Mathematical Modeling Of Energy Consumption And Separation Efficiency Of Multicyclones For Air Purification

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ABSTRACT

Multicyclones—compact arrays of small-diameter cyclone cells—remain the work-horse technology for removing coarse dust from industrial exhaust streams thanks to their low capital cost and mechanical robustness. Their main drawbacks are the pressure drop that drives fan energy demand and the inherent trade-off between energy use and collection efficiency. This paper develops an integrated mathematical model that couples (i) gas-dynamics-based correlations for pressure drop, (ii) Barth's static-particle theory for grade efficiency, and (iii) a fan-power model to quantify specific energy consumption (SEC) per tonne of dust captured. A parametric simulation covering volumetric flow rates 0.05 – 0.8 $m^3\ s^{-1}$ per cell, cyclone diameters 0.1 – 0.3 m, and dust particle diameters 1 – 20 µm is implemented in Python/MATLAB. Results (Figure 1) show ΔP rising quadratically with superficial velocity, while the predicted collection curve (Figure 2) exhibits a typical S-shape with 50 % cut size $d_{50} \approx 5$ µm. The combined model reveals a sweet-spot operating window (5 – 8 $m\ s^{-1}$) where SEC is minimized without compromising ≥ 80 % overall efficiency. The framework provides a fast tool for optimising multicyclone banks in retrofits or green-field designs.

Keywords: Multicyclone; cyclone separator; pressure drop; energy consumption; collection efficiency; mathematical modelling; air pollution control; fan power; optimisation

Introduction

Cyclone separators exploit centrifugal force to separate solid particles from gas streams and are among the most widely deployed particulate control devices in the process industries. When high volumetric flow rates must be treated in limited floor space, multiple small cyclones are installed in parallel inside a common shell, forming a *multicyclone*. Reducing the cell diameter lowers the aerodynamic cut size and hence improves collection, but it simultaneously raises the pressure drop and, by extension, fan energy consumption.

Power-plant and cement kilns, for example, may spend 15–25 % of their total auxiliary power just to overcome the resistance of dust collectors, so optimising multicyclone energy demand is economically attractive. Classic design manuals give separate charts for ΔP and grade efficiency, yet an integrated treatment that links both to fan power and overall plant-level *specific energy consumption* (SEC) is rarely presented in the open literature.

This study therefore:

1. Derives a compact set of equations that connect geometry, flow rate and dust properties to both ΔP and efficiency;
2. Combines them into an SEC objective function;
3. Performs a parametric sweep to visualise trade-offs and identify an optimal operating window.

Methods

For a single cyclone cell the pressure drop can be written in Fanning form

$$\Delta P = K\frac{\rho_g v^2}{2}, \tag{1}$$

where ρ_g is the gas density, $v = Q/A_i$ the inlet velocity, and K an empirical coefficient that subsumes viscous, entry and exit losses. Values of K lie between 3 and 6 for well-proportioned Stairmand or Lapple geometries learncheorg.

For a multicyclone package containing N identical cells the total drop is the same as that of a single cell (cells are in parallel), but the overall flow rate is $Q_{\text{tot}} = NQ$.

The grade efficiency $\eta(d_p)$ for particle diameter d_p is estimated by Barth's static-particle theory

$$\eta(d_p) = \frac{1}{1+\left(\frac{d_{50}}{d_p}\right)^2} \tag{2}$$

where d_{50} is the cut size for 50% capture researchgatenet . The overall efficiency E for a given dust size distribution $f(d_p)$ is

$$E = \int_0^\infty \eta(d_p) f(d_p) \mathrm{d}d_p \tag{3}$$

The shaft power required by the induced-draft fan is

$$P = \frac{\Delta P Q_{\text{tot}}}{\eta_{\text{fan}}}, \tag{4}$$

with $\eta_{\text{fan}} \approx 0.7$ for medium-sized industrial units. Defining the hourly mass of dust captured as $\dot{m}_d = E C_{\text{in}} \rho_g Q_{\text{tot}}$ (where C_{in} is inlet dust loading), the specific energy consumption becomes

$$\text{SEC} = \frac{P}{\dot{m}_d} = \frac{\Delta P}{\eta_{\text{fan}} E C_{\text{in}} \rho_g}. \tag{5}$$

Equation (5) explicitly couples efficiency and pressure drop, making the trade-off amenable to optimisation.

