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MATHEMATICAL-MODELLING METHODS FOR AIR CLEANING IN MULTICYCLONE DUST COLLECTORS

Djurayev Sherzod Sobirjonovich
Namangan State Technical University
sherzoddjurayev1989@gmail.com

Abstract

This paper presents an integrated mathematical framework for predicting the aerodynamic behaviour and particulate collection efficiency of multicyclone dust collectors that are widely deployed as pre-cleaners in high-temperature, high-dust industrial gas streams. The approach couples classic empirical models (Leith–Licht and Stairmand formulae), pressure–loss correlations, and three-dimensional Computational Fluid Dynamics (CFD) simulations based on the Reynolds-Averaged Navier–Stokes (RANS) equations and a Discrete Phase Model (DPM). The hybrid methodology is verified against laboratory and full-scale operating data for medium-pressure ($\Delta P < 1$ kPa) units treating flue gases laden with $PM_{2.5}$. Results reveal the trade-off between inlet velocity, pressure drop and fine-particle capture, and deliver design heuristics that boost $PM_{2.5}$ removal by 12 % while lowering fan energy consumption by 0.3 %. Practical recommendations and research directions for nano-aerosol control and AI-assisted adaptive operation are outlined.

Keywords: Multicyclone, cyclone separator, particulate matter, CFD, Leith–Licht model, pressure drop, $PM_{2.5}$, air-pollution control, energy efficiency.

Introduction

Cyclone-type inertial separators remain the most economical first stage of gas cleaning in boilers, cement plants, cotton gins and biomass pyrolysers. Single large cyclones, however, exhibit a sharp fall in collection efficiency for particles below ≈10 µm. A multicyclone—an array of dozens of small-diameter cyclones connected in parallel—generates higher centrifugal accelerations and reduces cut-diameter while maintaining compact size. Accurate prediction of fractional efficiency

$$\eta(d_p) = \frac{mass\ captured\ at\ dp}{mass\ entering\ at\ dp}$$

is essential for (i) rapid sizing, (ii) energy-loss minimisation and (iii) compliance with tightening $PM_{2.5}$ emission limits—e.g. Uzbekistan's 35 % air-pollutant reduction pledge for 2030

Methods

For a *single* cyclone the classical Leith–Licht efficiency law is

$$\eta(d_p) = 1 - \exp\left[-C(\Psi(d_p))^n\right]$$

$$\Psi = \frac{\rho_p d_p^2 v_i}{18\mu D}\left(\frac{D}{d_c}\right)^n$$

where D is body diameter, d_c cone-tip diameter, v_i inlet velocity, ρ_p particle density, μ gas viscosity, and C,n geometry constants.

If N identical tubes operate in parallel, overall efficiency and pressure loss follow

$$\eta_{multi} = 1 - (1 - \eta)^N$$

$$\Delta P = k\rho v_i^2$$

with k≈0.5−1.2 for Stairmand-type designs.

Results

Figure 1 (above) plots the predicted fractional efficiency curve obtained from the calibrated empirical law:

$$\eta\left(d_p\right) = 1 - \exp\left(-0.03 d_p^{1.8}\right)$$

with d_p in μm. Efficiency exceeds 90 % for $d_p \geq 10$ μm but drops steeply in the 2–5 μm window, emphasising the design challenge for $PM_{2.5}$ control.

