Wall-Integrated Surfaces for Indoor Particulate Control: A Simulation Study of Placement, Geometry, and Electrostatic Interaction

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1. Executive Summary

Indoor particulate matter does not distribute itself uniformly: recirculation, stagnation zones, and near-wall transport govern where particles travel and where they linger. This creates a design opportunity. Surfaces already present in a space, such as media screens, display panels, or wall cladding, can be engineered to influence particulate behaviour in their vicinity. This study uses computational fluid dynamics with individually tracked particles to evaluate that opportunity across eight room-scale cases, varying surface geometry (flat, recessed, ribbed), placement (wall-mounted versus extended into the flow), flow orientation, and an electrostatic attraction mechanism (on versus off).

Main findings:

- **Placement governs how many particles the surface can act on.** Extending the surface into the particle path raised the near-surface residence time by roughly 40 percent, far more than any change of geometry at that position. Of the variables tested, placement produced the largest effect.
- **Electrostatic attraction converts a passive surface into an active collector.** With a calibrated surface charge (average force on a 10 μm particle comparable to gravity), the charged screen sustained a steady deposition rate near one particle per second under the conditions tested; without it, deposition was negligible.
- **Surface geometry is a secondary factor.** Within the geometries evaluated (flat, recessed, ribbed), the profiles differed by only a few percent in particle residence time and deposition under matched conditions.
- **Effectiveness is the product of encounter and capture.** A surface only acts on particles that enter its interaction zone: placement governs how many arrive, and the interaction mechanism governs what happens to those that do.

These results come from a single room configuration, flow rate, and particle size range, with no physical validation yet. They are intended to rank design concepts and identify trends rather than predict absolute performance.

2. Why This Matters

Traditional air cleaning technologies are typically evaluated based on how effectively they process air through a device. This study explores a different question: can architectural surfaces already present within a space influence particle behaviour through their placement, geometry and interaction mechanisms? The simulations suggest that placement may be the most important design variable. Positioning a surface within a dominant particle pathway produced a substantially larger effect than modifying surface geometry alone. This finding supports the idea that understanding how particles move through a space may be just as important as the intervention itself. The study also indicates that electrostatic interaction can increase particle retention once particles enter the surface interaction zone. In simple terms, effectiveness appears to depend on two factors: how many particles encounter the surface, and what happens to those particles once they arrive. While these results do not predict absolute room-cleaning performance, they provide evidence that intelligent placement, airflow-aware design and particle-pathway interaction deserve further investigation as complementary approaches to conventional air treatment technologies.

3. Problem and Hypothesis

In a ventilated space, airborne particles follow the bulk air motion modified by gravity and local flow structures: recirculation cells carry them across the room, stagnation regions hold them in place, and thin near-wall layers carry them along surfaces. A wall-integrated surface therefore sees only the fraction of the particle load that local transport delivers to it. Adding a screen also reshapes the local flow, creating a stagnation zone ahead of it where approaching particles slow and linger.

The working hypothesis has two parts. **Encounter**: surface placement and orientation relative to the dominant flow determine whether particles reach the surface vicinity at all. **Capture**: once particles are in the surface vicinity, the surface geometry and any active interaction mechanism (here, electrostatic attraction) determine whether they are retained. The simulation campaign was designed to separate these two factors.

4. Simulation Approach

Airflow in a room-scale domain is solved numerically, and particles are tracked individually through the resulting flow field. Three particle size classes (PM1, PM2.5, PM10) are injected continuously from the inlet plane; each particle responds to aerodynamic drag and gravity, and in the electrostatic cases to an additional attraction toward the screen. A particle is counted as deposited when it is close to the screen surface and reaches near-zero velocity. The electrostatic force represents a uniform surface charge density, applied identically across geometries so the resulting field differs only through geometry, and is calibrated so that the average force on a 10 μm particle near the screen is approximately its weight. Numerical details are in Appendix A and the force model in Appendix B.

Three screen geometries are tested: a plain flat panel, a recessed panel with an array of shallow pockets, and a ribbed panel with vertical grooves (figure 1).

