Cyclone Separator Performance Analysis: Efficiency Characterization And Velocity Sensitivity Using Lapple's Model

A Technical Project Report

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March 2026

Abstract

Cyclone separators are an economical device used widely in the industries for removing particulate solids from a fluid system by induced centrifugal force, which increases the relative settling velocity of solids due to density difference between the fluid and solid . This study presents a performance analysis of a standard Lapple cyclone separator using theoretical modelling and parametric calculations carried out in Microsoft Excel. The cut size (d_{50}) was determined to be 6.79 μm at a base inlet velocity of 15m/s, indicating the particle diameter at which 50 % collection efficiency was achieved. A grade efficiency curve was plotted to characterize collection performance across a particle size range of 1-50 μm. Sensitivity analysis was implemented by varying the inlet velocity from 10 - 25 m/s, demonstrating that increasing velocity reduces the cut size by 37% and nearly doubles the collection efficiency for 5 μm particles. The pressure drop was calculated as 2160 Pa using the Shepherd and Lapple correlation. The findings provide useful insights into the design and operational optimization of cyclone separator for fine particle applications.

1. Introduction

Cyclone Separators also called centrifugal separators are mechanical devices that use centrifugal force to separate particles from gas stream widely used in the cement plants, pharmaceutical industry, food processing, power plants, chemical industries. Cyclone separators require minimal maintenance. Cyclone separators are widely preferred in industry as they are cost effective and can handle high temperatures and pressures and are favoured over filters and scrubbers for coarse to medium particle separation. Centrifugal separators have replaced gravity separators in production operations due to their greater effectiveness with fine drops and particles and their much smaller size for a given capacity. However, its efficiency drops significantly for very fine particles below 5-10 μm, which is why understanding cut size (d_{50}) and grade efficiency is important . This study applies the Lapple model, which is a theoretical framework developed to predict cyclone performance based on geometric and operational parameters to analyse performance, develop grade efficiency curve, and study effect of inlet velocity on separation efficiency.

2. System Specifications & Assumptions

This analysis is based on the standard Lapple cyclone geometry. All input parameters were selected based on the standard industrial practice and theoretical conventions established by Lapple. The Gas properties were taken at the following conditions: ambient air temperature 25 °C and pressure of 1 atm. The following table summarizes all input parameters that serves as the foundation for subsequent calculations and performance evaluations in this study.

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Parameter	Symbol	Value	Unit
Cyclone Diameter	D	0.4	m
Inlet height	a	0.2	m
Inlet width	b	0.1	m
Number of turns	Ne	5	None
Gas Velocity(inlet)	Vi	15	m/s
Gas density	ρg	1.2	kg/m^3
Particle density	ρp	1500	kg/m^3
Gas viscosity	μ	1.81E-05	Pa-s

Table 1 : Design Parameters and Input Specifications

The cyclone diameter D was set to be 0.4m, which is a realistic industrial cyclone size. The inlet height and width follow standard Lapple geometric ratios where a=D/2 and b=D/4, where a and b are 0.2m and 0.1m respectively. The number of effective turns follow the standard assumption in the Lapple model, thus taken as 5. An inlet velocity of 15m/s was chosen as it is the midpoint of typical industrial range of 10-25m/s, hence chosen as the base case for this study. Gas density and viscosity were taken as $1.2 kg/m^3$ and 1.81×10^{-5} Pa·s respectively, corresponding to air at 25°C and 1 atm pressure. Particle density of 1500 kg/m^3 was selected as it is representative of industrial dust and powder materials such as cement and grain. The gas flow is assumed to be steady and incompressible throughout the cyclone. Particles are assumed to have a sphericity of 1 and uniform in density with no interaction between particles. The assumptions are consistent with standard Lapple model conventions and are widely accepted for theoretical cyclone analysis.

3. Methodology

3.1 Lapple Overview

The Lapple model is a simplified, yet effective theoretical model developed by Lapple in 1951 to estimate separation efficiency and pressure drop, in cyclone separators used across various industrial applications . It predicts the overall collection efficiency of a cyclone based on the inlet particle size distribution, particle density, and cyclone dimensions. This model assumes steady, incompressible flow and that the collection efficiency is primarily influenced by the cyclone's geometric dimensions and that particles follow a force balance between centrifugal and drag forces.

