

Article

Numerical Evaluation of Coarse Particle Transport and Deposition over a Steep Ridge

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Abstract

Coarse-particle deposition over steep terrain is shaped by the mismatch between rapid flow deflection and slower particle motion. We apply an existing Eulerian–Lagrangian numerical model to simulate the transport of 100 μm spherical alumina over a flat floor and a 0.20 m high triangular ridge at an incoming wind speed of 10 m s^{-1} . Wind-tunnel measurements are used to evaluate the simulated flow, particle motion, and surface deposition. For centerline deposition flux, root-mean-square errors normalized by the corresponding mean measured flux are 8.6% over the flat floor and 9.8% over the ridge. Transverse profiles show larger normalized errors of 20.1–40.8%. Over the flat floor, centerline deposition peaks about 3 m downstream of release. With the ridge present, floor deposition is enhanced on the approach and reduced at the sampled lee-side stations, followed by partial downstream recovery. Separate aperture measurements show greater collection at the sampled windward than leeward locations. The approach-region maximum overlaps the flat-floor landing zone; the measured approach-to-lee contrast provides clearer evidence of terrain-associated redistribution. Flow deflection, particle inertia, upstream removal, and wake exchange provide a physical interpretation of this sequence. The model captures the main streamwise redistribution under the tested conditions, although substantial discrepancies remain in some transverse deposition profiles.

Keywords: coarse particles; complex terrain; dry deposition; Eulerian–Lagrangian simulation; separated flow

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1. Introduction

Coarse airborne particles contribute to atmospheric transport, surface loading, air-quality impacts, and the cycling of mineral nutrients [1–4]. Recent assessments suggest that the abundance and lifetime of particles larger than 10 μm are often underestimated [3,4]. Where those particles settle depends not only on their size and the incoming wind but also on how the surface modifies near-ground flow. Resolving local deposition is therefore important when the terrain cannot be approximated as flat.

A steep ridge provides a simple setting in which these effects become coupled. The approaching boundary layer turns upward and accelerates near the crest, whereas flow separation produces a low-speed wake downstream [5–8]. Coarse particles do not necessarily follow these changes: their inertia carries them across curved streamlines, while gravity and turbulent motions continue to move them toward the surface. Experiments and simulations over hills document windward enhancement and lee-side reduction, but their relative magnitudes depend on the particle and terrain scales [9–17]. Wind-tunnel measurements for spherical alumina across several idealized landforms provide a particularly relevant experimental basis [18].

Experiments provide direct deposition data but cannot resolve every trajectory or the full three-dimensional wake. Gong et al. [19] used IDDES and Lagrangian tracking with wind-tunnel validation to examine dust-collector aerodynamics. More generally, Eulerian-Lagrangian calculations retain particle inertia and trajectory history [20–26]. Two-way momentum coupling can be included when particle loading warrants it [27,28], while force scaling identifies terms that may be neglected for dilute suspensions of heavy particles [29]. For separated high-Reynolds-number flow, hybrid Reynolds-averaged Navier–Stokes and large-eddy simulation methods reduce near-wall cost while resolving large wake structures [30–32]. For terrain-induced deposition, however, model evaluations that connect the incoming airflow, particle response, and surface flux remain limited.

This study uses the established IDDES-based Eulerian–Lagrangian framework of Gong et al. [19], together with wind-tunnel measurements, to investigate how a steep triangular ridge modifies coarse-particle deposition from a localized source. The flat-floor case provides a reference for quantifying upstream enhancement and lee-side depletion without attributing the entire upstream deposition maximum to terrain. Particular attention is given to whether the downstream increase in lee-side deposition represents recovery toward the flat-floor level or a continuing deposition deficit. The specific contribution is a quantitative characterization of these changes, supported by numerical airflow and particle-motion fields that aid their physical interpretation. The findings are restricted to the tested particle properties, release conditions, wind speed, and ridge geometry.

2. Materials and Methods

2.1. Wind-Tunnel Experiment

The experimental data were obtained during a later campaign at Lanzhou University, following the experimental procedures described by Liu et al. [18] in a different wind-tunnel facility. The air-velocity, PIV particle-velocity, and deposition measurements used here were collected during this later campaign and had not been published previously. Reference [18] provides the methodological background; its published runs were not used in the present numerical comparison. Additional statistical analyses performed during revision used the measurements from the later campaign.

