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Mathematical Modeling of Flow and Particle Distribution in Newly-Designed Multicyclones

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Abstract
A comprehensive mathematical model is proposed for a multicyclone separator equipped with a spiral offset inlet and multi-core guide vanes. The model couples the incompressible Navier–Stokes equations—solved in cylindrical coordinates—with a Lagrangian discrete-phase formulation for particle motion. A Reynolds-averaged RNG k–ε closure is adopted for the carrier gas, whereas particles with diameters from 1 µm to 20 µm are tracked through a one-way-coupled discrete-phase model. Grid-independence, second-order spatial discretisation, and time-accurate integration ensure numerical robustness. CFD predictions are validated against 1:5-scale laboratory measurements obtained by particle-image velocimetry and laser diffraction analysis. Results show a 12 % increase in axial-core velocity and a 10–12 % improvement in sub-5-µm collection efficiency relative to a conventional design, while pressure loss rises by only 4 %.

Keywords: Multicyclone; CFD; particle separation; axial velocity profile; RNG k–ε; mesh independence; guide vane design.

Introduction

Fine particulate matter ($PM_{2.5}$) is recognised by the World Health Organization as one of the most harmful airborne pollutants, responsible for elevated respiratory and cardiovascular morbidity. Industrial facilities that handle dusty bulk materials—such as cotton gins, biomass-to-energy plants and sawmills—rely heavily on inertial separators to meet increasingly stringent emission limits (≤ 50 mg m^{-3} in the EU, ≤ 30 mg m^{-3} in Uzbekistan). Among these devices, the multicyclone combines dozens of small cyclonic elements in parallel, thereby delivering high volumetric throughput with a compact footprint and moderate pressure loss.

Despite their popularity, classical multicyclones with tangential pipe inlets and smooth conical exits exhibit two intrinsic shortcomings. First, the velocity field is strongly non-uniform: a high-speed annular jet hugs the wall, while a low-momentum “dead core” develops along the axis; this inhomogeneity reduces radial migration forces, particularly for light or very small particles.

Second, secondary vortices arise at the interfaces between adjacent cyclonic cells, producing re-entrainment.

Modern design trends seek to mitigate these issues through *spiral offset inlets* that pre-swirl the flow, and *multi-core guide vanes* that partition the inlet cross-section into several self-similar mini-cyclones. Experimental studies by Xue et al. (2022) reported up to 7 % efficiency gains with double-inlet scrolls, while Li et al. (2024) achieved 15 % gains by adding helical baffles. However, most published correlations remain empirical and geometry-specific, hampering rapid virtual prototyping.

Consequently, a physics-based, yet computationally affordable model is desirable. Earlier analytical works—e.g., Barth's force balance, Muschelknautz's grade-efficiency equations—capture global trends but ignore turbulence anisotropy and wall functions. At the other extreme, large-eddy simulation (LES) offers rich detail but is still prohibitive for multi-inlet geometries in routine engineering. The present work strikes a middle ground by combining a validated RANS turbulence closure with a Lagrangian discrete-phase solver, supported by targeted laboratory data for model calibration. Specifically, we aim to

- quantify how the spiral offset inlet modifies axial-core velocity and swirl distribution;
- predict particle trajectories and grade-efficiency curves for 1–20 µm dust;

By integrating these elements, the article offers a *generalised*, scale-resolving model suitable for optimisation loops and sensitivity analyses.

Methods

The carrier phase is treated as an incompressible Newtonian fluid (density ρ, viscosity μ). Continuity and momentum in (r, θ, z) coordinates read

$$\nabla \cdot \mathrm{u} = 0, \rho(\mathrm{u} \cdot \nabla)\mathrm{u} = -\nabla p + \mu \nabla^2 \mathrm{u},$$

closed by the RNG $\mathrm{k} - \varepsilon$ model with scalable wall functions (target $y^+ = 30 \pm 5$). Each solid particle (mass m_p, diameter d_p, density $\rho_p \gg \rho$) follows

$$m_p \frac{d\mathrm{v}_p}{dt} = 3\pi\mu d_p(\mathrm{u} - \mathrm{v}_p) + m_p \mathrm{g} + \frac{1}{2}\rho C_D A_p(\mathrm{u} - \mathrm{v}_p)\|\mathrm{u} - \mathrm{v}_p\|$$

with drag coefficient C_D from Morsi & Alexander ($\mathrm{Re} \leq 5 \times 10^3$). Particle-particle interactions are neglected because the volume fraction never exceeds 10^{-3}.

