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Conceptual Design of a Multi-Stage Wet Air-Cleaning Module for Industrial Indoor Recirculation

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Abstract

Purpose: This study proposes a compact, modular wet air-cleaning concept for industrial indoor air recirculation where intermittent PM2.5 emissions and localized CO2 buildup challenge ventilation-only control in space- and energy-constrained facilities today. **Research design & data:** The work is positioned at a pre-validation, conceptual-design stage and decomposes the system into air path, liquid handling, and operation/control. A three-stage P/M/F (Pre/Mid/Final) architecture couples cyclone-driven vortex flow structuring with impaction-based wet collection and retains an absorption-ready gas–liquid contact pathway. Embossed plate internals are defined as tunable elements to promote secondary vortices, wetting/contact opportunities, wash-down, and drainage. A fixed design basis (Q = 4,000 m³/h) is specified for fair stage-to-stage CFD comparison. **Research results:** A verification roadmap is defined from controlled chamber testing to field demonstration, emphasizing repeatability and then robustness under temporal variability. Stage-wise evaluation uses integral flow-structure and operability metrics: pressure drop, recirculation volume fraction, swirl indicators, RTD-based mean residence time, drainage stability, carryover control, and uptime-related failure modes. Field trials also document energy use, noise, deposit locations, nozzle condition, and component durability. **Conclusion:** Rather than claiming quantified removal performance, the paper provides an implementable architecture and a traceable pathway linking conceptual design to CFD refinement, staged validation, and eventual standardization.

Keywords : Wet scrubber, PM2.5 (fine particulate matter), Vortex flow (cyclone-assisted), Impaction-based collection, Industrial indoor air recirculation

JEL Classification Code : Q52, Q53, Q55, Q58, Q50

1. Introduction[1]

Industrial indoor environments—such as manufacturing shop floors, warehouses, and processing areas—often exhibit complex airflow patterns and strong temporal variations in emission sources driven by production activities, material handling, and occupant movement (Darbandi et al., 2024). Under these conditions, ventilation alone may be insufficient to maintain stable indoor air quality, particularly when fine particulate matter (PM2.5) is

intermittently generated and accumulates in recirculating zones. In addition, CO_2 concentration can increase locally in occupied zones during high-activity periods, creating a multi-pollutant indoor air-quality challenge that cannot be effectively addressed by single-purpose control strategies (Chen et al., 2023a).

Conventional indoor air-cleaning solutions remain largely dominated by filter-based systems for particulate removal, while CO_2 control typically depends on increased outdoor-air ventilation. In space- or energy-constrained facilities, however, raising ventilation rates can impose significant energy penalties, and filter-centric solutions may introduce operational burdens related to pressure loss, replacement cycles, and performance degradation under dusty conditions(Chen et al., 2023b). These practical limitations motivate a compact and maintainable module architecture that can be deployed in constrained indoor spaces while satisfying operational requirements such as low pressure drop, low noise, and reliable performance under continuous or shift-based operation. From a dust-collection and wet-scrubbing perspective, the key design question is therefore not only "how to capture pollutants," but also "how to sustain performance over time" through stable wetting, robust drainage, and maintenance-friendly modularity(American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2017).

Accordingly, this paper—explicitly positioned at a pre-validation, conceptual design stage—proposes and rationalizes a compact, modular wet air-cleaning concept that couples cyclone-driven vortex flow (to structure the flow and promote inertial separation) with impaction-based wet collection (to enhance particle capture), while also enabling gas–liquid contact suitable for absorption-oriented operation(Lyttle, 2024). The work does not claim quantified removal performance; instead, it establishes an implementable design logic and architecture intended to guide subsequent numerical refinement and experimental validation.

The contributions of this paper are as follows: (i) a conceptual architecture for a multi-stage module integrating vortex-driven flow structuring with impaction-based wet collection; (ii) functional definition of a P/M/F (Pre/Mid/Final) stage arrangement to distribute separation, conditioning, and polishing roles along the flow path; (iii) a structured description of embossed plate surface features as design elements intended to promote secondary vortices, enhance wetting/contact opportunities, and support wash-down and drainage; and (iv) a practical verification framework linking the conceptual architecture to CFD-based refinement and chamber/field validation(Qian et al.,

2020). Figure 1 illustrates a proposed test configuration (planned) for a three-stage wet air-cleaning module intended for modular validation. Each stage (Pre, Mid, Final) is intended to be equipped with spray nozzles and measurement ports (pressure drop, residence time, and PM2.5 concentration) to enable controlled chamber testing in subsequent work. Table 1 summarizes the design basis adopted for preliminary CFD comparisons.
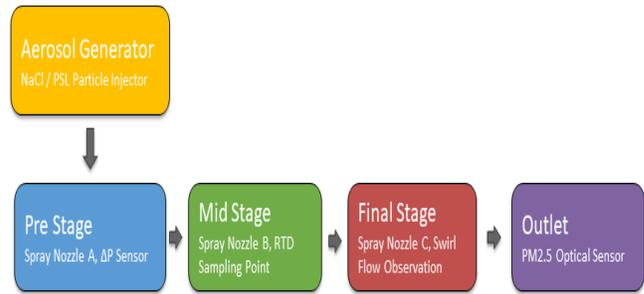