3.2 Cut Size Calculation

The cut size d_{50} represents the particle diameter at which 50% collection efficiency is achieved. It was calculated using the Lapple equation as follows:

$$d_{50} = \sqrt{\frac{9\mu b}{\pi N_e V_i(\rho_P - \rho_g)}}$$

Where:

- μ = gas viscosity (Pa·s)
- b = inlet width (m)
- N_e = number of effective turns
- V_i = inlet velocity(m/s)
- ρ_P = particle density (kg/m³)
- ρ_g = gas density (kg/m³)

The numerator contains viscosity and inlet width, where both of them resist separation, hence larger the values, larger the cut size, poorer the performance. Similarly, the denominator contains velocity, number of turns and density difference, where all the three drive separation, hence larger the values, smaller the cut size and better is the performance. Therefore , the cut size (d_{50}) decreases as velocity increases, which is the basis for the sensitivity analysis conducted in this study.

3.3 Grade Efficiency Calculation

The grade efficiency η(d) represents the collection efficiency for a particle diameter d. It was calculated using the following Lapple expression :

$$\eta(d) = \frac{1}{1 + (\frac{d_{50}}{d})^2}$$

Where :

- $\eta(d)$ = collection efficiency for particle diameter d
- d = particle diameter (μm)
- d_{50} = cut size (μm)

When d >> d_{50} , the ratio $(\frac{d_{50}}{d})$ becomes very small, as a result the efficiency approaches 100 %, it only approaches and can never be 100% efficient. When d << d_{50}, the ratio $(\frac{d_{50}}{d})$ becomes extremely large, as a result the efficiency drops close to 0%. However, at d = d_{50}, the efficiency is exactly 50 % by definition. This behaviour forms the theoretical basis for the grade efficiency curve plotted in this study.

3.4 Pressure Drop Calculation

The pressure drop ΔP across the cyclone was estimated using the Shepherd and Lapple correlation as follows :

$$\Delta P = \frac{1}{2} \rho_g V_i^2 \cdot N_H$$

Where :

- ΔP = pressure drop (pa)
- ρ_g = gas density (kg/m³)
- v_i = inlet velocity (m/s)
- N_H = number of velocity heads

A standard value of $N_H = 16$ is used for Lapple cyclone geometry. The pressure drop increases with gas density and velocity indicating that higher the velocity, better the separation, higher the pressure drop. This represents the key engineering trade-off between separation efficiency and operational energy consumption.

4. Results & Discussion

4.1 Cut Size Analysis

The cut size (d_{50}) was calculated to be 6.79 μm at base conditions. This means that particles larger than 6.79 μm are captured with greater than 50% efficiency and particles smaller than 6.79 μm are more likely to escape. This value is typical for industrial cyclones handling fine dust and powder.