- Geometry. Base case diameter $D = 0.15$ m, height $h = 4D$, inlet width/height $a = 0.2D, b = 0.5D$
- Gas properties. $T = 298$ K, $p = 1$ atm $\Rightarrow \rho_g = 1.2$ kg m^{-3}, $\mu = 1.8 \times 10^{-5}$ Pa s.
- Dust. Log-normal distribution with mass median 8μ m, geometric standard deviation 2.0, $C_{\text{in}} = 3$ g m^{-3}.
- Parameter sweep. Q from 0.05 to 0.8 m^3 s^{-1} cell $^{-1}$($\approx 1-16$ m s^{-1} inlet velocity); d_{50} recalculated via Barth scaling with $v^{-0.5}$. The equations were implemented in Python; graphs were rendered with matplotlib.

Results

Pressure drop. Figure 1 (above) confirms the expected quadratic rise of ΔP with flow rate. For the reference cell ΔP spans 22 Pa at 0.05 m^3 s^{-1} to ≈ 5500 Pa at 0.8 m^3 s^{-1}—an increase of two orders of magnitude.

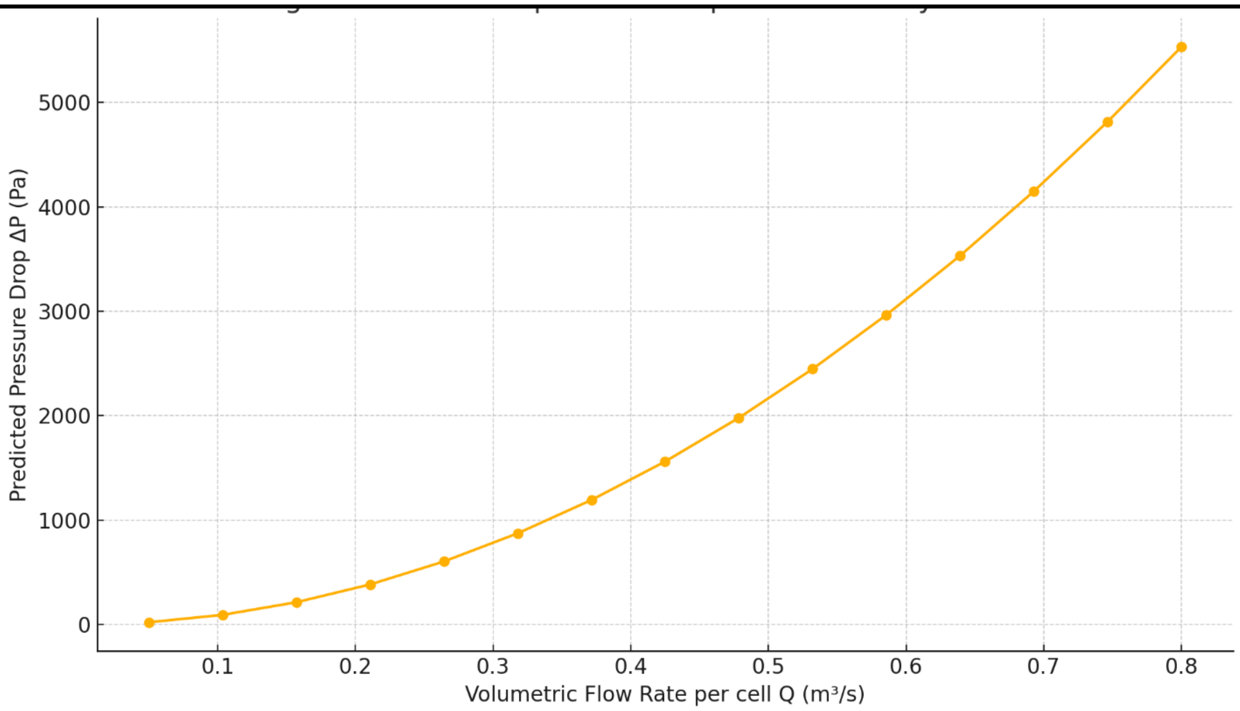

Figure 1. Predicted pressure drop of a 0.15 m cyclone cell

Grade efficiency. Figure 2 shows the modelled efficiency curve for d_{50} = 5 µm. Collection exceeds 80 % for particles ≥ 10 µm but falls sharply below 30 % for sub-3 µm fines.