Both cases used the nominal 10 m s^{-1} wind condition and alumina particles with a measured size distribution centered at approximately $100 \text{ }\mu\text{m}$. The streamwise coordinate is measured from the floor projection of the particle-release point.

The reference case used the flat rough floor. The terrain case contained a spanwise-uniform triangular ridge with height $H = 0.20 \text{ m}$ and full streamwise base length $L = 0.20 \text{ m}$. Thus, $L/H = 1$, and each face inclined $\arctan(2H/L) = 63.4^\circ$. The crest was located at $x = 4.0 \text{ m}$. This geometry matched the wind-tunnel model and provided an idealized steep, sharp-crested ridge for examining how flow deflection, lee-side separation, and particle inertia influence deposition relative to the flat-floor reference. The study focuses on interpreting these coupled processes under the tested conditions. Quantitative extrapolation to other ridge geometries or natural terrain requires further validation.

Spherical alumina particles had a measured size distribution centered at 100 μm and a material density of 3900 kg m^{-3} . The measured volume-based particle-size distribution is presented in Figure A1. The numerical particle source represented the measured size classes and their corresponding fractions. 100 μm denotes the nominal particle size. They were released downward through a 22 mm internal-diameter tube at $z = 0.50$ m. A phase Doppler analyzer (Dantec Dynamics A/S, Skovlunde, Denmark) measured a mean exit speed of 1.163 m s^{-1} . The incoming wind speed was 10 m s^{-1} . Each deposition run released 0.85326 kg over 20 min, equivalent to 7.11×10^{-4} kg s^{-1} . The bulk mass loading was of order 10^{-5} . Table 1 summarizes the experimental configurations used for the present numerical assessment.

Table 1. Experimental configurations used for the present numerical assessment.

Dataset	Working Section, Length $\times$ Width $\times$ Height (m)	Terrain Configuration	Particle-Release Height (m)
Flat-floor case	12 $\times$ 1.20 $\times$ 1.10	Flat rough floor	0.50
Ridge case	12 $\times$ 1.20 $\times$ 1.10	Triangular ridge: height 0.20 m, full streamwise base length 0.20 m, crest at $x = 4.0$ m	0.50

The wind-tunnel arrangements for the flat-floor and ridge cases are shown in Figure 1. Mean air velocity profiles were measured with a two-dimensional hot-wire probe (Dantec Dynamics A/S, Skovlunde, Denmark) at $x = -0.2, 0.9, 2.0, 3.1, 4.0, 5.3$, and 6.4 m and at heights up to 0.45 m. Each point was sampled for 3 min. The measured approach-flow profiles retained a substantial vertical velocity gradient above the ridge height of $H = 0.20$ m, indicating that the ridge was immersed in the sheared portion of the approaching boundary layer. However, the measurements extended only to $z = 0.45$ m and did not resolve a clear outer-flow velocity plateau. Thus, the profiles support a boundary layer thicker (δ_{99}) than the ridge, but do not provide a reliable quantitative estimate of δ_{99}/H . Images were acquired using a PIV system (Dantec Dynamics A/S, Skovlunde, Denmark) over a 0.43 m $\times$ 0.23 m window on the tunnel center plane and processed by particle tracking velocimetry (PTV), following Liu et al. [18]. Ten image sequences were acquired during each release run. Experimental particle velocities were grouped into 0.01 m $\times$ 0.01 m statistical bins. Numerical statistics used the computational cells, so the experimental and numerical spatial resolutions were not identical. For both datasets, particle speed was calculated from the two velocity components in the measurement plane as $s_i = (u_{p,x,i}^2 + u_{p,z,i}^2)^{1/2}$. Samples collected within each spatial bin over the sampling period were pooled with equal weights. The local mean and variance were calculated as $\bar{s} = N^{-1} \sum_{i=1}^N s_i$ and $\sigma_s^2 = N^{-1} \sum_{i=1}^N (s_i - \bar{s})^2$, respectively. Here, N is the number of pooled velocity samples within the bin. The mean is calculated from individual planar speed magnitudes. Mean speed and variance have units of m s^{-1} and $\text{m}^2 \text{s}^{-2}$, respectively. Empty bins were treated as missing data and excluded from statistical comparisons. Surface deposition was measured with 12 mm internal-diameter tubes mounted flush with the honeycomb floor. Three tubes were placed at each streamwise station from $x = 2.0$ to 7.5 m at 0.5 m intervals. Transverse arrays were placed at $x = 4$ and 5 m for the flat case and at $x = 5$ and 6 m for the ridge case. Flux was obtained from the collected mass, exposed area, and sampling time. For each run, the deposition flux was calculated as $J_r = M_r / (A_c T_r)$, where M_r is the combined net mass collected by the three tubes, A_c is their summed opening area, and T_r is the recorded collection duration. Station means and between-run sample standard deviations were calculated from the retained run fluxes. Five flat-floor runs and four ridge runs were conducted. The ridge was made of wood without an adhesive coating. Eight circular collection openings, each 8 mm in diameter, were installed flush with each inclined face. The