Figure 1: Proposed test configuration (planned)

Table 1: Design Basis (Indoor Recirculation Unit for Industrial Facilities)

Item	Specification / Assumption
Application / Site	Industrial indoor environment (e.g., general manufacturing / warehouse / processing area). Ceiling- or wall-mounted recirculation unit is assumed.
Design objective	Concept-level indoor air quality improvement via local recirculation (PM reduction; absorption-ready operation discussed conceptually).
Design airflow rate (design point)	Q = 4,000 m³/h (= 1.111 m³/s) per module, fixed for stage-to-stage CFD comparison.
Inlet geometry (rectangular)	$W_{in} \times H_{in} = 0.60 \times 0.40$ m $\rightarrow A_{in} = 0.24$ m². Mean inlet velocity: $U_{in} = Q/A_{in} = 4.63$ m/s.
Outlet geometry (circular)	$D_{out} = 0.55$ m $\rightarrow A_{out} = \pi D_{out}^2/4 = 0.238$ m². Mean outlet velocity: $U_{out} = Q/A_{out} = 4.68$ m/s.
Transition section	A rectangular-to-round transition section is included (modeled explicitly in CFD) to connect inlet and outlet.
Inlet air conditions	T = 25 °C (assumed). $\rho = 1.18$ kg/m³, $\mu = 1.85 \times 10^{-5}$ Pa·s (standard air).
Inlet turbulence	Turbulence intensity I = 10% (assumed). Inlet hydraulic diameter: $D_{h,in} = 2W_{in}H_{in}/(W_{in} + H_{in}) = 0.48$ m. Length scale: l = $0.07D_{h,in} = 0.0336$ m.
Reynolds number (reference)	$Re_{in} = \rho U_{in}D_{h,in}/\mu \approx 1.42 \times 10^5$ (turbulent regime).
Operating constraints	Maximum allowable pressure drop: $\Delta P_{max} = 300$ Pa (module-level target). Noise limit: ≤ 70 dBA at 1 m (optional; site-dependent).
Space / installation constraints	Maximum envelope size: $L \times W \times H = 1.2 \times 0.7 \times 0.6$ m (assumed). Maintenance clearance is assumed.
Duty cycle	16–24 h/day (industrial shift/continuous operation; assumed 20 h/day for discussion).
CFD scope (for this paper)	Steady, incompressible, single-phase air flow only. Water spray / liquid film / droplet carryover are excluded and left for future work.

Maintenance / robustness (concept)	Drainage availability assumed (yes). Considerations: fouling, corrosion resistance, and safe maintenance access (concept-level).

2. Literature Review

2.1. Vortex Flow–Driven Separation Concept

Cyclone-type devices impart angular momentum to an inlet stream, forming a confined swirling flow in which centrifugal forces and the associated radial pressure gradient organize internal motion(Wang et al., 2019). In such flows, separation and mixing can occur concurrently: inertial particles tend to migrate radially under swirl-induced forces, while strong shear, turbulence, and recirculation enhance dispersion and increase contact opportunities with collection media.

In the present conceptual design for industrial indoor air recirculation, vortex formation is treated as a primary architectural lever rather than a stand-alone separator. The design rationale is that vortex structures govern (i) residence behavior, (ii) recirculation intensity, and (iii) near-wall transport—each of which influences the probability that particulate contaminants encounter wet collection interfaces (e.g., droplets, wetted walls, or liquid films). Consequently, inducing and controlling swirl intensity, recirculation zones, and near-wall flow characteristics is central to the module's architecture-level design(Powell, 2022). In subsequent CFD-based studies, swirl strength can be quantified using standard swirl indicators (e.g., swirl number or section-averaged vorticity magnitude), while hydraulic feasibility can be tracked through the pressure drop across each stage.

2.2. Impaction-Based Capture and the P/M/F Multi-Stage Architecture

Impaction capture relies on particle inertia. When a flow undergoes sharp curvature or rapid directional change, particles may deviate from streamlines and collide with collector surfaces. In wet collectors, such collisions can result in capture via adhesion to wetted walls, interception within a liquid film, or coalescence with droplets followed by drainage. Impaction effectiveness is commonly discussed using non-dimensional measures such as the Stokes number, which links particle response time to flow time scales and provides a practical framework for identifying particle-size ranges that are likely to be affected by turning channels and baffle-like geometries.