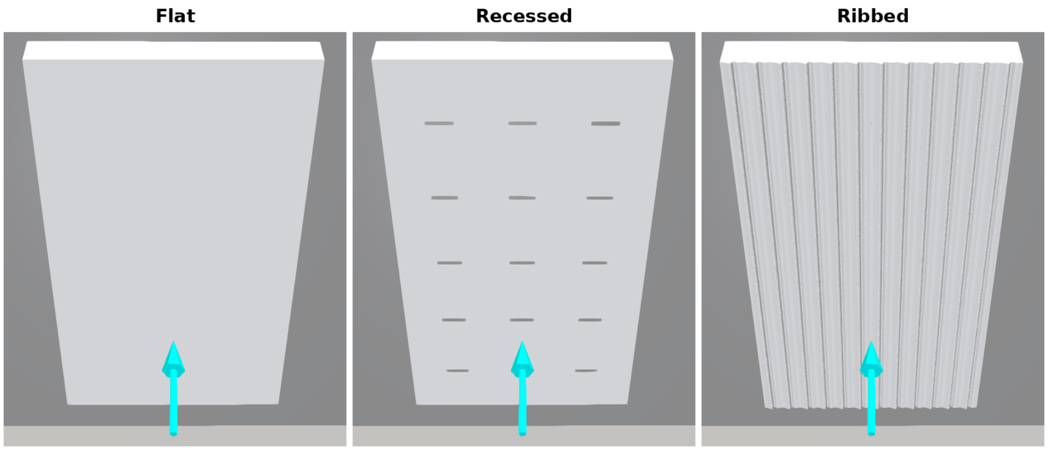

Figure 1: The three screen geometries: flat (plain), recessed (shallow pockets), and ribbed (vertical grooves). The cyan arrow shows the approaching flow direction.

Two mounting configurations are studied. In the **wall-mounted** configuration the screen (1.2 m wide, 2.2 m tall) sits on a wall, with flow approaching perpendicular or parallel to it. In the **extended upstream** configuration the screen is part of a longer flush assembly, so the incoming particle stream travels along the surface, directly through the screen's interaction zone.

Table 1: Simulation case matrix

Case	Screen	Placement	Flow direction	Electrostatic force	Duration (s)
A00	Flat	Wall	Perpendicular	No	360
A01	Recessed	Wall	Perpendicular	No	360
A02	Ribbed	Wall	Parallel	No	240
B00	Flat	Wall	Perpendicular	Yes	360
B01	Recessed	Wall	Perpendicular	Yes	360
B04	Ribbed	Wall	Perpendicular	Yes	360
A05	Ribbed	Extended upstream	Parallel	No	240
A06	Flat	Extended upstream	Parallel	No	240

The A cases (no electrostatics) test geometry alone; the B cases repeat them with the force, isolating its effect; A05 and A06 move the surface into the particle path to test placement against geometry. Where durations differ, comparisons use per-second rates, which are representative because the deposition curves are approximately linear after the initial transient (about 60 s). One caveat: the no-electrostatics geometry comparison (Section 5.1) uses the ribbed case A02 under parallel flow while the flat and recessed cases are perpendicular, so geometry and flow orientation are partly mixed there. The electrostatic comparison (Section 5.2) avoids this, running all three geometries under perpendicular flow.

5. Key Results

5.1. Surface Geometry Without Electrostatics

Without electrostatics, the three geometries behave broadly alike (figure 2). For the perpendicular cases A00 (flat) and A01 (recessed), particles spend roughly 30 to 40 percent longer in the screen region than in the upstream reference, reflecting the stagnation zone the screen creates. The ribbed case A02 ran under parallel flow, so its values are not directly comparable. The differences between geometries are small relative to the effects shown next.

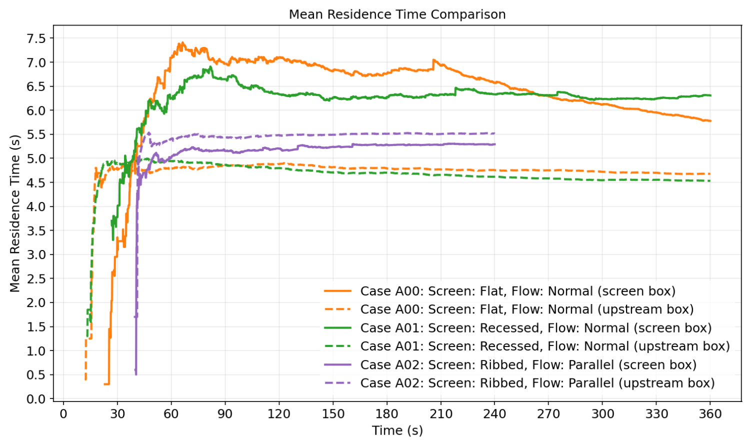

Figure 2: Mean residence time in the screen box (solid) and upstream box (dashed), three geometries without electrostatic force. A02 has parallel flow; A00 and A01 are perpendicular.