aperture record used in Figure A2 corresponds to model A, nominally 100 μm alumina, a nominal wind speed of 10 m s^{-1} , and a feeding rate of 42.663 g min^{-1} over a cumulative exposure of 75 min. Unlike the floor records processed separately for individual runs, this record contains cumulative aperture masses. Aperture fluxes were normalized by the actual opening areas and exposure duration. They characterize collection at the sampled openings.

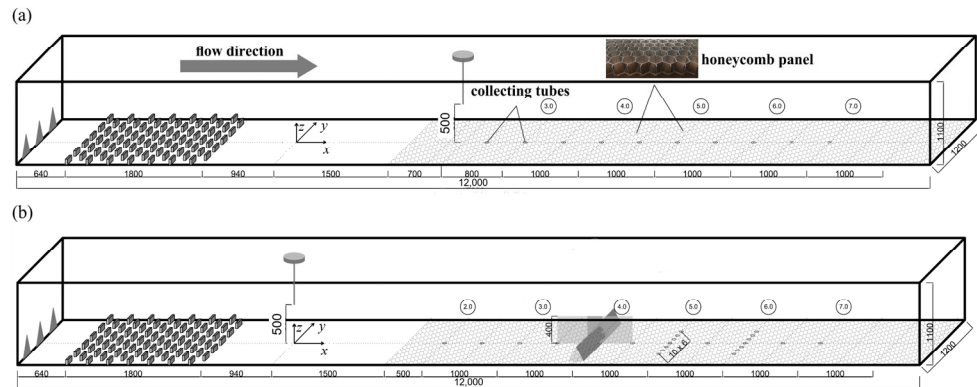


Figure 1. Wind-tunnel arrangement for (a) the flat-floor case and (b) the ridge case. Both panels show the inlet spires, roughness array, particle feeder, honeycomb floor, and deposition collectors. In (b), the ridge crest is 4.0 m downstream of release. The particle release height is 0.50 m in both cases. Dimensions are in millimeters; circled numbers denote streamwise positions in meters.

The balance had a nominal resolution of 0.001 g. For a 20 min collection period using three 12 mm diameter collectors, a 0.001 g change in the combined net collected mass corresponds to a flux change of approximately 0.00246 $\text{g m}^{-2} \text{s}^{-1}$. This is a weighing-resolution scale. The standard deviations in Figure A3a–c describe between-run variability.

2.2. Numerical Model

The present study applies the Eulerian–Lagrangian framework of Gong et al. [19] without modifying its underlying model formulation or solution algorithm. The application-specific setup includes the flat-floor and triangular-ridge geometries, local mesh refinement, flow boundary conditions, and particle-source parameters. Particle motion is compared within the experimental observation window, and deposition is evaluated through streamwise and spanwise flux profiles. The governing equations and numerical conditions are given below.

2.2.1. Governing Equations for the Fluid Phase

The fluid phase was treated as an incompressible, isothermal Newtonian fluid with density $\rho_f = 1.2 \text{ kg m}^{-3}$ and kinematic viscosity $\nu = 1.5 \times 10^{-5} \text{ m}^2 \text{s}^{-1}$. The resolved continuity equation is

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0. \quad (1)$$

The momentum equation is

$$\frac{\partial \bar{u}_i}{\partial t} + \bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{1}{\rho_f} \frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} [2(\nu + \nu_t) \bar{S}_{ij}] + f_i^p. \quad (2)$$

