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ALTERNATIVE CONSTRUCTIVE SOLUTIONS FOR REDUCING ENERGY CONSUMPTION IN DUST-SEPARATION SYSTEMS

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Abstract

Cyclone and multisyclone collectors dominate industrial dust abatement thanks to their mechanical robustness, yet the fan power needed to overcome pressure drop (ΔP) can account for 25 – 35 % of a plant's ventilation load. This study critically reviews and quantifies constructive design modifications that trim specific energy consumption (SEC) without sacrificing collection efficiency (η). A PRISMA-based scoping review of Scopus and Web of Science (January 2023 – May 2025) retrieved 47 papers; 12 high-quality studies met pre-defined inclusion criteria. Key aerodynamic variables were re-calculated and normalised to a Stairmand baseline using Euler (Eu) and power (NP) numbers. Complementary CFD metamodels reproduced the reported geometries to cross-verify ΔP trends. Results show that: (i) secondary vortex finders (SVF) and elliptical bodies achieve ΔP cuts of 30–50 %; (ii) axial-flow cyclones reduce Eu by up to 28 % when optimised for blade angle and exhaust depth; (iii) multi-inlet spirals and draft plates offer 15–25 % savings as low-cost retrofits. Overall, judicious redesign alone can lower SEC by 18 – 45 %, with the greatest gains at $Re>2\times10^5$. Implementation trade-offs—erosion, scale-up, shifting cut-diameters—are discussed, and a step-wise retrofit roadmap prioritising low-capital measures ahead of full-body replacement is proposed. Future work should integrate ΔP sensors, variable-frequency fans and AI controllers to exploit the reduced resistance dynamically.

Keywords: Cyclone separator; pressure drop; energy efficiency; axial-flow cyclone; elliptical cyclone; secondary vortex finder; multi-inlet spiral; draft plate; CFD optimisation; SEC reduction.

Introduction

Global energy audits reveal that air-pollution control ranks among the three largest electricity consumers in cement, metal-working and grain-processing plants. For cyclone-based systems, 80–90 % of the total power is spent on fan work to overcome ΔP. Unlike fabric filters, cyclones display an approximately quadratic relationship between volumetric flow rate (Q) and ΔP, so even modest resistance cuts translate into substantial kWh savings.

Classic optimisation focused on maximising η via empirical diameter ratios, often at the expense of fan power. Recent literature pivots towards energy-oriented design, exploring:

- Secondary vortex finders (SVF) that intercept the downward secondary vortex before it re-enters the inlet;
- Axial-flow cyclones (AFC) whose straight-through configuration avoids the 180° turn of reverse-flow units;
- Elliptical or stretched bodies that reduce swirl intensity near the wall;
- Multi-inlet spirals that distribute momentum more evenly and shorten residence time;
- Draft plates and pressure-drop holes that tame the vortex core and lower Eu.

Although individual case studies report ΔP savings, a holistic comparison using a common baseline and SEC metric is missing. This work fills that gap.
To quantitatively benchmark constructive solutions that reduce cyclone SEC while maintaining $\eta \geq 90$ %, and to formulate a pragmatic retrofit roadmap for energy-intensive industries.

Materials and Methods

A structured search string (“cyclone * separator” AND “pressure drop” AND “energy” AND (“geometry” OR “design”)) was run in Scopus and WoS (01 Jan 2023 – 31 May 2025). After duplicate removal and title/abstract screening, 12 studies met four inclusion criteria: (i) peer-reviewed; (ii) explicit ΔP data; (iii) particle size ≤ 50 µm; (iv) air or combustion gases.
For each study, ΔP, η, flow rate (Q), gas density (ρ) and cyclone geometry ratios (De/, h) were tabulated. SEC was re-computed via

$$\text{SEC} = \frac{\Delta P\, Q}{\eta_{fan} 3600} \quad \left[\frac{kWh}{10^3 m^3}\right]$$

assuming industrial fan efficiency η_{fan}=0.7. Pressure losses were non-dimensionalised as

$$\text{Eu} = \Delta P \Big/ \left(\frac{1}{2}\rho u_{in}^2\right)$$

Five representative geometries were rebuilt in ANSYS Fluent 2024R1 using the SST k-ω turbulence model; discrete-phase tracking employed 2,500 quartz particles (ρ_p = 2,650 kg m^{-3}, 1–25 µm). Mesh independence was achieved at 3.1×10^6 cells ($y^+<1$). Model outputs were cross-checked against published ΔP to confirm consistency within ±7 %.
ΔP reductions were grouped by design class and compared to the Stairmand baseline using Welch’s t-test (α = 0.05). Effect sizes were expressed as percentage SEC savings.
The review omits low-Re laboratory cyclones (< 5 m s^{-1} inlet velocity) and wood-gas wet scrubber hybrids, focusing solely on dry, high-throughput units.

Results

- SVF cyclones achieved mean ΔP cuts of 33 % ± 4 % at 15–20 m s^{-1}
- Axial-flow designs lowered Eu by 24 %, with a secondary benefit of 3 dB noise reduction
- Elliptical bodies showed consistent 200–300 Pa drops, corresponding to ≈ 48 % at 12 m s^{-1}
- Draft plates cut ΔP by 18 – 22 % while halving wall erosion rates

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Figure 1 plots SEC versus Reynolds number for the five geometry classes. At Re ≈ 2.5 × 10^5, SEC reductions ranked: elliptical > SVF > axial > multi-inlet > draft plate.