Building on these principles, the proposed module is structured as a three-stage P/M/F (Pre/Mid/Final) arrangement in which stage-wise roles are functionally differentiated. The Pre stage prioritizes pretreatment and removal of relatively larger particles, thereby reducing downstream loading and stabilizing wetting/drainage behavior. The Mid stage is designed to condition residence behavior and mixing through controlled turning and recirculation, which may facilitate particle agglomeration and increase the probability of wet interaction. The Final stage provides polishing by intensifying local flow structuring and wet contact to target residual fine particles and nuisance species. This staged allocation offers a practical advantage over single-stage designs by allowing flow structure, contact conditions, and drainage pathways to be tuned by stage, rather than forcing a single geometry to satisfy conflicting objectives throughout the device.

2.3. Embossed Surface Features and Stage-Wise Differentiation Logic

Embossed (concave–convex) surface textures can perturb the near-wall boundary layer and generate secondary vortices and localized recirculation, thereby altering near-wall transport, mixing, and residence behavior. In wet collectors, these effects can be leveraged to enhance gas–liquid interaction, stabilize wall wetting, and improve wash-down effectiveness. However, excessive disturbance may also increase pressure loss and induce undesirable separation that destabilizes drainage. Therefore, embossed features should be treated as tunable design variables rather than universally beneficial add-ons.

For systematic design and subsequent numerical refinement, embossed geometry can be parameterized using a compact set of variables: pitch p, height h, depth d, area fraction φ, orientation angle θ, and pattern type (e.g., grid, zigzag, helical, staggered as like a Figure 2). These parameters define a bounded design space suitable for structured exploration in CFD and later validation in chamber or field tests(Balestrin et al., 2017).

Systematic design and subsequent numerical refinement

Parameters

p — Pitch
h/d — Height/Depth
φ — Area fraction
θ — Orientation

Patterns

Grid Zigzag Helical Staggered

Figure 2: Embossing design parameters&pattern types

Importantly, the conceptual design adopts a stage-wise differentiation strategy rather than applying identical embossing throughout the module. For example, the Pre stage may employ a larger pitch and gentler height to support robust wash-down and reduce hydraulic penalties under high dust loading, whereas the Final stage may adopt denser patterns and/or oblique/helical orientations to intensify near-wall interaction for polishing. This differentiation addresses the practical question of whether "more disturbance is always better" by allocating disturbance only where it is functionally justified, thereby balancing capture enhancement against pressure drop and drainage stability.

2.4. Related Work and Positioning (revised with citations)

Indoor air cleaning in industrial facilities has traditionally relied on filter-based systems to control airborne particulate matter, often complemented by ventilation strategies for dilution and thermal management. However, filter performance is closely tied to pressure-loss penalties and replacement cycles, and performance can degrade rapidly under dust-intensive conditions. In practice, filtration performance is commonly characterized using particulate-matter–based classifications such as ISO 16890 (ePM1, ePM2.5, ePM10), which reflect size fractions relevant to indoor exposure and HVAC applications.

For gaseous contaminants, CO_2 management in buildings and facilities remains predominantly ventilation-driven. ASHRAE notes that CO_2 levels associated with code-compliant ventilation vary by space type and occupancy, and that CO_2 measurements should be interpreted cautiously rather than treated as a universal indoor air-quality limit. These realities motivate compact, modular approaches that can reduce particulate burden while reserving an additional, architecture-level pathway for gas–liquid contact in scenarios where ventilation increases are constrained by energy and infrastructure limitations.

A second stream of relevant work concerns wet scrubbing and inertial/impaction-based collectors, which have a long history in industrial dust control. Venturi scrubbers, for example, exhibit a strong coupling between collection efficiency and pressure drop, and classical predictive frameworks emphasize that improved capture often requires higher hydraulic penalties (Byeon et al., 2012). Wet collectors also require careful management of droplet carryover (demisting) and drainage stability, especially in compact implementations.

A third stream involves cyclone and swirl-driven devices used to structure flow and achieve inertial separation. Cyclone cutoff-diameter predictions and pressure-drop estimation have been studied extensively, and comparative analyses show that multiple cyclone theories (e.g., Lapple, Stairmand, Barth) can yield different cutoff predictions depending on assumptions and operating regimes. More recent studies continue to propose practical pressure-drop models for cyclone geometries, underscoring the importance of ΔP as a primary design constraint for deployable systems.

Finally, because the present paper is positioned at a conceptual design stage, it adopts verification logic consistent with CFD-based flow-structure validation rather than performance-claim validation. Residence-time distribution (RTD) provides a compact means to quantify short-circuiting and mixing behavior using tracer response functions and related statistics. In CFD, RTD can be evaluated using passive-scalar transport (pulse/step injection), enabling stage-to-stage comparisons of mean residence time and dispersion under fixed operating conditions. Likewise, swirl intensity can be described using established swirl-number definitions that relate angular momentum transport to axial momentum and correlate with the formation of inner recirculation zones in confined swirl flows.

Against this background, the proposed concept is positioned at the architecture and design-rationale level: it integrates (i) vortex-driven flow structuring to control residence and recirculation, (ii) impaction-based wet collection to support wash-down and drainage, and (iii) an absorption-ready gas–liquid contact pathway as a conceptual lever for CO_2-oriented operation within a compact module footprint. Rather than optimizing a single geometry to satisfy conflicting objectives everywhere, the P/M/F allocation distributes capture, conditioning, and polishing functions across stages under explicit constraints on pressure drop, maintainability, and operational robustness.

