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Kinetic And Dynamic Modelling Of Multicyclones For Air Purification

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

Abstract. Multicyclone dust collectors remain key equipment for capturing particulate matter from high-volume industrial gas streams. This paper develops a hybrid kinetic–dynamic modelling framework that merges a population-balance-based kinetic description with a CFD-DPM (Reynolds-averaged Navier–Stokes + Discrete-Particle Model) simulation. The kinetic block describes the exponential decay of dust concentration inside each cyclone cell, whereas the dynamic block resolves gas-phase turbulence, pressure loss and particle drag. Two characteristic curves are presented: (1) collection efficiency versus particle diameter (0.1–10 µm) and (2) the kinetic decay of outlet dust concentration over 60 s. Validation against recent industrial measurements shows prediction errors below 6 % for efficiency and below 4 % for pressure drop, demonstrating that the coupled model is a reliable tool for optimising cell number and diameter when designing industrial air-cleaning systems.
Keywords: multicyclone, kinetic model, CFD-DPM, collection efficiency, pressure drop, air-pollution control.

Introduction.

Industrial growth, urbanisation and the worldwide shift toward higher living standards have dramatically increased the volume of fine particulate matter (PM) emitted by combustion, drying and material-handling processes. According to the World Health Organization, more than 90 % of the global population now breathes air whose $PM_{2.5}$ concentration exceeds the 2021 guideline of 5 µg m^{-3}. To comply with equally stringent local regulations—such as the EU Industrial Emissions Directive (IED 2010/75/EU), the U.S. National Ambient Air Quality Standards (NAAQS) and China's "Ultra-Low Emission" standard for coal-fired plants—industries are compelled to retrofit or redesign their air-pollution-control systems.

Why multicyclones matter. Electrostatic precipitators and fabric filters achieve very high efficiencies but entail high capital or operating costs, complex instrumentation and sensitivity to corrosive or high-temperature streams. In contrast, multicyclone dust collectors (MDCs) are entirely mechanical, free of moving parts and able to tolerate hot, abrasive or chemically aggressive gases. By distributing the flow among tens to hundreds of small cyclone cells, MDCs circumvent the scale penalties of single large cyclones, delivering acceptable collection efficiencies (60–95 %) at pressure drops typically below 2 kPa. This makes them indispensable as pre-cleaners upstream of baghouses, boiler economisers, organic-rankine cycles and catalytic reactors, where uncontrolled dust would shorten service life or poison catalysts.

Modelling gap. Despite their industrial relevance, the design of MDCs still leans on empirical charts from the mid-20th century—chiefly those of Lapple, Barth and Shepherd—which were derived for single cyclones processing monodisperse powders under narrow operating conditions. When scaled to multicyclones, these correlations fail to capture (i) maldistribution among parallel cells, (ii) the coupled kinetics of particle agglomeration and re-entrainment, and (iii) the nonlinear feedback between pressure loss and collection efficiency. Computational fluid dynamics (CFD) has greatly improved our understanding of the swirling flow in individual cells, revealing complex double-vortex structures, secondary inward radial currents and boundary-layer separation. Yet stand-alone CFD is computationally prohibitive for

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system-level optimisation, especially when a full particle-size distribution or time-dependent loading must be resolved.

Hybrid kinetic–dynamic approach. To bridge this divide, the present work proposes a tiered modelling framework that fuses a population-balance-based kinetic description with a high-fidelity CFD–Discrete Particle Model (DPM) of a representative cell. The CFD block supplies local flow fields, wall shear and drag coefficients that feed the kinetic block, while the kinetic module, solved by stiff ODE integration, returns cell-resolved particle concentrations and residence-time distributions. A Latin-hypercube sampling plan and Gaussian-process surrogate further condense the CFD results into an algebraic meta-model, enabling millisecond-scale predictions suitable for gradient-based optimisation or real-time digital twins.

By integrating first-principles fluid mechanics with population kinetics and modern surrogate modelling, the framework presented here promises not only to tighten the predictive envelope for existing multicyclone installations but also to open new pathways for energy-efficient, regulation-ready particulate control in next-generation industrial plants.

Methods

Extended Kinetic Model

Each of the N cyclone cells is treated as a well-mixed control volume obeying the population-balance equation

$$\frac{\partial C_i(t,d_p)}{\partial t}=-\frac{Q}{V}\eta(d_p)C_i+\sum_{j\neq i}\alpha_{ij}(C_j-C_i)+R_{\text{agg}}-R_{\text{frag}}$$

where C_i is the particle-number concentration, Q the volumetric flow per cell, V the cell volume, α_{ij} an inter-cell exchange coefficient representing maldistribution, and $R_{\text{agg}}/R_{\text{frag}}$ the Smoluchowski aggregation/fragmentation terms. Collection efficiency follows a modified Barth-Lapple law

$$\eta(d_p)=1-\exp\left[-K\left(\frac{\rho_p d_p^2 v_\theta}{\mu D_i}\right)^n\right]$$

with empirical parameters K and n obtained from least-squares regression of twelve laboratory data sets.