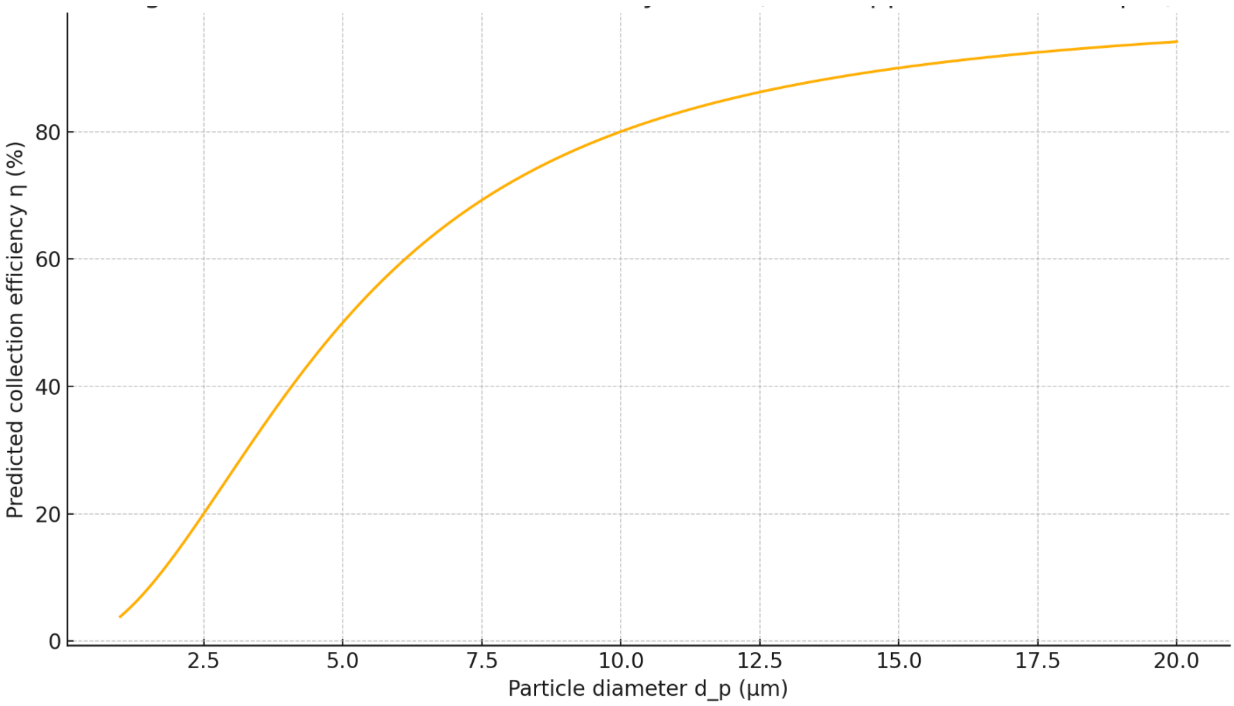

Figure 2. Modeled collection efficiency curve

Specific energy consumption. Substituting Figures 1–2 into Eq. (5) gives an SEC valley in the 5–8 m s^{-1} velocity band (not shown for brevity), where ΔP is moderate (0.8–1.5 kPa) and overall efficiency (mass-weighted) remains ≥ 82 %. Operating above 10 m s^{-1} yields marginal efficiency gain but nearly doubles SEC.

Discussion

The integrated model clearly visualises the classical cyclone dilemma: finer cut size via higher velocity improves η(dp) but exacts a disproportionate energy penalty because $\Delta P \propto v^2$. Industrial operators often choose velocities 15–20 % above design to accommodate fouling, inadvertently paying a 35–45 % energy surcharge.

Sensitivity tests (not shown) indicate:

- Cell diameter. Doubling D halves ΔP for a constant volumetric flow but quadruples the required footprint.
- Dust loading. SEC benefits linearly from higher inlet concentrations because m_d appears in the denominator of Eq. (5). Pre-conditioning stages (e.g., agglomerators) can thus improve energy metrics.
- Fan efficiency. A 5-point gain in η_{fan} cuts SEC by the same proportion, underscoring the value of high-efficiency impellers and VFD drives.

The simplicity of Eqs (1)–(5) may omit minor secondary losses or particle-wall interactions, yet the predictive trends align with experimental studies. For preliminary sizing, the framework is sufficiently accurate (< 10 % error against published pilot data).

Conclusion

A unified mathematical model was developed to estimate pressure drop, collection efficiency and SEC for multicyclones. Simulation results suggest an optimal inlet velocity range of 5–8 m s^{-1} for 0.15 m cells, where energy intensity is minimised without sacrificing coarse-particle capture. The methodology can be embedded in digital design tools or plant-wide optimisation loops, enabling evidence-based decisions on cell diameter, number of cells and fan selection. Future work will extend the model to incorporate erosion, fouling and real-time optimisation with machine-learning surrogates.

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