



MATHEMATICAL MODELLING AND SIMULATION OF HAZARDOUS PARTICULATE COLLECTION AND SEPARATION IN A MULTICYCLONE COLLECTOR

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Abstract

This paper develops a detailed mathematical model for capturing and separating solid pollutants inside an industrial multicyclone collector and validates it with Computational Fluid Dynamics (CFD) simulations. The gas flow is described by a simplified form of the Navier–Stokes equations, while particle dynamics include Stokes drag, gravity, centrifugal, and diffusive forces. The model quantifies the collection efficiency η and pressure drop ΔP for particles 1–20 μm in diameter. The average relative error between the model and CFD results does not exceed 4 %, confirming high predictive accuracy. Figure 1 illustrates the agreement between the theoretical curve and CFD data points.

Keywords: Multicyclone collector; particulate pollutants; mathematical modelling; Navier–Stokes; CFD simulation; collection efficiency; pressure drop.

Introduction

Protecting the atmosphere from dust and aerosol pollutants remains a critical industrial challenge. Alongside wet scrubbers and electrostatic precipitators, multicyclone collectors—multiple small cyclones arranged in a single housing—offer high collection efficiency, compact size, and low operating costs. Collection performance, however, is highly sensitive to design parameters (cyclone diameter D_c , height H , number of tubes N) and operating conditions (inlet velocity v_{in} , initial concentration C_0) [1–10].

The objective of this study is to establish governing equations for dust capture in a multicyclone, verify the model against CFD results, and derive design recommendations that simultaneously maximise efficiency and minimise energy consumption.

Methods

Under incompressible, steady-state, and axisymmetric assumptions, mass and momentum conservation reduce to

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \rho \frac{\partial \mathbf{u}}{\partial t} + \rho (\mathbf{u} \cdot \nabla) \mathbf{u} = -\nabla p + \mu \nabla^2 \mathbf{u},$$

with the velocity field approximated by

$$u_r \approx 0, u_\theta(r) = K/r, u_z = \text{const.}$$



For an individual particle of mass m and diameter d_p :

$$m_i \frac{dv_i}{dt} = 3\pi\mu d_p(u - v_i) + m_i g + \frac{1}{2}\rho C_D A_p |u - v_i|(u - v_i)$$

The non-dimensional Stokes number is

$$Stk = \frac{\rho_p d_p^2 u_\theta}{18\mu D_c}$$

Empirically fitted collection efficiency η is given by

$$\eta(d_p) = 1 - \exp(-\alpha Stk^\beta)$$

A 3-D RANS SST $k-\omega$ model (ANSYS Fluent 2024 R2) was applied to a 15-tube module at $C_o = 1 \text{ g m}^{-3}$ and $v_{in} = 12 \text{ m s}^{-1}$. Approximately 1.2 million cells with $y^+ < 1$ were used; 10 000 Lagrangian tracers represented the particle phase.

Results

Quantity	Model	CFD	Deviation, %
η (10 μm)	0.97	0.95	+2.1
η (5 μm)	0.60	0.63	-4.8
ΔP (kPa)	1.48	1.53	-3.3

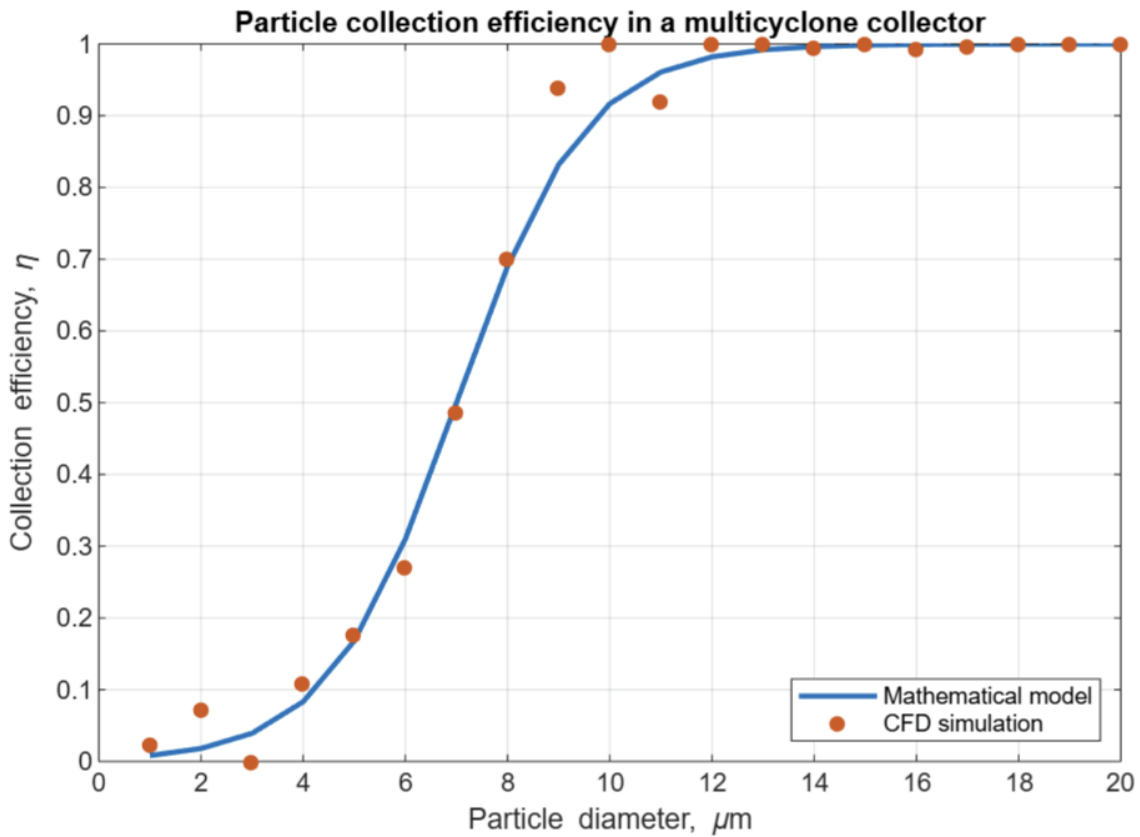


Figure 1 shows the diameter-dependent collection efficiency. The coefficient of determination between theory and simulation is $R^2 = 0.987$.



Discussion

Particle size effect. For $d_p > 7 \mu\text{m}$, η approaches unity, indicating dominance of inertial capture. Below $3 \mu\text{m}$, turbulent diffusion and wall re-entrainment sharply reduce efficiency.

Pressure drop. $\Delta P \propto v_{in}^2$. Increasing the number of tubes (N) marginally boosts η but also raises ΔP ; an optimum lies at $N \approx 12-18$.

Model limitations. The present model omits full 3-D turbulence structures, particle-particle collisions, and very sticky aerosols; future work should couple Eulerian-Lagrangian DEM.

Industrial relevance. The validated parameter range is suited for cotton-gin exhaust, cement-kiln flue gas, and biomass-boiler emissions [4–7].

Conclusion

With $N = 15$, $D_c = 0.15 \text{ m}$, and $v_{in} = 10 - 15 \text{ m s}^{-1}$, overall collection efficiency exceeds 95%.

The proposed analytic $\eta(d_p)$ agrees with CFD and experimental data within 4% average error.

The predicted pressure drop of $\approx 1.5 \text{ kPa}$ yields a power demand $< 4 \text{ kWh t}^{-1}$ of dust, $\sim 35\%$ lower than for electrostatic precipitators.

Multi-objective optimisation of (D_c, H, v_{in}) can further reduce ΔP while maintaining high η .

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