Here, the overbar denotes a velocity resolved by the hybrid formulation, $\bar{S}_{ij} = 1/2 (\partial \bar{u}_i / \partial x_j + \partial \bar{u}_j / \partial x_i)$ is the resolved strain-rate tensor, $\bar{p}$ is pressure, ν_t is the modeled eddy viscosity, and f_i^p is the particle-to-fluid momentum source. Momentum transferred by the particles was accumulated in each computational cell as

$$f_i^p = -\frac{1}{\rho_f V_{\text{cell}}} \sum_{n=1}^{N_{\text{cell}}} F_{D,i}^{(n)}, \quad (3)$$

where V_{cell} is the cell volume, N_{cell} is the number of computational particles in the cell. Parcel n represents w_n physical particles of diameter d_n . The single-particle mass and represented parcel mass are $m_{p,n} = \rho_p \pi d_n^3 / 6$, $M_n = W_n m_{p,n}$. The quantity $F_{D,i}^{(n)}$ in Equation (3) denotes the total drag force on parcel n , equal to W_n times the corresponding single-particle force. Thus, no additional multiplicity factor is applied to this whole-parcel force. The mass $m_{p,n}$ in Equation (5) refers to one physical particle, whereas deposited-mass accounting uses M_n . The negative sign in Equation (3) accounts for the reaction on the fluid. Two-way momentum coupling was retained, although its mean-flow effect is expected to be small at the measured loading [27,28].

Turbulent viscosity was calculated using the SST-based improved delayed detached-eddy simulation (IDDES) approach [30–32]. It treats attached near-wall flow in a Reynolds-averaged mode and resolves larger motions in sufficiently refined separated flow.

2.2.2. Particle Motion and Deposition

Each computational particle represented a parcel of spherical alumina particles. Its position $\mathbf{x}_p$ and velocity $\mathbf{u}_p$ were advanced from

$$\frac{d\mathbf{x}_p}{dt} = \mathbf{u}_p \quad (4)$$

And

$$m_p \frac{d\mathbf{u}_p}{dt} = \frac{1}{2} \rho_f C_D A_p |\mathbf{u} - \mathbf{u}_p| (\mathbf{u} - \mathbf{u}_p) + m_p \left(1 - \frac{\rho_f}{\rho_p}\right) \mathbf{g}, \quad (5)$$

where m_p is the particle mass, $A_p = \pi d_p^2 / 4$ is its projected area, $\mathbf{u}$ is the instantaneous resolved fluid velocity interpolated to the particle position, and $\mathbf{g}$ is gravitational acceleration. The drag coefficient was evaluated from [21,22]

$$C_D = \begin{cases} \frac{24}{Re_p} \left(1 + \frac{Re_p^{2/3}}{6}\right), & Re_p \leq 1000, \\ 0.424, & Re_p > 1000, \end{cases} \quad (6)$$

With

$$Re_p = \frac{|\mathbf{u} - \mathbf{u}_p| d_p}{\nu}. \quad (7)$$

The particle-to-fluid density ratio exceeded 3000, so drag and gravity with buoyancy dominated the motion. Added mass, pressure-gradient, Basset-history, and lift forces were omitted based on force scaling for small heavy particles [20,29]. Particle-particle collisions were neglected because the suspension was dilute.

First-contact trapping was imposed on the floor and ridge as an idealized capture boundary condition. Deposited mass was accumulated over each sampling area, and the deposition flux was calculated as

$$J_d = \frac{1}{A_c \Delta t_s} \sum_{n \in D(A_c, \Delta t_s)} w_n \frac{\rho_p \pi d_n^3}{6}, \quad (8)$$

where A_c is the collection area; for inclined surfaces, the collection area is the actual surface area, $\Delta t_s = 1200s$ is the deposition accumulation interval, matching the experimental sampling duration, $D(A_c, \Delta t_s)$ denotes the parcels deposited within the collection area A_c during interval Δt_s ; each parcel contributes its represented physical mass once.

The summation includes particles deposited within A_c during this interval. The initial airflow-development period, completed before particle injection, was excluded from the deposition statistics.

2.2.3. Computational Domain and Numerical Settings

The computational domain was 10.0 m long, 1.20 m wide, and 1.10 m high. A 2.0 m upstream recycling region supplied the inflow. The instantaneous velocity field sampled 2.0 m downstream was mapped back to the inlet, with its mean adjusted to maintain the prescribed throughflow. This arrangement recirculated velocity variations from the internal flow solution. In the analysis coordinates, particles were released at $x = 0$ and $z = 0.50$ m, and the ridge crest was at $x = 4.0$ m. Solver visualizations retain the precursor length, placing the release point and crest at 2.0 and 6.0 m, respectively (Figure 2).