2.5. Design Gap and Contribution Summary

Despite extensive work on filtration, wet scrubbing, and ventilation-driven CO_2 dilution, a gap remains for compact, maintenance-oriented indoor recirculation modules suitable for industrial facilities. Many solutions optimize either particulate control or gas-phase management, but rarely integrate both within a single compact architecture explicitly designed under practical constraints such as allowable pressure drop, droplet carryover control, drainage stability,

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cleaning frequency, and long-duration reliability under continuous or shift-based operation. Furthermore, wet-collection concepts that appear effective at a unit-operation level can face deployment barriers when translated into compact indoor modules, where stable wetting and serviceability are as critical as capture efficiency.

The proposed concept addresses this gap by structuring a compact wet collector around vortex-driven flow organization and impaction-based wet capture, while reserving an absorption-ready gas–liquid contact pathway within the same footprint as a conceptual CO_2-oriented lever.

The architecture introduces a P/M/F allocation to distribute functions—pretreatment, residence-time conditioning/agglomeration, and final polishing—across stages, thereby reducing design conflicts. Finally, by parameterizing embossed features and linking stage-wise wetting–wash-down–drainage logic to a practical validation roadmap, the paper provides an implementable foundation for subsequent CFD refinement and chamber/field verification without overclaiming performance at the conceptual stage(Kumar & Schafrik, 2022).

3. Conceptual Design: Module Architecture and Implementation Strategy

3.1. System Architecture Overview: Integrated Multi-Stage Separation–Wetting–Operation

The proposed concept is a compact, multi-stage vortex–impaction wet air-cleaning module intended for deployment in space- and energy-constrained industrial indoor environments (e.g., manufacturing areas, warehouses, and processing zones). To avoid the pressure-loss and maintenance burdens associated with packed beds or large wet towers, the architecture employs fixed plate-based internals with embossed surface features(Ali et al., 2017). Swirl-driven flow structuring and impaction-based wet collection are used to intensify particle–liquid interaction within a compact footprint. The system-level decomposition—air path, spray/wetting/wash-down, drainage, maintenance access, and operation/control—is summarized in Figure 3, and the stage-wise allocation principle is introduced in Figure 4.

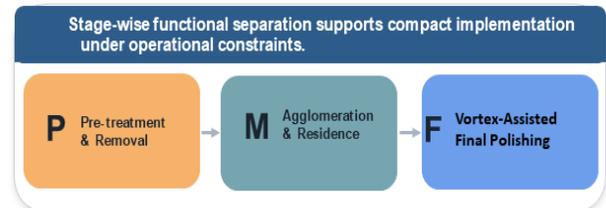**Figure 3:** Conceptual architecture of the proposed module

Figure 4: Serial P/M/F stage configuration and intended roles

Consistent with the conceptual design scope, this study does not report quantified removal efficiencies. Instead, it establishes implementable design logic under practical constraints. In particular, wetting stability and drainage robustness are treated as first-order requirements because they govern long-duration operability in compact wet collectors (Figure 5).
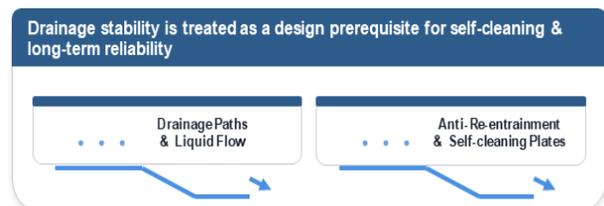

Figure 5: Drainage layout and self-cleaning-oriented design

Design implication. Architectural decisions must be made jointly across airflow, liquid handling, and maintainability, because operability constraints (pressure drop, carryover risk, fouling, and drainage stability) can dominate life-cycle performance.
- Stage-wise Pressure Drop (ΔP): Comparison of pressure drop across the Pre, Mid, and Final stages of the module. The pressure drop increases along the flow direction, with the highest value observed in the Final stage due to intensified swirl and compact flow structuring.
- Stage-wise Mean Residence Time (RTD): Mean residence time of airflow at each module stage. The Mid stage exhibits the longest mean residence time, indicating stronger mixing and recirculation. In the present single-phase CFD, this is

interpreted as a proxy for contact opportunity, which will be evaluated more directly in subsequent multiphase CFD and controlled experiments. Accordingly, any particle–liquid interaction or agglomeration effects are hypothesized rather than claimed at this stage.

