



Review Article

Microcyclones, Fundamentals, and Applications: A Review

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ABSTRACT

Microcyclones are fluid separation devices that utilize centrifugal forces generated by tangential fluid injection to remove fine particles from gas or liquid streams. This review synthesizes recent advances in microcyclone fundamentals, performance enhancement strategies, and applications. Electrostatic field integration improved collection efficiency from 88.3% to 96.2% for fly ash and from 46.2% to 99.1% for submicron pollen. Stereolithographic 3D printing enabled minimum channel dimensions of 0.75 mm and cut diameters as low as 0.05 μm at 5 L/min with fabrication costs of approximately \$10 per device. Optimized geometries achieved classification precision of 95.94% and efficiency of 72.89% for 25 μm silica particles. Miniature hydrocyclones demonstrated 99.98% oil-water separation efficiency at 1 L/min, while virtual cyclones reduced cut-off diameters by 38.6% with only 7.3% pressure drop increase. Openable cyclone designs achieved sampling yields 1.3 times higher than unopenable alternatives. Persistent challenges include particle entrainment, clogging susceptibility, and non-linear pressure drop versus cut-size relationships. Future directions focus on device integration, refined turbulence models, and emerging applications in aerovirology and personalized air monitoring.

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1. Introduction

Using centrifugal forces to extract particulate debris from gas or liquid streams, macrocyclones and microcyclones are fluid separation devices that work on the same basic concept but at very different sizes [1-5]. Denser particles are thrown outward against the wall and spiral down to a collection outlet by the high-speed vortex created when the fluid is introduced tangentially into a cylindrical or conical chamber. Meanwhile, the cleaned fluid reverses direction and leaves through a central top vortex finder. In heavy industries like cement production, sawmills, and power plants, macrocyclones (usually larger than one meter in diameter) are used as main separators to cheaply remove huge amounts of coarse dust from flue gases or process air with a reasonable level of efficiency. Microcyclones, on the other hand, are used in precision applications

that require high separation efficiency for fine particles (1–10 microns), such as biomedical aerosol monitoring, microfluidic cell sorting, and fine chemical powder classification. However, because of their small size, they are susceptible to clogging and pressure drop, necessitating arrays of multiple parallel units to achieve practical flow rates. Therefore, even though both devices have the same cyclonic principles, the microcyclone allows for high-resolution particle control in smaller systems, while the macrocyclone prioritizes reliable, low-maintenance bulk separation [6].

While the fundamental centrifugal principle is shared, the transition from the macro- to the microscale introduces unique challenges and opportunities, including higher pressure drops, increased susceptibility to clogging, and a greater

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influence of turbulent dispersion and boundary-layer effects on collection efficiency [9, 18]. Consequently, substantial research efforts have been directed toward enhancing the performance of microcyclones through electrostatic field integration, the application of high-resolution additive manufacturing for complex geometry optimization, and the development of sophisticated numerical models to predict particle behavior under diverse flow regimes [8, 10, 13]. This review aims to provide a comprehensive overview of the state of the art in microcyclone technology. It begins by outlining the fundamental principles governing cyclone separation. Subsequently, it synthesizes recent advances across several key areas, including electrostatic enhancement, 3D-printed designs, miniature hydrocyclones for liquid-liquid separation, virtual cyclones for particle concentration, and boundary-layer corrected efficiency models. The review further explores diverse applications, from atmospheric bioaerosol sampling to oceanographic studies, before concluding with a critical discussion of current challenges, research gaps, and promising future directions for the field.

2. Fundamentals

2.1. Operating Principles and Classification

Cyclones are static separation devices that impart a rotational flow pattern on the fluid passing through them, generating a centrifugal force field that facilitates the separation of particles from the continuous phase [7]. The fundamental design can be classified into two categories: counter-current cyclones, characterized by reversed flow within the separation device, and unidirectional cyclones, which offer advantages including space-saving design and reduced pressure drop due to the absence of flow reversal [7]. The separation mechanism relies on the balance between centrifugal forces propelling particles toward the wall and drag forces from the carrier fluid, with particles possessing sufficient inertia migrating to the cyclone wall for collection [8].

The flow field within a cyclone comprises a complex three-dimensional structure consisting of an outer downward vortex near the wall and an inner upward vortex at the center [9]. Under the combined action of shear forces, centrifugal forces, and gravity, particles of different sizes exhibit distinct migration velocities and movement trajectories. Coarse particles rapidly move toward the side wall and enter the downward outer swirl, while fine particles move toward the center and enter the upward inner

swirl, resulting in a stratified particle distribution [9].