5.2. Electrostatic Deposition

The electrostatic force is the difference between a surface that collects particles and one that does not. Without it (A cases), particles approach, linger in the stagnation zone, and are swept away; deposition is negligible. With it (B cases), the same geometries sustain a steady deposition rate near one particle per second under the conditions tested. Cases B00, B01, and B04 share identical perpendicular flow and 360 s duration, giving a clean three-way comparison (table 2, figure 3).

Table 2: Deposition comparison, electrostatic force, perpendicular flow, 360 s

Metric	B00 (Flat)	B01 (Recessed)	B04 (Ribbed)
Deposited particle count	340	363	342
Deposited percentage (of total injected)	0.42%	0.45%	0.42%
Deposition rate (particles/s)	0.94	1.01	0.95
Mean residence time, screen box (s)	6.46	6.25	6.87
Mean residence time, upstream box (s)	4.74	4.48	5.22
MRT improvement, screen vs upstream	+36.2%	+39.3%	+31.5%

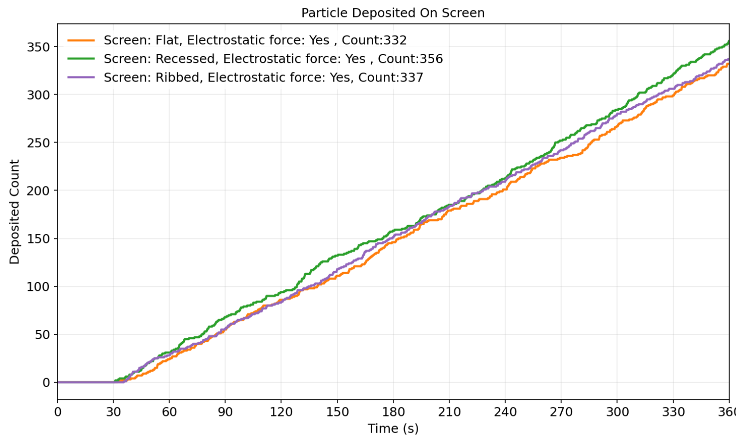

Figure 3: Cumulative deposition on the screen, three geometries with electrostatic force under perpendicular flow. The curves are approximately linear after the initial transient.

The three geometries are closely grouped: deposition spans 340 to 363 particles (about 7 percent) and rates span 0.94 to 1.01 particles per second, with the recessed screen marginally ahead. The ribbed screen has the highest screen-box residence time (6.87 s, figure 4) and retains the most particles in the domain, yet without proportionally higher deposition, showing that residence time alone does not govern capture at this force level. All three show a positive residence-time gain from the upstream to the screen box, confirming the force slows particles near the screen regardless of geometry.

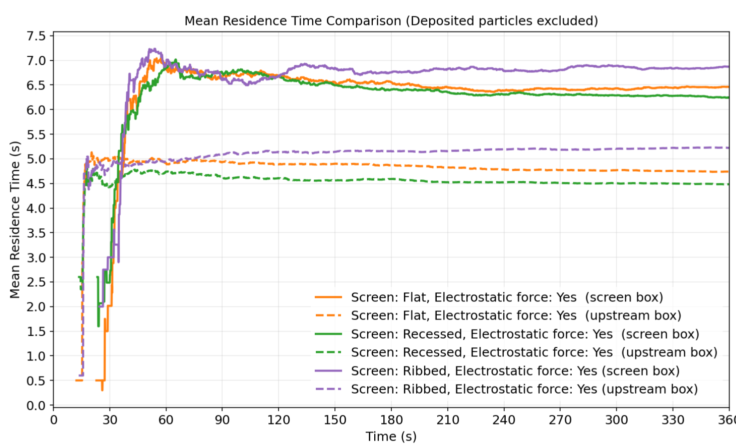

Figure 4: Mean residence time in the screen box (solid) and upstream box (dashed), three geometries with electrostatic force under perpendicular flow.

The deposited fractions are small (under 0.5 percent of all injected particles) because injection covers the full 72 m^2 inlet plane while the screen presents only 2.64 m^2, so most particles never reach it. Normalised by the roughly 8 particles per second that geometrically correspond to the screen area, the charged screen captured on the order of one in eight of the particles passing through its vicinity, under the single flow and charge condition tested. This ratio should be read as indicative of the mechanism rather than as a performance figure. Deposition spreads across the full screen, with closely overlapping patterns across geometries.

5.3. Placement Versus Geometry

Cases A05 and A06 place the surface in the particle path: the screen is integrated flush into a thin slab so the incoming stream travels along it before reaching the screen. A05 is ribbed and A06 flat, both without electrostatics. The mean residence time near the screen, over the last 60 s, is 9.32 s (ribbed) versus 9.25 s (flat), a difference under one percent (figure 5).

