyclone's bottom due to lack of momentum and the particles were captured.

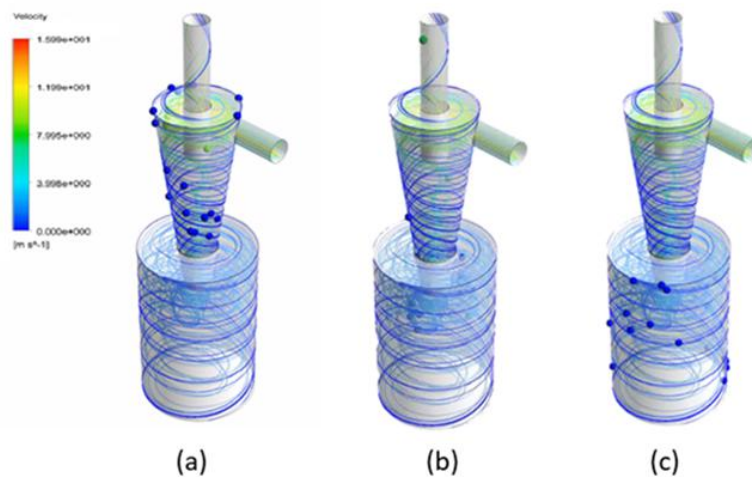


Figure 10. Airflow series in the cyclone dust collector by Ansys, (a) the particles through the cone, (b) lighter particles exit to the outlet, (c) heavy dust trap at the storage barrel.

4. CONCLUSION

A cyclone dust collector system was designed and fabricated using the integration of the CCD and TRIZ methods. The development process involved two main stages i.e., main parameter study of Classical Cyclone Design (CCD) and idea generation using the TRIZ method. The conceptual design was modelled using CATIA Version 5 and fabrication of the prototype was made considering TRIZ strategic solutions of low-cost materials and ease of manufacturing technique. The efficiency of the cyclone dust collector to filter dust and debris was tested using pebbles, coarse sand, and sawdust. The fraction efficiency (FEC) and overall collection efficiency were 99.99% and 96.02%, respectively. The pressure drops and airflow inside the cyclone dust collector was also analysed using Ansys Version 16. Using the developed cyclone dust collector system would require less maintenance as most of the particles would be separated in the first

stage of the collection system. Thus, the application of the cyclone dust collector system is recommended because it would improve the performance of the vacuum cleaner and requires less maintenance.

ACKNOWLEDGEMENTS

The authors would like to thank the staff of the Faculty of Mechanical Engineering, Universiti Teknikal Malaysia Melaka for their supports. Also special thanks to the members of Advanced Materials Characterization Laboratory (UTeM) and Academia-Industry Collaboration Laboratory, UTeM.

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