2.2. Dimensionless Performance Parameters

Cyclone performance is characterized by several dimensionless parameters. The Euler number $Eu = \Delta p / (0.5\rho u^2)$ describes the pressure drop across the cyclone relative to the dynamic pressure [10]. The cut-size (ψ_{50}) represents the dimensionless particle diameter at which 50% collection efficiency is achieved, while the slope of the transformed penetration curve (k_1) characterizes the sharpness of separation [10]. The Stokes number, defined as $St = (\rho_p - \rho)d_p^2 U_{in} / (18\mu D_c)$, quantifies the particle's tendency to follow fluid streamlines versus being separated centrifugally [11].

The Reynolds number in the aspiration nozzle ($Re_{as} = u_{as} d_{as} \rho / \mu$) and at the outlet (Re_{out}) determines the flow regime, with studies identifying three main flow regimes, laminar, transient, and turbulent, and four sub-regimes based on cyclone performance characteristics [10]. A one-term power series model has been proposed to describe the dependence of Euler number, cut-size, and slope coefficient on Reynolds number within each regime [10].

2.3. Modeling Approaches

Computational fluid dynamics has emerged as a powerful tool for cyclone analysis, with the Reynolds Stress Model proving superior to $\kappa - \epsilon$ models for simulating anisotropic swirling flows [8]. Large Eddy Simulation offers even greater accuracy for capturing vortex dynamics and turbulence effects, though at substantially higher computational cost [11]. The Lagrangian Discrete Phase Model is commonly employed for particle tracking, accounting for drag forces, gravity, and turbulent dispersion through stochastic methods such as the Discrete Random Walk model [12].

3. Advance in the Field

3.1. Electrostatic Enhancement

The integration of electrostatic fields into microcyclones represents a significant advancement for fine particle collection. Mofarrah et al. [13] demonstrated that applying a high-voltage electric field to a micro-cyclone improved collection efficiency from 88.3% to 96.2% for fly ash at a flow rate of 60 L/min, with the cut-size diameter decreasing to 1.98 μm (Fig. 1). The electrostatic force preferentially aids the separation of smaller particles, with efficiency for

6 μm pollen particles increasing from 46.2% to 99.1% when voltage was applied, while 10 μm particles achieved 96% efficiency under optimized conditions [14].

The charging mechanism involves field charging and diffusion charging within a pre-charger device upstream of the cyclone [13]. The maximum particle charge, calculated using the Pauthenier equation, depends on the electric field strength and the dielectric properties of the particles. For pollen particles, optimal performance was achieved at lower inlet velocities with higher static voltages, as this combination increases residence time within the electric field [14].

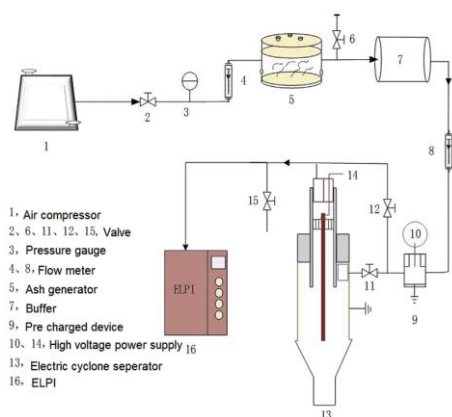


Fig. 1. Setup of an electro-cyclone [13].

3.2. Three-Dimensional Printing and Geometrical Optimization

Additive manufacturing has revolutionized microcyclone fabrication by enabling complex geometries unattainable through conventional subtractive methods. Bhattacharya et al. [15] fabricated microcyclones using stereolithographic 3D printing with minimum channel dimensions of 0.75 mm, achieving cut diameters as low as 0.05 μm at flow rates up to 5 L/min with cut sharpness below 1.2 (Fig. 2). The fabrication cost was estimated at approximately \$10 per device, compared to over \$1000 for commercially available machined cyclones, demonstrating significant economic advantages. The incorporation of helical grooves within the vortex finder wall was shown to reduce cut-size diameters by more than 50% compared to smooth-walled designs, as the grooves encourage greater rotational flow without significantly degrading the friction factor. Zhang et al. [9] systematically investigated the effects of operating parameters, cyclone structural characteristics, and particle properties on classification precision, achieving classification precision of 95.94% and efficiency of 72.89% for

25 μm SiO_2 particles under optimal conditions (inlet flow rate 22.5 L/min, split ratio 9:1, cone angle 15°).