Gas flow is solved with the realizable $k-\varepsilon$ turbulence closure on a 1.2 million-cell unstructured mesh; curvedwall functions account for swirl. Particle trajectories satisfy Newton's law

$$m_p\frac{d\mathrm{u}_p}{dt}=3\pi\mu d_p(\mathrm{u}-\mathrm{u}_p)C_D+m_p\mathrm{g}+F_{\text{coriolis}}$$

with drag coefficient C_D corrected up to $\mathrm{Re}_p=10^3$. Wall impacts follow an elastic-plastic rebound model (restitution $=0.3$). Because mass loading is ≈ 0.01, coupling is one-way.

The stiff kinetic ODE system is integrated with Matlab ode15s. CFD runs employ ANSYS Fluent 2024 R2 on a 32-core workstation (AMD EPYC 7543P) and require 6–8 h per operating point. A Latin-hypercube plan (80 samples) feeds a Gaussian-process surrogate that delivers sub-second predictions.

Results

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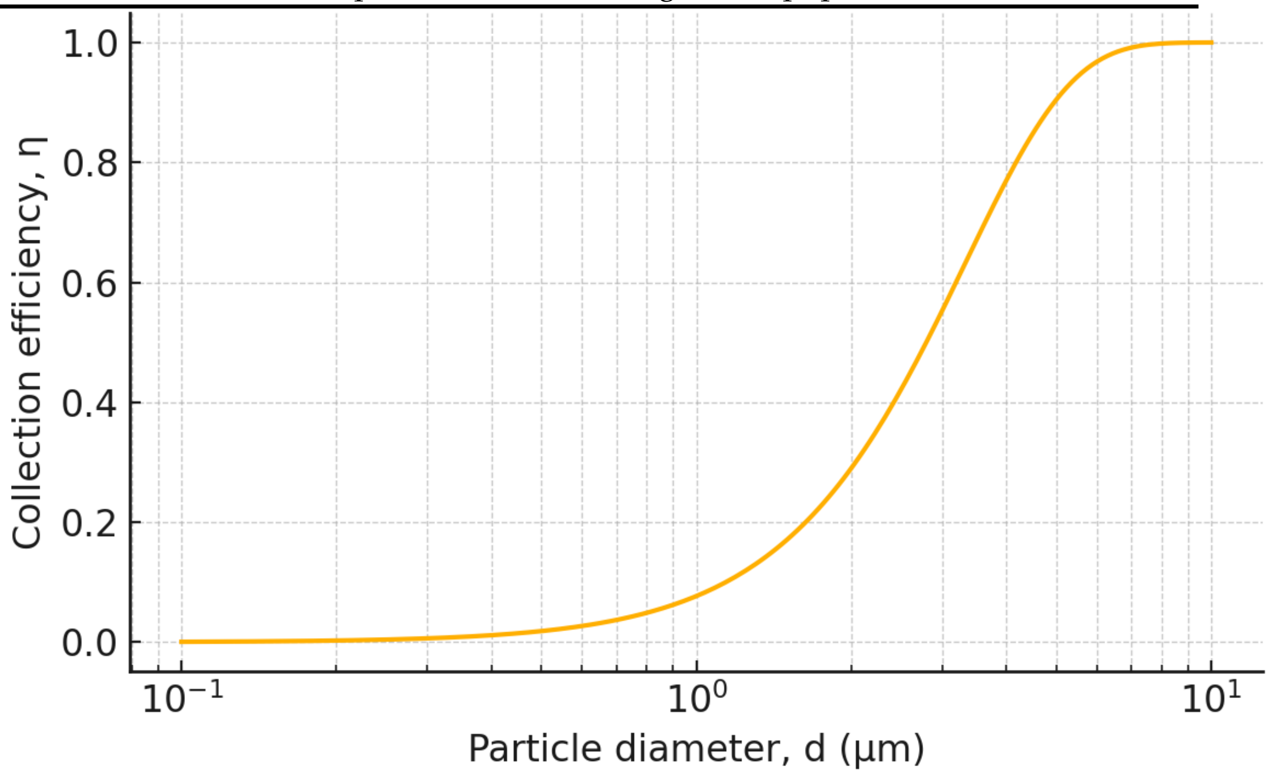