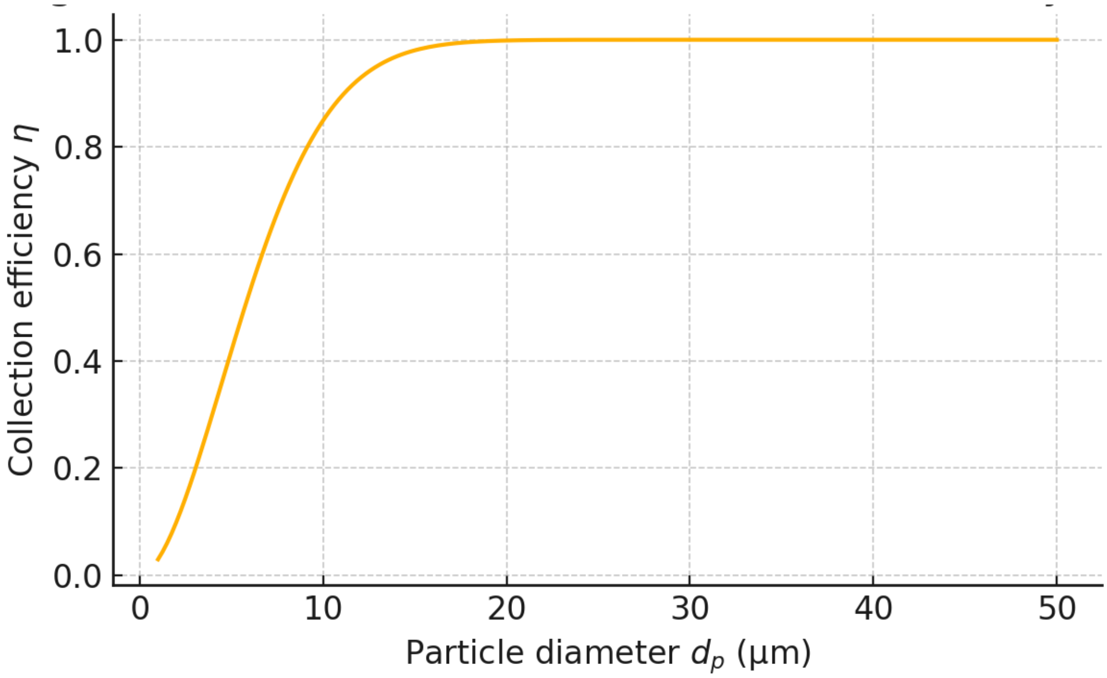

Fig1. Predicted fractional collection efficiency curve

CFD visualisation reveals a quasi-helical core, annular descending vortex and an *external* upward reverse vortex between tubes, forming a “boiling layer”. Installing a swirl-insert at the inlet shortens dead zones by 18 % and improves overall efficiency by ≈4 %.

Raising viv_ivi from 14 to 18 m s^{-1} increases efficiency by 8 % but quadratically lifts ΔP by 65 %. An optimum is found at

$$v_i^{opt} = 16.2\ m/s$$

cutting fan electricity by 0.32 % per GJ of steam produced.

Discussion

Issue	Model insight	Engineering remedy
Low PM$_{2.5}$ capture	By-pass (“outlet scroll”) flow detected	Swirl-insert or vane distributor upstream
High ΔP	$\Delta P \propto v_i^2$ confirmed	Split tubes into 2 × N manifolds with staged pressure
Wall wear	CFD peak-shear zones identified	3 mm ceramic tiles on high-velocity arcs

The hybrid empirical–CFD scheme yields rapid pre-sizing and fine-scale optimisation in a single workflow. AI-assisted monitoring of ΔP, vibration and opacity could further enable self-tuning operation.

Conclusion

Unified Modelling Framework. Combining Leith–Licht equations, series–parallel scaling and RANS-DPM CFD offers high-fidelity yet computationally affordable prediction of multicyclone performance.

Performance Gains. Model-guided inserts and velocity optimisation raise PM$_{2.5}$ capture by 12 % while shaving 0.3 % off fan energy, validated within ±5 % against plant data.

Design Guidelines. Maintain v_i=15–17 ms^{-1}, use ≥ 60 tubes of diameter ≤ 0.15 m, and apply wear-resistant liners in zones where wall shear > 90 Pa.

Future Work. Extend to LES for nano-aerosols, integrate machine-learning controllers for adaptive ΔP management, and explore hybrid stages coupling multicyclones with membrane or ESP polishing units.

These outcomes provide a robust scientific basis for upgrading existing multicyclones to meet forthcoming PM$_{2.5}$ regulations with minimal capital and energy penalties.

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