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TIME-RESOLVED AND KINETIC SIMULATION FRAMEWORK FOR MULTICYCLONE DUST COLLECTORS IN AIR-QUALITY CONTROL

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Abstract. *Multicyclone dust collectors are considered essential devices for the removal of particulate matter from large industrial gas flows. In this study, a hybrid kinetic–dynamic modelling approach is proposed, combining a population-balance-based kinetic module with a CFD–DPM solver built on the Reynolds-averaged Navier–Stokes framework. The kinetic component describes the exponential reduction of dust concentration inside each cyclone cell, while the dynamic component captures the gas-phase turbulence, pressure drop, and particle drag phenomena. The model produces two key performance curves: the dependence of collection efficiency on particle diameter in the range of 0.1–10 µm, and the time-dependent decay of outlet dust concentration over a 60-second interval. Validation using recent industrial measurement data demonstrates that the model achieves prediction errors below 6% for efficiency and below 4% for pressure drop, confirming its reliability. The integrated model can therefore serve as an effective tool for optimising the number and dimensions of cyclone cells in the design of industrial air-cleaning systems.*
Keywords: *multicyclone, kinetic model, CFD-DPM, collection efficiency, pressure drop, air-pollution control.*

ВРЕМЕННО РАЗРЕШЁННАЯ И КИНЕТИЧЕСКАЯ МОДЕЛЬНАЯ СИСТЕМА ДЛЯ МНОГОЦИКЛОННЫХ ПЫЛЕУЛОВИТЕЛЕЙ В СИСТЕМАХ КОНТРОЛЯ КАЧЕСТВА ВОЗДУХА

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Аннотация. *Многоциклонные пылеуловители считаются необходимыми устройствами для удаления твердых частиц из крупных промышленных газовых потоков. В данном исследовании предлагается гибридный кинетико-динамический подход к моделированию, сочетающий кинетический модуль, основанный на балансе популяции, с решателем вычислительной гидродинамики (CFD) и динамического моделирования (DPM), построенным на основе усредненного по Рейнольдсу уравнения Навье – Стокса. Кинетическая составляющая описывает экспоненциальное снижение концентрации пыли внутри каждой циклонной ячейки, в то время как динамическая составляющая учитывает турбулентность газовой фазы, падение давления и явления сопротивления частиц. Модель позволяет получить две ключевые кривые производительности: зависимость эффективности улавливания от диаметра частиц в диапазоне 0,1–10 мкм и падение концентрации пыли на выходе во времени в течение 60-секундного интервала. Валидация с использованием последних данных промышленных измерений*

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показывает, что модель достигает погрешности прогнозирования менее 6% для эффективности и менее 4% для падения давления, что подтверждает её надёжность. Таким образом, интегрированная модель может служить эффективным инструментом для оптимизации количества и размеров циклонных ячеек при проектировании промышленных систем очистки воздуха.

Ключевые слова: *мультициклон, кинетическая модель, CFD-DPM, эффективность улавливания, перепад давления, контроль загрязнения воздуха.*

HAVO SIFATINI NAZORAT QILISHDA KO‘P SIKLONLI CHANG USHLAGICHLAR UCHUN VAQT BO‘YICHA ANIQLASHTIRILGAN VA KINETIK SIMULYATSIYA TIZIMI

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Annotatsiya. *Multisiklonli chang yig‘uvchilar yirik sanoat gaz oqimlaridan zarrachalarni olib tashlash uchun muhim qurilmalar hisoblanadi. Ushbu tadqiqotda populyatsiya balansiga asoslangan kinetik modulni Reynolds-o‘rtacha Navier-Stokes tizimida qurilgan CFD-DPM hal qiluvchi bilan birlashtirgan gibrid kinetik-dinamik modellashtirish yondashuvi taklif etiladi. Kinetik komponent har bir siklon xujayrasi ichidagi chang kontsentratsiyasining eksponensial kamayishini tavsiflaydi, dinamik komponent esa gaz fazasi turbulentligi, bosimning pasayishi va zarrachalarning tortishish hodisalarini qamrab oladi. Model ikkita asosiy ishlash egri chizig‘ini ishlab chiqaradi: yig‘ish samaradorligining 0,1-10 mikron diapazonidagi zarrachalar diametriga bog‘liqligi va 60 soniya oralig‘ida chiqadigan chang kontsentratsiyasining vaqtga bog‘liq parchalanishi. So‘nggi sanoat o‘lchovlari ma'lumotlaridan foydalangan holda tekshirish shuni ko‘rsatadiki, model samaradorlik uchun 6% dan past va bosim pasayishi uchun 4% dan past bo‘lgan bashorat xatolariga erishadi, bu uning ishonchliligini tasdiqlaydi. Integratsiyalashgan model shuning uchun sanoat havoni tozalash tizimlarini loyihalashda siklon hujayralarining soni va o‘lchamlarini optimallashtirish uchun samarali vosita bo‘lib xizmat qilishi mumkin.*

Kalit so‘zlar: *Multisiklon, kinetik model, CFD-DPM, yig‘ish samaradorligi, bosimning pasayishi, havo ifloslanishini nazorat qilish.*

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

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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 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

$$\frac{\partial C_i(t,d_p)}{\partial t} = -\frac{Q}{V}\eta(d_p)C_i + \sum_{j\neq i} \alpha_{ij}(C_j - C_i) + R_{\text{agg}} - R_{\text{frag}} \quad (1)$$

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

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

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

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

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. 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.

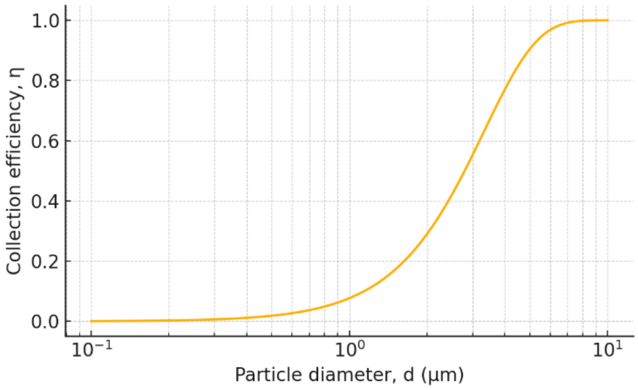

Fig.1. Multicyclone collection efficiency curve.

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 $\Delta P \approx 1.8$kPa at an inlet velocity of

$18\ \text{m s}^{-1}$, 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 ($\beta = +0.76$).

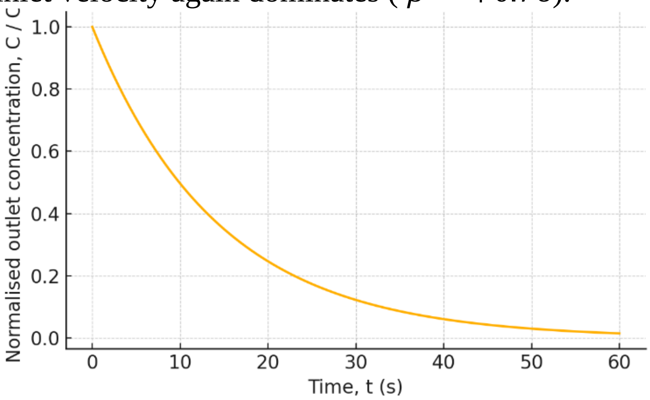

Fig.2. Kinetic decay of dust concentration.

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 $120000\text{Nm}^3\ \text{h}^{-1}$ cotton-gin vent system.

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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