4.2 Grade Efficiency Curve

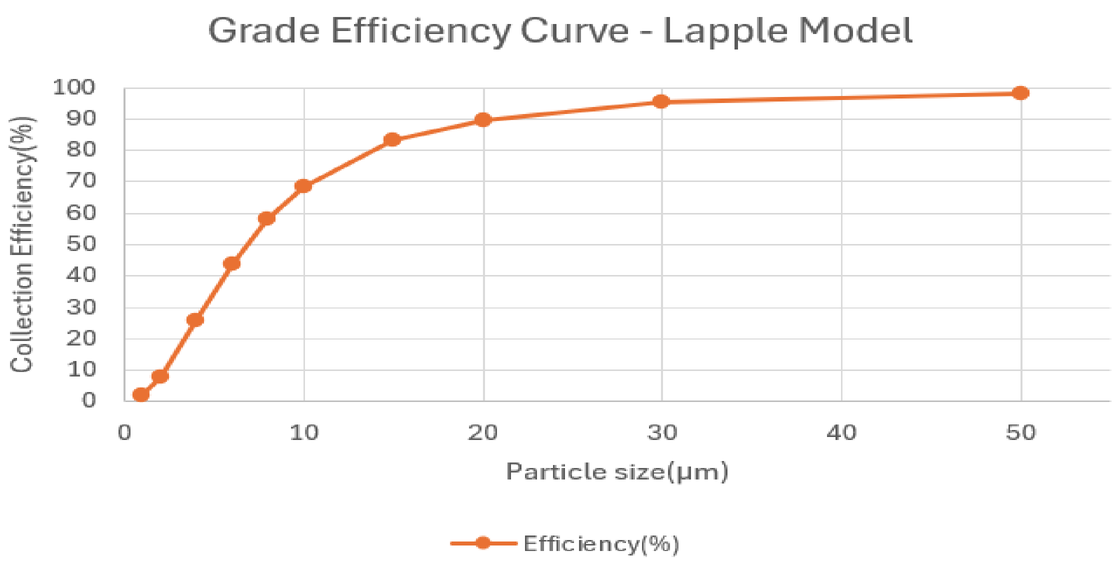

Figure 1 : Grade Efficiency Curve - Lapple Model

The above grade efficiency curve shows S-shaped behaviour as it starts low, rises steeply around d_{50} and flattens at larger sizes. At 1 μm, it is only 2.12% efficient, indicating that very fine particles mostly escape. At 20 μm, it is 89.66% efficient, indicating that large particles are mostly captured. At 50 μm, it is 98.19 % efficient, indicating that, almost all the particles are captured completely. The steep rise occurs around the d_{50} region (6.79 μm), which confirms the theoretical prediction. These results thus confirm that the cyclone performs well for particles above 20 μm but struggles significantly for particles below 5 μm.

4.3 Sensitivity Analysis

Inlet Velocity(m/s)	Cut size d50(µm)	Efficiency at 5µm(%)
10	8.32	26.54
15	6.79	35.15
20	5.88	41.95
25	5.26	47.46

Table 2 : Sensitivity Analysis Results

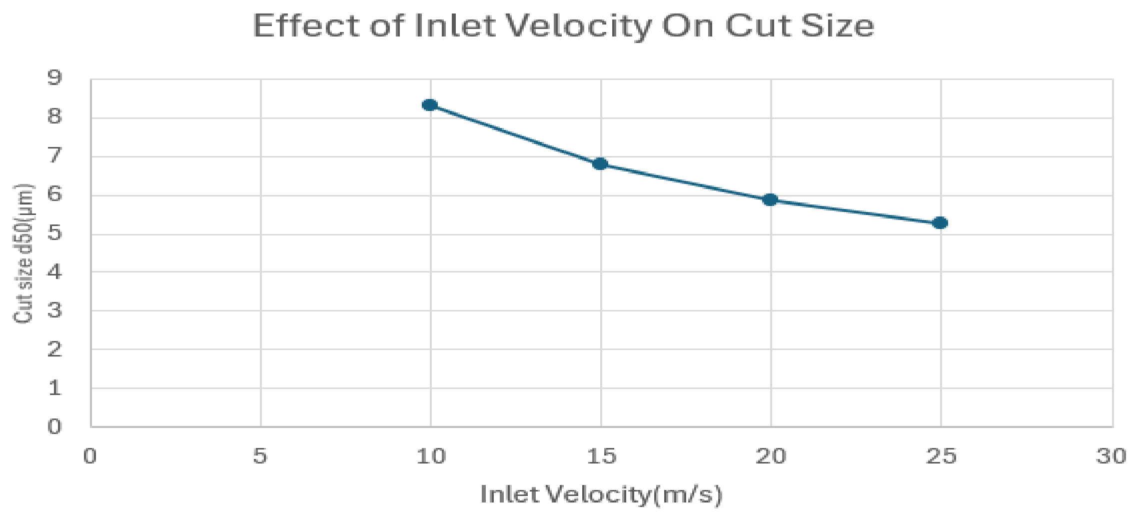

Figure 2 : Effect of Inlet Velocity on Cut Size (d_{50})