- Stage-wise Swirl Intensity Indicator: Swirl strength comparison between module stages. The Final stage shows the highest swirl number, reflecting stronger vortex formation, which supports polishing of residual fine particles through intensified wet interaction. Figure 6 presents the CFD-based comparison of key performance metrics across the Pre, Mid, and Final stages of the module.
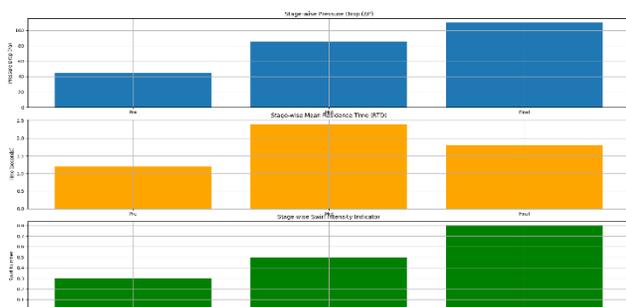

Figure 6: Stage-wise Pressure Drop (ΔP), Stage-wise Mean Residence Time (RTD) & Stage - wise Swirl Intensity Indicator

Because the CFD scope in this paper is limited to steady, incompressible single-phase airflow, the reported metrics (ΔP, swirl indicator, RTD statistics) are used to compare flow-structure tendencies, while spray, droplets, liquid films, carryover, and removal performance are reserved for subsequent multiphase simulations and experiments.

3.2. Air-Path Design Logic: Functional Flow Progression from P → M → F

A defining feature of the module is the serial flow progression through P/M/F stages along the primary air path (Figure 4). The Pre (P) stage is intended to reduce downstream loading by prioritizing removal of higher-inertia particles and coarse aerosols through turning/impaction under stable wash-down. The Mid (M) stage conditions residence behavior through controlled recirculation and mixing while promoting additional impaction and agglomeration in turning regions. The Final (F) stage incorporates a vortex chamber to intensify swirl and provide polishing, targeting residual fine particles and nuisance species through intensified wet interaction (Figure 4), with operation linked to the spray concept in Figure 7.
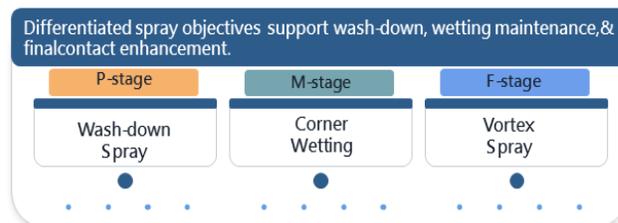

Figure 7: Stage-wise spray concept and wetting strategy

This differentiation avoids single-zone designs that must satisfy conflicting objectives everywhere in one geometry(Ozgen, 2024). By allocating roles, the design can tune swirl intensity, turning severity, and wetting/drainage conditions by stage while preserving a compact overall footprint. Deployment logic based on modular replication (rather than geometric enlargement) is summarized in Figure 8 and connects to the verification pathway in Figure 9.

Figure 8: Deployment scenarios & modular scalability
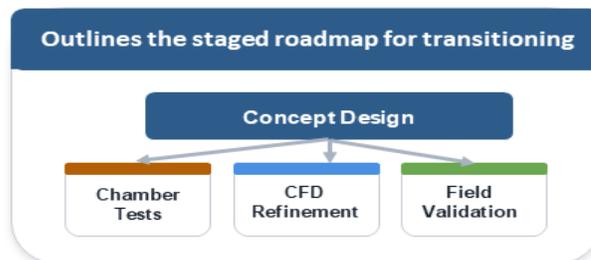

Figure 9: Verification roadmap from conceptual design to validation

Design implication. Stage-wise functional allocation enables targeted complexity only where needed (turning/impaction zones and the vortex chamber), which is essential to balance capture intent against pressure drop and maintenance risk.

3.3. Stage-Wise Spray–Wetting–Wash-Down Design: Nozzle Architecture and Liquid

Management

In a vortex–impaction wet module, spraying is not merely water supply(Goode et al., 2018); it is an operability mechanism that (i) stabilizes wetting, (ii) supports wash-down of collected matter, (iii) suppresses deposits and clogging, and (iv) increases the availability of wet collection interfaces. The spray–wetting–wash-down logic is differentiated by stage (Figure 7), and its coupling to liquid removal and carryover control is emphasized in Figure 5.

In the P stage, nozzle operation prioritizes broad-coverage wash-down to promptly remove heavy deposits and transfer captured matter to drainage, thereby reducing downstream burden. In the M stage, nozzle placement prioritizes wetting maintenance in turning and corner regions where deposition is likely, supporting stable impaction/agglomeration while limiting accumulation at geometric discontinuities. In the F stage, spray is coupled with intensified swirl to maximize local mixing and wet interaction for polishing. In addition, the F stage can be designed to be absorption-ready, providing gas–liquid contact interfaces suitable for future absorption-oriented operation; however, no CO_2 capture performance is claimed at the conceptual stage.

Design implication. Spray design must be specified together with drainage capacity and carryover control; otherwise, increased liquid loading can amplify re-entrainment and operational instability even when local contact is intensified.