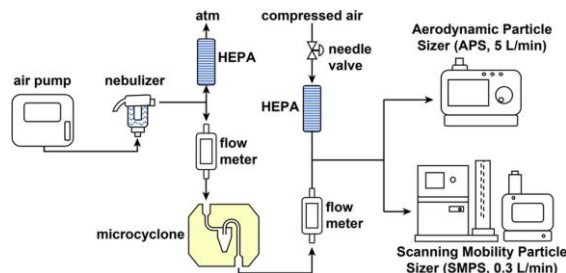


Fig. 2. Experimental setup of a microcyclone [15].

3.3. Miniature Hydrocyclones for Liquid-Liquid Separation

The application of mini-hydrocyclones for oil-water separation under ultra-low inlet flow rates has been extensively studied. Cai [16] demonstrated that a 7 mm diameter mini-hydrocyclone (Fig. 3) achieved a separation efficiency of 99.98% for 300 μm oil droplets at an inlet flow rate of 1 L/min, a split ratio of 30%, and an oil phase volume fraction of 2%. For 100 μm droplets, efficiency remained above 84%, verifying the adaptability of small-diameter hydrocyclones to tiny droplet sizes. The analysis of velocity distributions revealed that tangential velocity, the dominant component influencing separation, increases with inlet flow rate, generating stronger centrifugal forces that promote droplet migration toward the axis [16]. The separation cut-size was determined to be below 50 μm , with efficiency exceeding 95% for oil droplets larger than 150 μm .

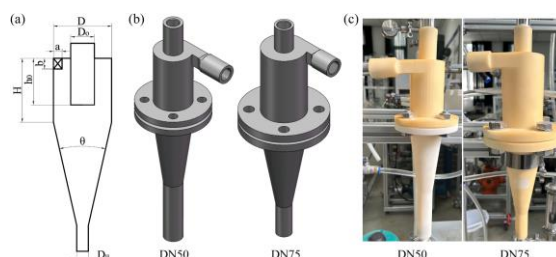


Fig. 3. Geometry of cyclone models and their 3D printed [16].

3.4. Virtual Cyclones and Particle Concentration

The virtual cyclone concept, incorporating a minor flow extracted from the dust outlet, has been developed for particle concentration applications. Kim et al. [17] reported that at a fixed inflow of 80 L/min, increasing the minor flow ratio to 0.2 reduced the 50% cut-off diameter by 38.6% with only a 7.3% increase in pressure drop. The concentration factor exhibited a reversed U-shaped curve with a

maximum in the region of the cut-off diameter, indicating that virtual cyclones can concentrate particles within a specific size range near the 50% cut-off diameter.

For influenza virus aerosol collection, the 1× microcyclone design achieved 85% recovery efficiency through a low-volume elution process requiring only 1.5 mL of buffer, representing a significant advantage over conventional filter-based methods that typically require large dilution volumes [15].

3.5. Boundary Layer Effects and Collection Efficiency Modeling

The velocity boundary layer formed on the collecting wall surface plays a critical role as a barrier for particle deposition due to the sharply decreasing centrifugal force near the wall. Kim and Lee [18] developed a collection efficiency model dividing the cyclone into core and boundary layer regions, with turbulent diffusion considered in the core and particle motion analyzed within the boundary layer. The model successfully predicted efficiency curves for low flowrate conditions (cut-sizes in the micron range) and high flowrate conditions (cut-sizes in the submicron range), with an empirical constant C_y of 100 for low flowrates and 8 for high flowrates [18].

The residual migration velocity, representing particle motion that does not become zero even at the wall surface, was modeled as being proportional to particle inertia, with the residual penetration depth linearly proportional to the dimensionless particle relaxation time [18].

3.6. Small-Scale Cyclone Performance

The performance of small-scale reverse-flow cyclones operating under high flow rates and light solid loadings has been systematically characterized. Haig et al. [19] demonstrated that pressure drop, rather than inlet velocity, is the critical parameter influencing particle behavior when comparing different cyclone designs. Cyclones with a smaller vortex finder diameter exhibited superior separation efficiency and increased particle attrition due to higher pressure drops, despite similar inlet velocities.

The non-linear relationship between pressure drop and cut-size diameter suggests diminishing returns on cut-size improvement with increasing pressure drop, indicating that optimum performance is achieved when balancing separation efficiency against mechanical energy loss.

3.7. Atmospheric and Bioaerosol Sampling

The development of small, openable cyclones for atmospheric particulate matter sampling has addressed the challenge of sample recovery for toxicological experiments. Nishita-Hara et al. [20] designed a stainless steel cyclone with an aerodynamic cutoff diameter of approximately $0.2 \mu\text{m}$ at 90 L/min, achieving sampling yields 1.3 times higher than unopenable commercial cyclones (Fig. 4). The stainless-steel construction reduced sample contamination compared to aluminum cyclones, with an estimated cyclone-origin Al_2O_3 concentration of 4% in aluminum cyclone samples versus approximately 1% stainless steel contamination in the openable design.