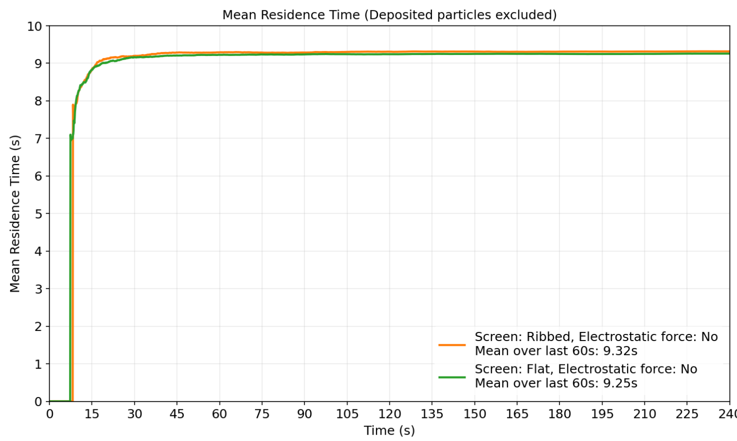

Figure 5: Mean residence time near the screen in the extended upstream configuration: ribbed (A05) versus flat (A06), no electrostatic force.

The same metric in the wall-mounted configuration is around 5 to 7 s (Sections 5.1 and 5.2). Moving the surface into the particle path raised the near-surface residence time by roughly 40 percent; changing the profile at that position moved it by under one percent. The lever that matters is where the surface sits, not the fine detail of its profile.

6. Interpretation

The effectiveness of a wall-integrated surface is the product of an encounter probability and a capture efficiency.

- **Encounter is governed by placement and flow.** A surface mounted flush on a wall, away from the dominant particle pathways, interacts with only the small fraction of particles that local transport delivers; a surface placed along a pathway holds particles in its vicinity far longer.
- **Capture is governed by the interaction mechanism.** At realistic force levels, electrostatic attraction reliably retains slow, nearby particles, sustaining deposition where a passive surface retains essentially nothing.
- **Geometry is a secondary factor within the range evaluated.** Across the flat, recessed and ribbed profiles tested, with or without electrostatics and in both configurations, the geometries stayed

within a few percent of each other on every metric measured. Placement and electrostatic interaction produced larger effects than geometry within the geometries evaluated.

These conclusions carry honest limits. The geometry effects are modest and should not be extrapolated to other profiles or scales, and the no-electrostatics comparison mixes the ribbed case with a different flow orientation. The electrostatic model is a calibrated simplification of real charge physics (Appendix B). All results come from a single configuration, flow rate, and particle size range (1 to 10 μm), with statistically small deposition counts. No physical validation has been performed; the findings rank design concepts and identify trends rather than predict absolute performance, and physical testing remains the outstanding next step.

7. Future Work and Next Steps

Several directions would build on these findings:

- **Exposure reduction in breathing zones.** Extend the analysis from near-surface deposition to particle concentration in occupied breathing zones, the metric most relevant to human exposure.
- **Multiple surfaces and room layouts.** Test several surfaces together and a range of room geometries and ventilation layouts to understand how placement strategies generalise.
- **Broader operating conditions.** Vary flow rate, particle size distribution, and charge level to map the sensitivity of the encounter and capture effects.
- **Physical validation.** A physical test campaign remains the key next step to move from a relative ranking of concepts to measured performance.

The strongest message from this work is that intelligent placement and particle-pathway interaction, rather than surface geometry alone, are the design levers most worth pursuing. Designing surfaces around how particles actually move through a space is the direction most likely to yield meaningful real-world benefit.

Appendix A: CFD Details

Domain (hall). The domain is a 20 m by 12 m by 6 m volume. Air enters at a uniform 0.2 m/s through the full 12 m by 6 m end plane (72 m^2) and leaves through the opposite end; the remaining outer boundaries and floor are no-slip walls. Air density is 1.2 kg/m^3 and kinematic viscosity is 10^{-5} m^2/s. The screen measures 1.2 m by 2.2 m. The mesh is locally refined around the screen, with the geometric features (the recessed cavity and the ribs) refined further; total mesh size ranges from 1.3 to 3.8 million points across the cases. At the screen length scale (1.2 m) the Reynolds number is 24,000, and the estimated y+ in the screen region is between 2 and 8 (around 2 over the refined geometric features).

Solver and turbulence. Airflow and particles are solved together in a transient Eulerian-Lagrangian framework with k-omega SST turbulence. Momentum uses second-order (linear-upwind) spatial discretisation; time integration is first-order implicit with an adaptive time step held at a Courant number of 1.