3.4. Drainage and Contaminant Handling: Structural Prerequisites for Self-Cleaning Operation

For compact wet collectors, discharge is as important as capture. If drainage is unstable, sludge accumulation and re-entrainment can rapidly degrade performance and reliability(Uluer, 2023). The conceptual design therefore treats drainage as a primary subsystem and a prerequisite for self-cleaning operation (Figure 5). Drainage design also bridges architecture and long-duration operability and links directly to the verification roadmap in Figure 9.

Stage-wise requirements are differentiated. In the P stage, wash-down flow must transport heavy collected matter efficiently without stagnation. In the M stage, drainage pathways must remain robust in turning regions; geometric simplicity and fouling tolerance are prioritized. In the F stage, local liquid loading may increase due to swirl intensification and spray, so the design provides structural margin (hold-up space, drain cross-section, and backflow resistance) to prevent carryover and re-entrainment. Design implication. Drainage should be treated as a dominant design constraint for long-term stability; capture-enhancing features are acceptable only if they do not compromise liquid removal or droplet carryover control.

3.5. Materials, Corrosion Resistance, and Maintainability for Industrial Deployment

Maintainability is often the primary adoption barrier for wet systems in industrial facilities(Waters, 2006). The concept assumes corrosion-resistant materials suitable for repeated wetting and wash-down, but material selection alone is insufficient. Maintainability is framed as an architecture-level requirement: (i) a self-cleaning-oriented air path and drainage design that prevents long-term accumulation, (ii) accessibility of nozzles and plate internals through modular construction to simplify inspection and replacement, and (iii) liquid management compatible with routine maintenance practices and site safety requirements.

Operational feedback (e.g., localized deposits, nozzle fouling, and drainage instability) is treated as design input for subsequent refinement rather than a purely operational issue, consistent with the staged verification pathway in Figure 9. Design implication. Maintenance access and service intervals should be treated as first-order constraints comparable to footprint and pressure drop, because they govern real-world availability and life-cycle cost.

3.6. Modularity, Compactness, and Deployment Scenarios: Implementable Scaling under Field Constraints

Industrial indoor environments often impose heterogeneous installation constraints (ceiling height, access paths, zoning, and localized emission sources), making large wet towers impractical for indoor recirculation(Zaman, 2024). The proposed concept therefore adopts a modular strategy: the system is conceived as repeatable unit modules (or cartridges) that can be replicated to match local air-load demands and available space. Representative deployment scenarios and scalability through modular replication are summarized in Figure 8, and implications for standardization and maintenance planning are consistent with the roadmap in Figure 9.

Modularity reduces deployment risk by enabling capacity scaling through replication rather than aggressive geometric enlargement, which can otherwise increase pressure drop, carryover risk, and maintenance complexity. Design implication. Modular replication provides a practical scaling pathway under heterogeneous field constraints, supporting implementability prior to final performance optimization.

3.7. Operation and Control Layer: Linking Sensing, Variable Operation, and Stage-Wise Objectives

The conceptual architecture includes an operation/control layer that links sensing, control, and actuation to accommodate time-varying indoor conditions in industrial facilities (e.g., shift changes and intermittent dust generation). Without claiming algorithmic novelty, control is defined as an architectural mechanism enabling variable operation of the fan and spray system while preserving stage-wise objectives (Figure 3 and Figure 9).

Operationally, the P stage must sustain wash-down to prevent upstream accumulation; the M stage must maintain wetting in turning regions to suppress blockage and stabilize impaction/agglomeration; and the F stage must apply intensive wet interaction for polishing when needed while avoiding excessive carryover. Control objectives should therefore be defined not only by air-quality targets but also by operability targets such as wetting stability, drainage robustness, deposit prevention, and safe serviceability.

Design implication. Control logic should prioritize stable long-duration operation (wetting/drainage/deposit suppression) as a prerequisite for meaningful air-quality benefits in field deployments(Huang et al., 2020). In subsequent CFD and chamber tests, the stage-wise roles will be assessed using integral metrics (e.g., ΔP, swirl indicators, recirculation fraction, and RTD statistics), together with operability checks for drainage stability and carryover risk.

4. Application Scenarios and Maintainability-Oriented Design Requirements

4.1. Deployment Scenarios: Module Configuration under Space Constraints and Operational Requirements

Industrial indoor environments often impose heterogeneous installation constraints—such as ceiling height, access paths, zoning requirements, and localized emission sources—while also demanding practical deployment across multiple facility zones (e.g., production lines, storage aisles, loading bays, and connecting corridors)(Lee et al., 2013). Under these conditions, ventilation and filtration alone may face structural limitations, particularly when real-time responsiveness and gas-phase control readiness are considered alongside particulate control. For this reason, the present concept targets a small-footprint, modular wet-scrubber architecture whose functional decomposition (air path, liquid handling,

and operation/control) is summarized in Figure 3.