Chemical analysis confirmed that the composition of water-soluble ions in cyclone-collected samples closely resembled that of total $\text{PM}_{2.5}$ collected on filters, validating the representativeness of cyclone sampling for toxicological studies.

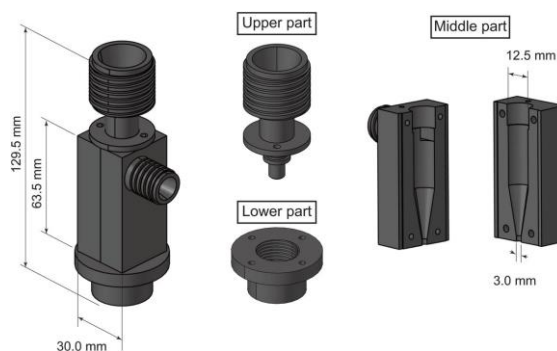


Fig. 4. Design of an openable cyclone [20].

3.8. Oceanographic and Environmental Applications

The influence of small-scale cyclonic features on marine ecosystems has been documented in oceanographic studies. Ressler and Jochens [21] reported that a sub-mesoscale cyclone (approximately 50–1000 m water depth) in the northeastern Gulf of Mexico exhibited elevated nutrients, with nitrate concentrations up to $2 \mu\text{M}$ within the euphotic zone and surface chlorophyll exceeding $1 \mu\text{g/L}$. Acoustic volume backscattering strength, a proxy for mesozooplankton and micronekton abundance, was up to 15 dB greater within the cyclone than in surrounding waters, indicating locally enhanced biomass that attracted higher-trophic-level predators, including seabirds and cetaceans.

3.9. Reduced-Order Modeling

Dwars and Mehring [7] developed a reduced-order model for miniaturized

unidirectional air cyclones serving as gas-liquid separators for oil aerosol removal. The model, based on conservation equations for mass, momentum, and energy, predicts pressure loss and separation efficiency using a modified residence-time approach. Validation against experimental data for numerous cyclone geometries demonstrated good agreement, with the model suitable for rapid design of uniflow cyclones.

4. Challenges, Research Gaps, and Future Directions

Despite significant advances, several challenges remain. The occurrence of "coarse particles entrainment" in the overflow and "fine particles entrainment" in the underflow cannot be fundamentally eliminated, only alleviated by sacrificing classification precision or efficiency [9]. Microcyclones remain susceptible to clogging and pressure drop due to their small dimensions, necessitating arrays of multiple parallel units to achieve practical flow rates [15].

Research gaps include the need for improved understanding of particle agglomeration and attrition mechanisms within small-scale cyclones operating under high flow rates [19]. The relationship between pressure drop and cut-size appears non-linear, suggesting an optimum beyond which increased pressure drop yields diminishing returns [10]. Furthermore, the effects of cyclone material on sample contamination require continued attention, particularly for toxicological and bioaerosol applications [20].

Future directions should focus on integrating microcyclones with downstream analytical functionalities to create monolithic instruments combining sample collection, manipulation, and sensing [15]. The development of refined models for turbulent dispersion in the core region and improved understanding of the boundary layer's influence on particle deposition will enhance predictive capabilities [18]. Additionally, exploring the potential of microcyclones for emerging applications in aerovirology and personalized air sampling represents a promising avenue for future research [15].

5. Conclusions

Microcyclones represent a versatile and increasingly sophisticated technology for particle separation across diverse applications ranging from industrial dust collection to biomedical aerosol monitoring and environmental sampling.

The fundamental principles governing cyclonic separation—centrifugal force, vortex dynamics, and particle inertia—scale effectively to microscale dimensions, though with unique challenges including increased pressure drop and susceptibility to clogging. Recent advances in electrostatic enhancement, three-dimensional printing, and computational modeling have significantly improved collection efficiency for submicron particles, achieving cut-sizes as low as 0.05 μm at practical flow rates. The integration of microcyclones with pre-chargers, virtual cyclone configurations, and optimized geometrical features continues to push the boundaries of separation performance. As additive manufacturing technologies advance and our understanding of microscale fluid-particle interactions deepens, microcyclones will play an increasingly important role in environmental monitoring, occupational hygiene, biomedical diagnostics, and pharmaceutical processing.

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