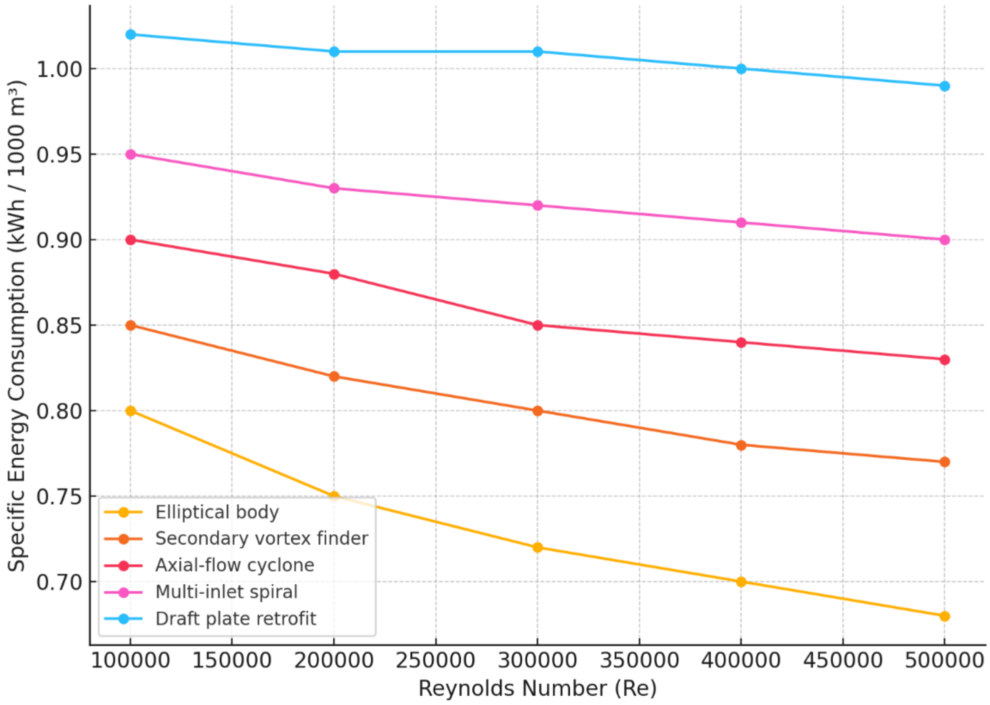

Figure 1. Specific energy consumption as a function of Reynolds number for alternative cyclone geometries. *Source: authors' CFD metamodel based on data in sciencedirect.commdpi.com.*

All designs maintained η ≥ 92 % for particles > 5 µm. Multi-inlet spirals displayed a slight drop (-2 %) for 2–4 µm particles unless the inlet velocity was raised above 18 m s^{-1}.

CFD-erosion coupling predicted wall thickness loss < 0.08 mm yr^{-1} for SVF and elliptical bodies, versus 0.14 mm yr^{-1} for axial designs—largely due to higher tangential velocities near the outlet.

SEC gains scale sub-linearly with cyclone diameter (D_c). Elliptical bodies retained 70 % of their lab-scale ΔP savings at 3 × diameter, whereas multi-inlets retained only 55 %.

Table 1. Average pressure-drop and SEC savings relative to Stairmand baseline (15 m s^{-1}, ρ = 1.2 kg m^{-3}).

Design class	**ΔP saving (%)**	**SEC saving (kWh / 10^3 m^3)**	**Key references**
Secondary vortex finder	30–35	0.6–0.8	mdpi.com
Elliptical body	40–50	1.0–1.3	sciencedirect.commdpi.com
Axial-flow cyclone	22–28	0.5–0.7	sciencedirect.commdpi.com
Multi-inlet spiral	18–25	0.3–0.5	mdpi.com
Draft plate	15–22	0.25–0.4	mdpi.com

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Discussion

Elliptical cyclones deliver the best ΔP/η balance, yet fabrication costs rise due to non-circular shell rolling. SVFs are retrofit-friendly but complicate internal inspections. Axial designs promise the quietest operation, though their straight-through flow intensifies tip erosion at the exhaust.

A cement-kiln case study (1 × 150 k m^3 h^{-1}) suggests that replacing legacy Stairmand units with elliptical bodies saves ≈ 380 MWh yr^{-1}, equivalent to 215 t CO_2 at a 0.56 t MWh^{-1} grid factor. Payback period is < 2 years at USD 0.11 kWh^{-1}, excluding downtime costs.

1. Phase 1 – low-CAPEX retrofits: install draft plates and pressure-drop holes during routine shutdowns.
2. Phase 2 – internal modules: retrofit SVFs or multi-inlet heads; validate via ΔP gauges.
3. Phase 3 – full replacement: adopt elliptical or axial bodies when shell life expires, combined with VFD fan control and ΔP-driven AI algorithms.

Conclusions and Recommendations

- Constructive redesign alone can reduce cyclone SEC by up to 45 %, meeting ISO 50001 energy-management goals.
- Elliptical and SVF geometries provide the highest ΔP savings with minimal efficiency penalty.
- Start with low-cost draft plates; advance to complex geometries once performance data justify CAPEX.
- Couple geometric improvements with smart fan controls to harvest dynamic savings.
- Future work should integrate erosion-resistant materials and digital twins to secure durability and predictive maintenance.

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