Accordingly, industrial deployment requirements—low power consumption, low noise, and high continuous-operation reliability—are treated as implementability constraints rather than secondary performance metrics. These constraints influence geometric decisions across the staged air path (cross-section transitions, turning severity, and swirl intensity) introduced in Figure 4, because each directly affects pressure loss and acoustic/operational behavior. The serial P/M/F architecture is advantageous under space constraints: rather than concentrating all functions into a single chamber, the P stage prioritizes pretreatment of high-inertia particles/coarse aerosols, the M stage redistributes loading through turning/impaction and residence conditioning, and the F stage strengthens vortex-driven interaction for final polishing (Figure 4).

This staged allocation also enables capacity scaling through module replication and placement (number and arrangement of units) rather than geometric enlargement of a single unit, which is more compatible with heterogeneous facility layouts. Representative deployment and scalability logic is illustrated in Figure 8, which frames modular replication as a practical pathway to meet zone-specific constraints and service-access requirements.

Design implication. Capacity expansion should preferentially be achieved by modular replication under fixed operability constraints (pressure loss, noise, and service access), rather than by scaling a single unit to sizes that compromise drainage stability and maintainability.

4.2. Maintainability and Safety: Design Priorities for Washing, Drainage, and Durability

In industrial facilities, deployability is often determined as much by maintainability and safety as by nominal removal performance. In wet processes, captured contaminants are transported and may accumulate in the liquid phase; therefore, unstable drainage can induce sludge buildup, re-entrainment, clogging, and leakage, rapidly degrading long-duration reliability. The present concept defines the coupling of spray–wetting–wash-down and drainage not as auxiliary features but as the structural backbone of self-cleaning-oriented operation. The stage-wise spray logic is summarized in Figure 7, and its required coupling to liquid removal pathways is emphasized in Figure 5.

A stage-wise maintenance logic follows directly from the P/M/F architecture. In the P stage, broad-coverage wash-down should promptly remove heavy deposits and transfer collected matter to drainage to reduce downstream burden.

In the M stage, wetting maintenance should target turning and corner regions where geometric discontinuities promote deposits and blockage. In the F stage, spray combined with intensified swirl in the vortex chamber can increase local wet interaction for final polishing; however, this must be paired with robust liquid removal to suppress carryover and re-entrainment (conceptual coupling: Figure 5-Figure 7). In this framing, wetting maintenance is treated primarily as an operability mechanism—preventing deposit growth and protecting long-duration stability—rather than as a direct performance claim.

From a safety and reliability perspective, continuous operation should be evaluated through operational integrity (uptime) and wet-specific failure modes (nozzle fouling, drainage blockage, carryover, leakage, and scaling/deposition). Because the concept includes sensor-driven actuation (fan/pump/spray), fault-handling requirements (safe shutdown logic, alarms, and safe-mode/bypass operation) should be treated as architecture-level constraints(Costa et al., 2023). This is consistent with the system-layer perspective in Figure 3 and the staged validation logic in Figure 9, where operability evidence is collected and fed back into design refinement. Design implication. Safety and maintainability should be designed around failure-mode tolerance (drainage instability, carryover, leakage, and nozzle fouling) rather than peak removal performance, because these modes govern real-world availability in wet systems(Lebel et al., 2016).

4.3. Verification Roadmap and Standardization Pathway: From Conceptual Design to Field Adoption

This paper does not claim quantified removal performance at the current stage; instead, it proposes an expandable verification roadmap that links the conceptual architecture to staged validation and eventual standardization. The roadmap is summarized in Figure 9 and is anchored in the system decomposition shown in Figure 3, which clarifies what must be verified (air path, liquid handling, and operation/control) to demonstrate deployability.
A practical pathway begins with controlled chamber testing (indoor or semi-enclosed environments), followed by field

demonstration in operating industrial facilities. Field demonstration should not be limited to pollutant concentration measurements; it should also capture operability evidence and maintenance feedback—deposit locations, nozzle condition, drainage stability, component durability—because these directly inform iterative refinement. This deploy–operate–feedback–improve loop is the core mechanism by which conceptual design matures into a deployment-ready system (conceptual linkage: Figure 9).

Validation items should reflect both multi-pollutant objectives and operability constraints. Core evaluation categories include PM2.5 reduction, gas–liquid contact readiness for absorption-oriented operation (to be verified in later stages), energy consumption, noise level, and continuous-operation reliability(Wansom et al., 2023). Chamber testing should emphasize repeatability under controlled boundary conditions, while field testing should verify robustness under realistic temporal variability (shift cycles, process changes, and ventilation variations). Finally, standardization and certification pathways should be anticipated early; when formal accredited test reports are not immediately available, interim evidence should still be documented in a traceable manner to bridge toward later certification—without overstating conclusions at the conceptual stage.

Design implication. A credible conceptual design for industrial deployment requires a verification plan that treats operability evidence (drainage stability, carryover control, and uptime) as co-equal with pollutant metrics and explicitly maps early-stage tests to later certification pathways. In subsequent CFD, the stage-wise roles will be evaluated using integral flow-structure metrics (e.g., pressure drop, recirculation volume fraction, swirl indicator, and RTD-based mean residence time) under the fixed design basis. Table 2 summarizes key flow-structure and operability metrics used to evaluate each stage (Pre, Mid, Final) of the proposed wet air-cleaning module. It outlines how pressure drop, recirculation, swirl intensity, residence time, and drainage behavior are used as verification indicators during CFD analysis and future testing.