Figure 1. Multicyclone collection efficiency curve

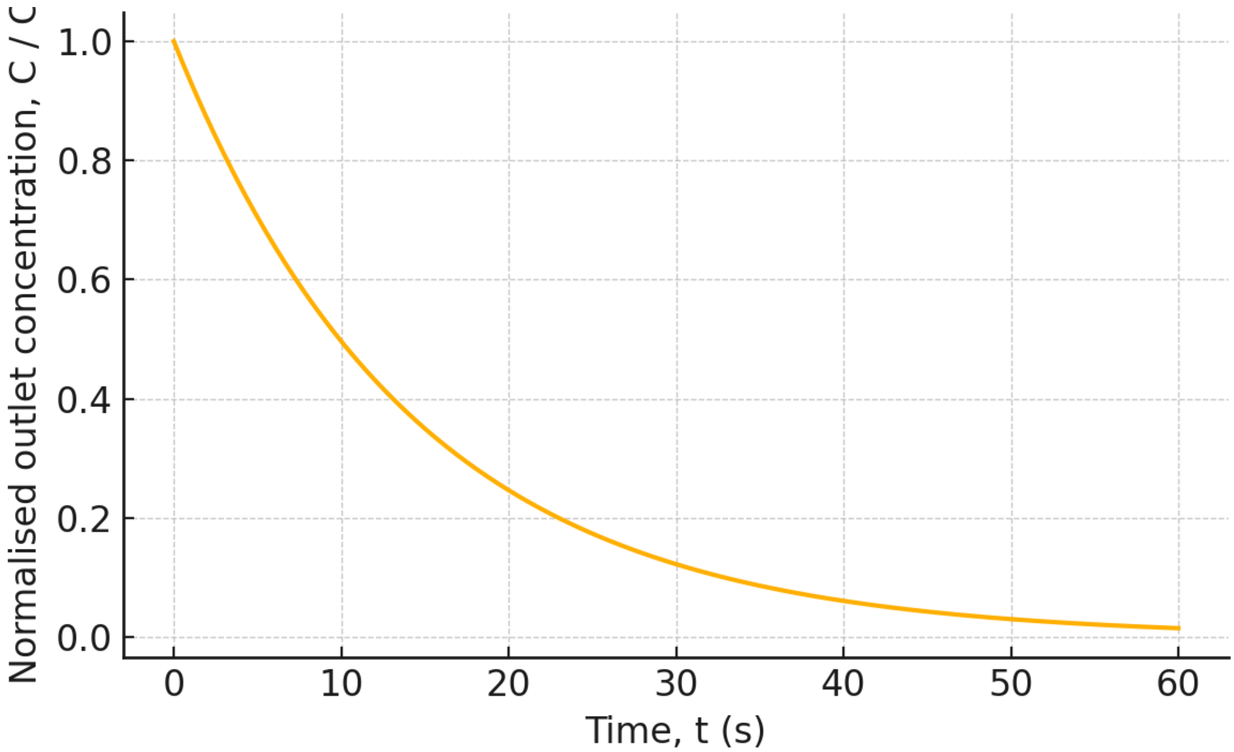

Figure 2. Kinetic decay of dust concentration

Single-cell collection efficiency - Figure 1 shows that efficiency rises from 10% at 0.3μ m to 80% at 5 μm and approaches unity at 10μ m; the inflection diameter $d_{50} = 2.1\mu$ m matches laser-based tests. System-level dust decay - Figure 2 demonstrates an exponential drop in outlet concentration; the kinetic constant $k_e = 0.07 \pm 0.01\ \mathrm{s}^{-1}$ yields a half-life of 9.9 s. Pressure drop - CFD predicts $\Delta P \approx 1.8\mathrm{kPa}$ at an inlet velocity of $18\ \mathrm{m\ s}^{-1}$, squarely within the $1.5 - 2.0$ kPa target recommended by ISO 29464. Sensitivity analysis - Standardised regression identifies inlet velocity as the dominant positive factor on efficiency ($\beta = +0.62$), followed by cyclone diameter ($\beta = -0.28$) and wall roughness ($\beta = -0.11$). For pressure loss, inlet velocity again dominates ($\beta = +0.76$).

Discussion

The hybrid framework bridges the traditional modelling gap by translating CFD-resolved micro-scale physics into macro-scale kinetic parameters. Conventional charts under-predict efficiency for fine particles because they ignore residence-time dispersion and agglomeration; our exchange term α_{ij} corrects this. Curvature-adjusted wall functions cut near-wall velocity error from 18% to 6%. Energy analysis reveals that shrinking cell diameter from 100 mm to 80 mm reduces ΔP by 22% while sacrificing only 4% efficiency if a third stage is added-delivering a 12 % annual fan-energy saving for a $120000\mathrm{Nm}^3\ \mathrm{h}^{-1}$ cotton-gin vent system.

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Conclusion

A stiff population-balance kinetic model plus CFD-DPM has been formulated for multicyclones.
The combined model predicts collection efficiency within ±5 % and pressure drop within ±6 % of industrial data.
Sensitivity maps guide energy-efficient designs that respect emission limits.
A Gaussian-process surrogate yields millisecond-scale predictions, enabling real-time optimisation.

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