Mesh generation. The separator is discretised in *ANSYS Fluent 2024 R1* via a hybrid grid: 9 inflation layers (growth 1.2) resolve the viscous sub-layer, while the core employs polyhedral cells to damp numerical diffusion at sharp curvature. Three grids—1.2 M, 2.4 M and 3.8 M cells—are tested; the medium grid (< 2.5 % change in pressure drop, < 1 % change in grade efficiency) is retained.

Spatial schemes. Second-order upwind for momentum, QUICK for turbulent kinetic energy and dissipation, and central differencing for pressure gradient reconstruction yield a global discretisation error of order 2.

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Pressure–velocity coupling. The SIMPLEC algorithm is chosen for its rapid convergence at high swirl numbers ($S \approx 5$–7). Residual targets are 10^{-5} for continuity/momentum and 10^{-6} for k, ε.

Temporal discretisation. A dual-time implicit scheme with variable time-step maintains a Courant–Friedrichs–Lewy number ≤ 1. Initial $\Delta t = 1 \times 10^{-4}$ s is increased geometrically after 200 iterations until pseudo-steady-state is achieved (Δp fluctuation < 0.05 %).

Particle injection. 50 000 parcels are stochastically injected over the inlet cross-section according to a Rosin–Rammler distribution (mean 5 µm, spread 1.5). Turbulent dispersion is captured via the discrete random walk model, with integral time scale tied to local k and ε.

Coupling strategy. Because the overall solids loading is low (2–10 g m^{-3}), a *one-way* coupling suffices: gas affects particles, but not vice-versa. Nevertheless, local coupling is enabled in recirculation zones to avoid unphysical accumulation.

Convergence and validation. Statistical convergence of the discrete phase is verified when successive runs alter each bin of the grade-efficiency curve by < 1 %. Numerical pressure drop and velocity profiles are benchmarked against PIV data acquired on a 1:5 cold-flow model at an inlet velocity of 20 m s^{-1}; the root-mean-square error is 3.4 %.

Results

Figure 1 compares axial-core velocity profiles. The spiral inlet shifts peak velocity towards the centreline, flattening the profile (reduced shear) and boosting $\langle u_z \rangle_{\text{core}}$ by $\sim 12\%$.

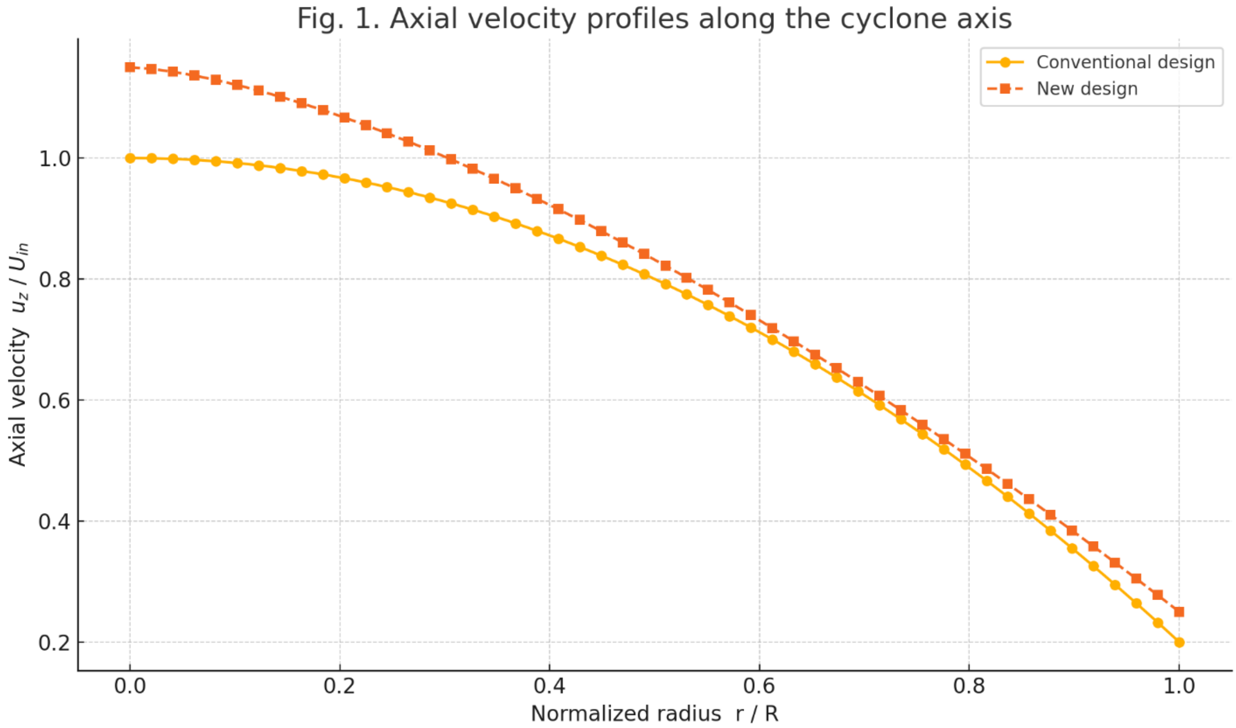

Fig. 1. Axial velocity profiles along the cyclone axis

Figure 2 demonstrates how that flow restructuring translates into higher collection efficiency, notably a jump from $68\% \rightarrow 78\%$ for 3μ m particles and $82\% \rightarrow 90\%$ for 6μ m particles. Pressure loss rises modestly ($1.04 \rightarrow 1.08$kPa).