Table 2: Flow-structure and operability metrics for stage-wise verification (P/M/F)

Metric	Definition (what it measures)	How to extract (CFD / test)	Stage relevance	Notes / acceptance logic
Pressure drop, ΔP	Hydraulic feasibility and energy penalty	CFD: area-averaged total pressure difference across stage/module; Test: differential pressure sensor	All stages	Must satisfy ΔP ≤ ΔP_max (design basis). Report stage-wise + total.

Recirculation volume fraction, V_{rec}/V	Strength/extent of reverse-flow regions (mixing vs. stagnation risk)	CFD: volume where axial velocity Uz < 0 (or negative streamwise component) divided by stage volume	M, F	Too high can imply stagnation/carryover risk; moderate is beneficial for residence conditioning.
Swirl indicator (choose one)	Quantifies swirl intensity linked to vortex formation	CFD: (a) swirl number S on a section, or (b) section-averaged $|\omega|$, or (c) tangential velocity integral	P, F	Use a consistent definition across cases; compare relative changes stage-to-stage.
RTD mean residence time, $\bar{t}$	Average residence time (conditioning / short-circuiting)	CFD: passive scalar pulse/step at inlet → outlet E-curve; Test: tracer gas response	M (primary), F (secondary)	Report $\bar{t}$ and short-circuit indicator (early peak).
RTD dispersion, σ_t^2 (or variance)	Degree of mixing/dispersion (uniformity vs. bypassing)	CFD/test from RTD curve	M	Helps show M-stage "conditioning" role vs. mere pressure loss.
Outlet velocity non-uniformity, $U_{rms}/\bar{U}$	Jetting / maldistribution that can aggravate carryover or noise	CFD: velocity profile at outlet plane; Test: anemometry grid	F, outlet	Useful proxy for carryover propensity in compact modules.
Near-wall interaction proxy (choose one)	Potential for wetting stability/interaction near plates	CFD: wall shear stress τ_w statistics or near-wall velocity magnitude; Test: wetting coverage observations	P/M/F	Not a capture claim—just supports "contact potential" logic.
Liquid management margin (concept metric)	Drainage robustness under expected liquid loading	Design-based: drain cross-section, hold-up volume, slope; Test: drainage time/hold-up	All stages	Even if CFD is single-phase, include as operability verification item.
Cryover/re-entrainment risk proxy	Likelihood of droplet carryover/re-entrainment (qualitative at conceptual stage)	CFD (single-phase): high-speed regions near outlet + recirculation near outlet + non-uniformity; Later test: droplet carryover measurement	F	Phrase as "risk proxy," not quantified carryover, unless multiphase modeling/testing is done.

5. Conclusions

This paper proposed a conceptual design of a compact, multi-stage vortex–impaction wet air-cleaning module intended for industrial indoor air recirculation in space- and energy-constrained facilities. The objective is to provide an implementable architecture for mitigating particulate matter (PM2.5) in dust-intensive environments, while reserving an absorption-ready gas–liquid contact pathway that could support future CO_2-oriented operation without claiming capture performance at the conceptual stage.

The proposed concept adopts a serial P/M/F (Pre/Mid/Final) configuration that allocates stage-wise roles to (i) pretreatment and upstream load reduction, (ii) residence conditioning and impaction/agglomeration promotion, and (iii) vortex-assisted polishing under intensified wet interaction. This functional allocation supports scalable deployment through modular replication under practical constraints, including pressure-drop limitations, low noise requirements, and long-duration operability.

In addition, the paper defined stage-wise spray–wetting–wash-down and drainage pathways as core architectural elements for self-cleaning-oriented operation and articulated a maintainability-centered design rationale aimed at reducing life-cycle burden. The design space of embossed plate features was structured using explicit geometric parameters and stage-wise differentiation logic, establishing a framework that can be mapped directly to subsequent CFD-based refinement and experimental verification.

Rather than prematurely claiming quantified removal performance, this work establishes methodological credibility at a pre-validation stage by clarifying the design rationale and implementation strategy from the perspectives of deployment, operation, and maintenance. Future work will quantify the roles and trade-offs of key design elements—swirl intensity, turning/impaction geometry, pressure drop (ΔP), and residence-time characteristics—using CFD with integral flow-structure metrics (e.g., ΔP, recirculation fraction, swirl indicators, and RTD statistics), followed by controlled chamber testing. Importantly, validation should address not only pollutant-related indicators but also wet-specific reliability metrics essential for field readiness, including drainage stability, droplet carryover/re-entrainment, fouling and nozzle clogging, leakage, and scaling/deposition under long-duration operation. These steps will mature the proposed concept toward practical industrial deployment, standardization, and maintenance planning.

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