The target incoming velocity profile was

$$U(z) = \frac{u_*}{\kappa} \ln\left(\frac{z}{z_0}\right), \quad (9)$$

with friction velocity $u_* = 0.70 \text{ m s}^{-1}$, von Kármán constant $\kappa = 0.41$, and aerodynamic roughness length $z_0 = 1.0 \times 10^{-3} \text{ m}$. The reported wind speed of approximately 10 m s^{-1} denotes the representative mean inlet velocity derived from the experimental profile. The developed precursor field supplied the main domain. The lateral boundaries were treated as solid walls corresponding to the sidewalls of the experimental wind tunnel. The upper boundary was treated as a solid wall representing the wind-tunnel roof, and the outlet used an open pressure condition. The tunnel height of 1.10 m and ridge height of 0.20 m matched the experimental geometry, giving a ridge-to-tunnel height ratio of approximately 0.182 [33,34].

The calculations used an in-house Eulerian–Lagrangian solver developed from the standard components of OpenFOAM 3.0.1. The SST-IDDES coefficients were retained without study-specific tuning. Particle tracking used the interpolated instantaneous resolved fluid velocity. In LES-dominated regions, resolved turbulent motions contributed directly to particle dispersion. In RANS-dominated regions, modeled turbulence affected the carrier-flow solution but did not supply additional random particle-velocity fluctuations. This treatment targets the principal redistribution of the nominally $100 \mu\text{m}$ alumina particles, whose finite inertia attenuates their response to some rapid fluctuations. The floor and ridge faces used the Rough Wall Function, with roughness Height = 0.0003 m, roughness Constant = 0.5, and roughness Factor = 1. The ridge-case mesh contained 5,176,730 cells, with local refinement in the central particle-transport region, around the ridge, and in the near wake (Figure 2). The volume-equivalent cell size, defined as $\Delta_v = V_c^{1/3}$, ranged from 1.554 to 41.273 mm.

Fluid time integration used the second-order backward scheme. Velocity convection used Gauss LUST, and velocity gradients used Gauss linear with a coefficient of 0.1. Laplacian terms used Gauss linear interpolation with limited non-orthogonal correction, with a correction coefficient of 0.33; the same coefficient was used for the surface-normal gradient correction. Pressure was solved using GAMG with Gauss–Seidel smoothing, an absolute residual tolerance of 10^{-6} , and a relative tolerance of 0.05. The final pressure solve used zero relative tolerance. Velocity was solved using smooth Solver with symmetric Gauss–Seidel smoothing, an absolute tolerance of 10^{-7} , and zero relative tolerance. PISO used two pressure corrections and no additional non-orthogonal correction loops [35]. The fluid time step was $2 \times 10^{-4} \text{ s}$. Particle velocity was integrated using the Euler scheme. Fluid velocity was interpolated to particle positions using cellPoint, while fluid density and dynamic viscosity were interpolated using cell interpolation.

Particle injection followed a 300 s particle-free flow-development period. Deposition accumulation began with particle release and continued for 1200 s, excluding the preceding flow-development interval. The particle source used the experimentally measured size classes. The volume fractions shown in Figure A1 were used as mass fractions because the alumina particles have a common material density. For size class k with mass fraction f_k , the prescribed injected mass was $M_k = f_k M_{inj}$, with $\sum_k f_k = 1$ and $M_{inj} = 0.85326$ kg over 1200 s. The corresponding total mean mass flow rate was 7.1105×10^{-4} kg s⁻¹. Parcel multiplicities specify the physical mass represented by the injected computational parcels.

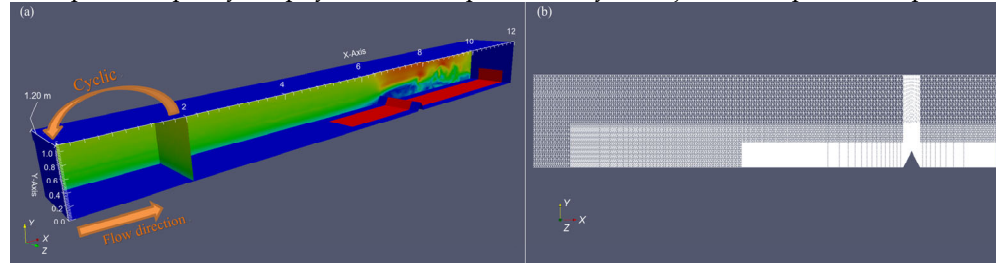


Figure 2. Computational domain and mesh for the ridge case. (a) Three-dimensional domain with a 2 m cyclic precursor. (b) Mesh refinement near the floor and ridge. The flat-floor case uses the corresponding domain without the ridge. The crest lies at 6 m in solver coordinates and $x = 4$ m from release.