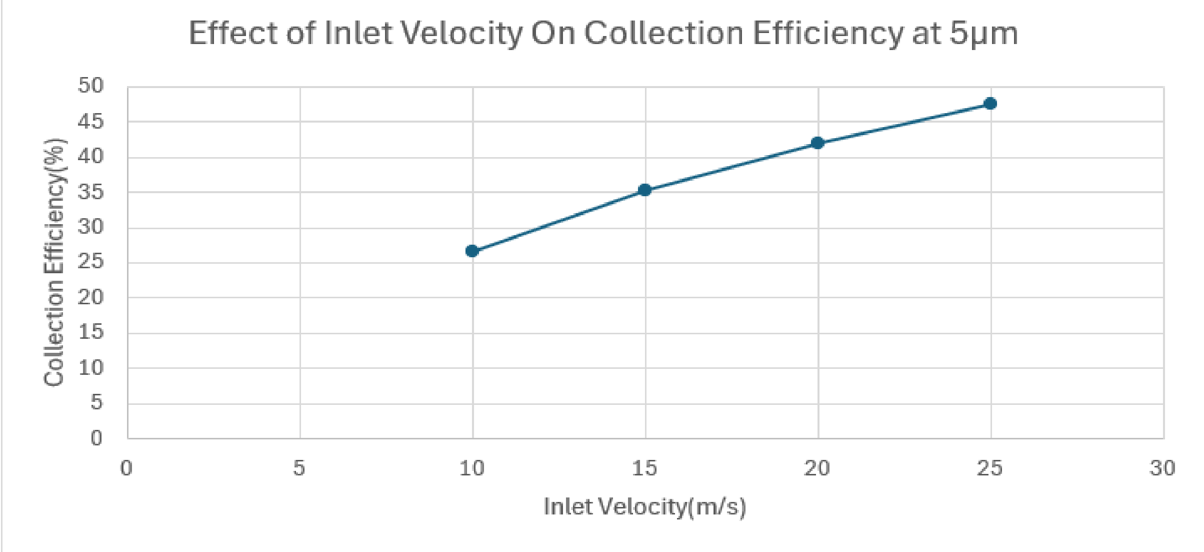

Figure 3 : Effect of Inlet Velocity on Collection Efficiency at 5µm

From the above graphs and tables, it's clear that as velocity increases from 10 to 25m/s , the cut size (d_{50}) decreases from 8.32 to 5.26 μm a 37% reduction. This means at higher velocities, finer particles can be captured. Furthermore, at 5 μm the efficiency nearly doubles, from 26.5 % to 47.5%. However, higher the velocity, better the separation, higher the pressure drop, which is a key engineering trade-off between separation efficiency and operational energy consumption, as optimal operating velocity depends on the specific application requirements.

4.4 Pressure Drop

The pressure drop at the base inlet velocity of 15m/s was calculated as 2160 Pa (220.18 mm H_2O) by the Shepherd and Lapple formula. This value is within the typical range for industrial cyclones. This confirms that the system is operationally feasible and it will vary as the velocity increases.

5. Conclusions & Recommendations

5.1 Conclusions

This study presented a theoretical performance analysis of a standard Lapple cyclone separator. The calculations were carried out using Microsoft Excel based on Lapple's model covering cut size (d_{50}), grade efficiency, sensitivity analysis and pressure drop. The cut size was determined to be 6.79 μm at a base inlet velocity of 15m/s, indicating that the cyclone is capable of capturing particles in the fine dust range, making it suitable for applications like cement and grain processing. The grade efficiency curve was an S shaped curve which aligns with the theoretical predictions. The collection efficiency exceeds 89% for particles above 20 μm but drops below 8% for particles under 2 μm, thus indicating the cyclone's limitations for ultrafine particles.

Furthermore, Increasing the inlet velocity from 10 to 25m/s reduced cut size by 37%, and nearly doubled the efficiency at 5 μm. This demonstrates that velocity is the most crucial operational parameter for improving fine particle capture. The pressure drop of 2160 Pa at the base conditions confirms the operational feasibility within typical industrial ranges . The engineering trade-off between the separation efficiency and operational energy consumption is a critical consideration in the real industrial design. The Lapple model despite its simplifying assumptions serves as a reliable and widely used tool for cyclone design and performance estimation.

5.2 Recommendations

1. Study the series cyclone arrangements for capturing ultra fine particles below 5 μm.
2. Validate the results using simulation software like ASPEN Plus.
3. Study the effect of particle size distribution on overall efficiency.
4. Investigate the effect of temperature on gas properties for high temperature industrial applications.
5. Extend the analysis to multiple cyclone geometries beyond the standard Lapple configuration to identify optimal designs for specific applications.

6. References

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