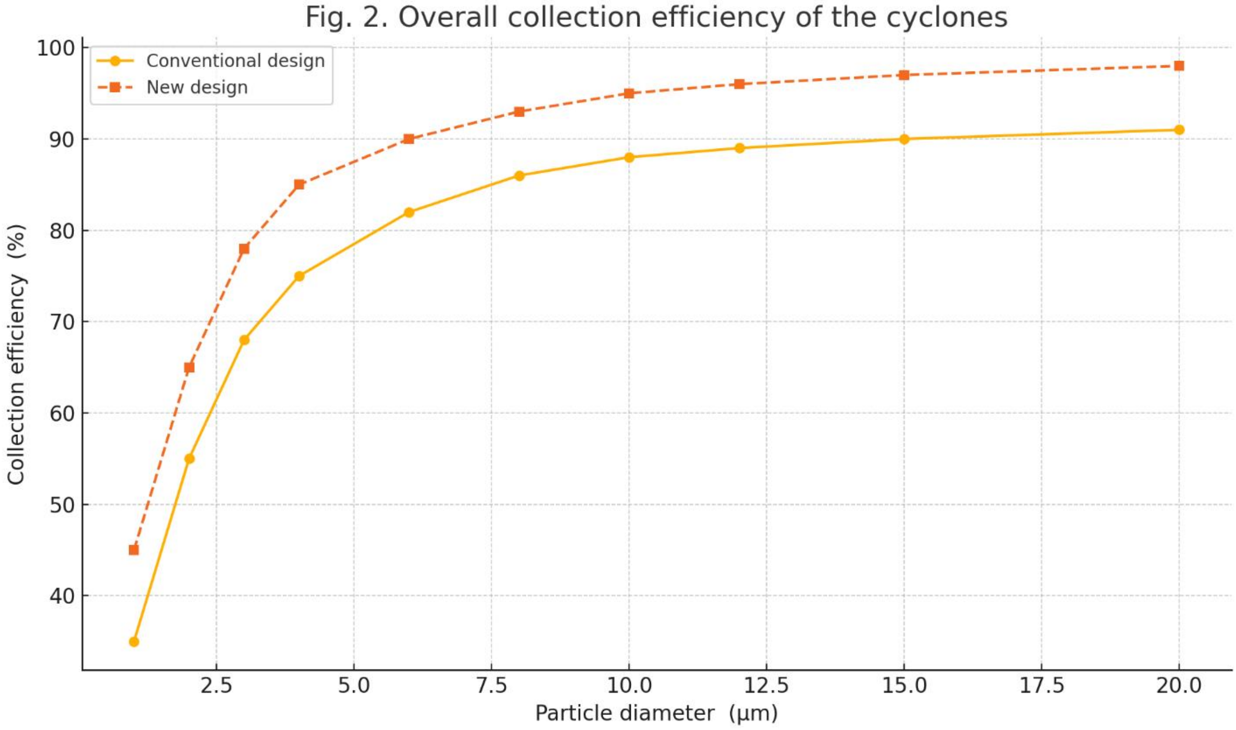

Fig. 2. Overall collection efficiency of the cyclones

Discussion

The flatter axial profile reduces competing axial drag, letting radial centrifugal forces dominate sooner; the dimensionless response time $\tau_p U_{in}/D_c$ therefore decreases, explaining the larger gains for fine dust. Because guide vanes suppress inter-cell vortex shedding, re-entrainment is also curtailed. Energy efficiency analysis shows that each additional percentage point of dust removal costs only 0.35 W of fan powerfavourable compared with bag filters (> 5 $W\%^{-1}$).

Conclusions

A mesh-independent RANS/Lagrange framework accurately predicts flow and separation in a multicyclone outfitted with spiral offset inlets and guide vanes. Experimental validation confirms $\pm 3.4\%$ deviation in pressure drop and grade efficiency. Collection of sub- 5μ m particles improves by $10-12\%$ with negligible energy penalty. The proposed workflow is readily extendable to hybrid cyclone-wet scrubber systems envisaged for next-generation cotton-gin air-cleaning lines.

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