2.3. Characteristic Scales and Model Validation

The ridge Reynolds number, particle response time, and ridge-scale Stokes number were estimated as

$$\begin{aligned} Re_H &= \frac{U_{ref} H}{\nu} = 1.33 \times 10^5, \\ \tau_p &= \frac{\rho_p d_p^2}{18\mu} \approx 0.12 \text{ s}, \\ St_H &= \frac{\tau_p U_{ref}}{H} \approx 6.0, \end{aligned} \quad (10)$$

where $\mu = \rho_f \nu$ and $U_{ref} = 10$ m s⁻¹. The corresponding Froude number, $Fr_H = U_{ref}/\sqrt{gH}$, is approximately 7.1. The Stokes response time is a scale estimate; the trajectory calculation uses the Reynolds-number-dependent drag coefficient in Equation (6). The value $St_H \approx 6$ indicates that particle adjustment is slower than the fluid motion over one ridge height [16].

We compared measured and simulated mean air-velocity profiles to check the approaching boundary layer. The spatial distributions of mean planar particle speed and local pooled-sample speed variance were compared qualitatively within the observation region. Finally, collected-mass measurements were compared with the calculated stream-wise and spanwise deposition fluxes in both terrain configurations. Deposition-flux errors were evaluated at the measurement locations using linear interpolation of the numerical profiles without extrapolation. Each matched location was weighted equally. The root-mean-square error (RMSE) was calculated as the square root of the mean squared difference between simulated and measured fluxes. The normalized RMSE (NRMSE) was defined as RMSE divided by the mean measured flux of the matched locations, expressed as a percentage. The mean absolute error (MAE) was calculated as the arithmetic mean of the absolute differences between simulated and measured fluxes. Mean bias was calculated as the arithmetic mean of simulation minus measurement, with positive values indicating overprediction. The comparison locations, sample counts, and all four error metrics are reported in Table A1.

The numerical framework was previously assessed against wind-tunnel measurements of air velocity and surface particle deposition by Gong et al. [19]. Together with the present experimental comparisons, this provides support for interpreting the main deposition redistribution under the tested conditions.

3. Results and Discussion

3.1. Fluid Flow and Ridge-Induced Separation

Over the flat floor, measured velocity increases with height, and the downstream profiles are similar (Figure 3a). The calculated profiles agree well with the measurements throughout the sampled boundary layer, supporting the incoming airflow used in the particle calculation. Figure A4 additionally presents measured approach and lee-side mean-speed profiles for both terrain configurations. These measurements document the experimental flow conditions.

With the ridge present, the incoming flow turns upward and accelerates near the crest (Figure 3b). The streamlines then separate from the sharp lee edge and enclose a low-speed recirculation region. Faster flow passing above this region forms a shear layer that bends toward the floor farther downstream. Upstream blockage, crest acceleration, and pressure recovery are consistent with this streamline pattern and with established observations of flow over steep ridges [6–8]. This sequence creates distinct paths for particles approaching, clearing, or entering the wake.

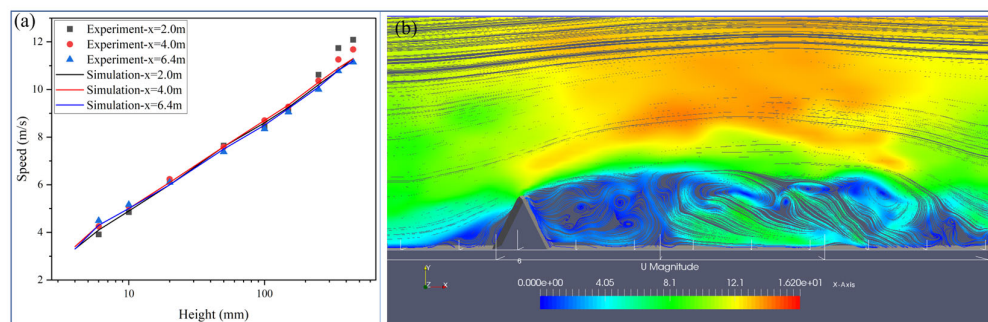


Figure 3. Airflow assessment and simulated ridge-flow structure. (a) Comparison of measured and simulated air-velocity profiles for the flat-floor reference case. The profiles correspond to $x = 2.0$, 4.0 , and 6.4 m measured from the particle-release position. (b) Instantaneous simulated streamlines colored by air-speed magnitude, illustrating flow deflection near the crest and recirculating structures in the low-speed wake downstream of the ridge.