Particle injection. Three size classes (PM1 1.0 μm, PM2.5 2.5 μm, PM10 10.0 μm) are injected from the inlet plane at 75 particles per second per class (225/s total), from rest, at density 1500 kg/m^3. This gives about 81,000 particles over 360 s, or 54,000 over 240 s.

Particle forces. Aerodynamic drag (Ergun-Wen-Yu model), gravity, and, in the B cases, the electrostatic attraction of Appendix B. Momentum coupling with the air is negligible at this dilute loading. At the boundaries, particles stick on the screen and back wall. Other walls are modelled as non-sticky. Brownian motion and thermal buoyancy are not modelled; above roughly 0.3 μm in ambient flow, Brownian diffusion is negligible against drag and gravity.

Residence-time sampling. Two sampling boxes record particle statistics: one flush with the screen (screen box) and one upstream as an unobstructed reference (upstream box), shown in figure 6. Mean residence time is taken from the stabilised end of each run, with deposited particles excluded (no finite residence time can be assigned to them), which biases the metric slightly downward for higher-deposition cases.

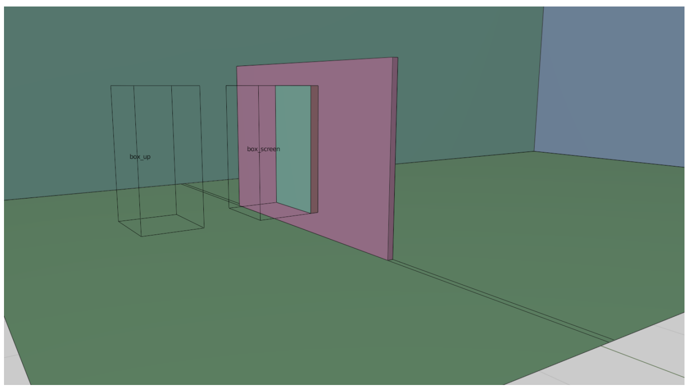

Figure 6: Sampling box locations: the screen box flush with the screen and the upstream box as an unobstructed reference.

Appendix B: Electrostatic Force Model

The charged surface attracts a nearby particle through an inverse-square interaction integrated over the screen:

$$F = C \times G \tag{1}$$

where C is a tuning constant and G a precomputed geometric factor summing the area-weighted inverse-square contributions from all points on the screen. Area weighting makes C act as a surface charge density, so the same C applies one charging condition across geometries and field differences arise only from geometry. The field was calibrated so that the average near-screen force on a 10 μm particle equals its weight, with a local peak of 4.9 times gravity (figure 7).

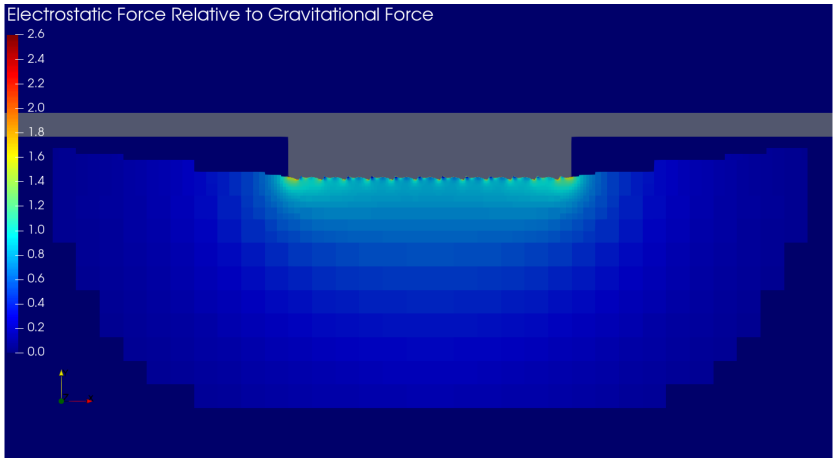

Figure 7: Electrostatic force near the ribbed screen, normalised by the gravitational force on a 10 μm particle (top view).

The model represents a uniform, constant surface charge; charge variation, decay, humidity, and agglomeration are not captured, and C is tuned for plausible force magnitudes rather than measured. Results identify trends and compare concepts rather than predict absolute performance, and physical testing is recommended.

Acknowledgement

The computational fluid dynamics simulations and analysis in this study were carried out by Nishan Jain, PhD in Aerospace Engineering (University of Maryland), a CFD consultant specialising in turbulence and multiphase, particle-laden flow.