3.2. Particle-Speed Statistics

Figures 4 and 5 are used to compare the spatial organization of particle speed and its local variance. The panels retain separate color limits to display variations within each field. These maps support qualitative comparisons of spatial patterns. Over the flat floor, both the simulation and PIV show particle speed increasing with height (Figure 4a,b). Particles near the surface move through the slower inner boundary layer, whereas those higher in the tunnel encounter faster flow. Their finite response time smooths the steepest fluid-velocity changes. The model reproduces the dominant vertical organization, although the measured field contains finer local structure.

Over the ridge, the faster particle stream rises above the crest, while a lower-speed region develops behind it (Figure 4c,d). Particles passing over the crest retain streamwise momentum and respond more slowly to flow turning; those entering the wake spend longer in slower air. The two fields show how flow separation affects the particle supply to the surface.

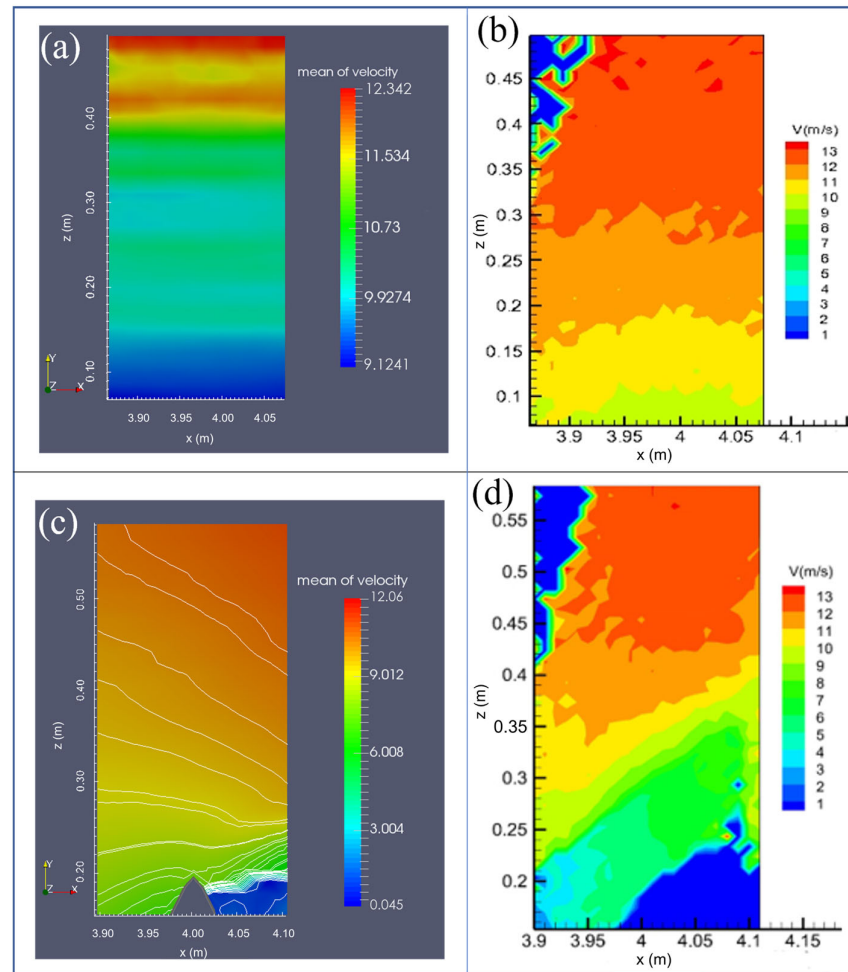


Figure 4. Comparison of simulated and PIV-measured particle speed within the PIV observation window. (a,b) Flat floor: (a) simulation and (b) measurement. (c,d) Ridge: (c) simulation and (d) measurement.

Particle-speed variance is less uniform than the mean field (Figure 5). Over the flat floor, both datasets show stronger fluctuations near the surface and weaker fluctuations aloft. Near the ridge, increased variance borders the lifted particle stream and the separated wake, where particles with different trajectories meet. The PIV field contains more localized variability than the simulation. Further tests of wake resolution and sampling time may help explain this difference.

3.3. Deposition over the Flat Surface

The simulated wall-collection pattern shows a broad deposit concentrated near the centerline that weakens downstream (Figure 6a). The localized source confines the deposit laterally, while downward release and gravity bring particles to the floor. Upstream deposition reduces the airborne particle supply farther downstream. Streamwise and spanwise flux comparisons are shown in Figure 6b,c. The boundary field kinematicCloud records the accumulated represented particle mass on each computational face, in kg. Under the prescribed floor and ridge capture condition, it records mass removed upon surface impact. The corresponding face-averaged deposition flux over an interval Δt is $J_f = \Delta M_f / (A_f \Delta t)$, where A_f is the actual face area. Figures 6a and 7a show unnormalized face mass. Quantitative comparisons use the area- and time-normalized profiles in Figures 6b,c and 7b,c.

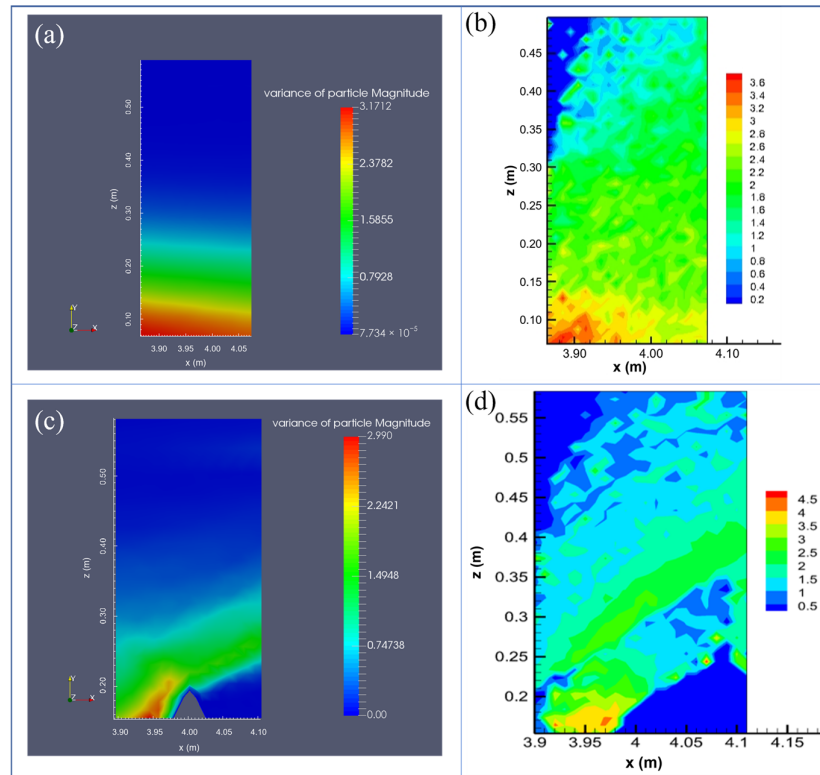


Figure 5. Variance (m^2s^{-2}) of particle-speed magnitude in the PIV observation window. (a,b) Flat floor: (a) simulation and (b) measurement. (c,d) Ridge: (c) simulation and (d) measurement.

Measured and simulated centerline deposition reaches a maximum near $x = 3$ m and then decreases downstream (Figure 6b). The peak marks the main landing region of the released particles; continued deposition gradually reduces the particle mass available farther downstream.

At $x = 4$ and 5 m, the measured and simulated deposits are concentrated toward the plume interior (Figure 6c). At $x = 4$ m, the calculated flux is higher over much of the sampled width. At $x = 5$ m, the simulated distribution lies closer to the measurements. The comparison shows the centerline concentration and downstream reduction in lateral flux. Across the 10 centerline measurement locations, the RMSE was $0.0179 \text{ g m}^{-2} \text{ s}^{-1}$, corresponding to an NRMSE of 8.6%. For the transverse profiles at $x = 4$ and 5 m, each comprising seven measurement locations, the RMSEs were 0.0528 and $0.0166 \text{ g m}^{-2} \text{ s}^{-1}$, respectively, with NRMSEs of 40.8% and 21.2%. At $x = 4$ m, the simulation overpredicts deposition at all seven transverse locations, giving identical MAE and positive mean bias values of $0.04601 \text{ g m}^{-2} \text{ s}^{-1}$ (Table A1). This discrepancy therefore extends across the sampled width and cannot be described solely as local fluctuations. At $x = 5$ m, the mean bias becomes negative ($-0.01341 \text{ g m}^{-2} \text{ s}^{-1}$), showing that the direction of the transverse-profile

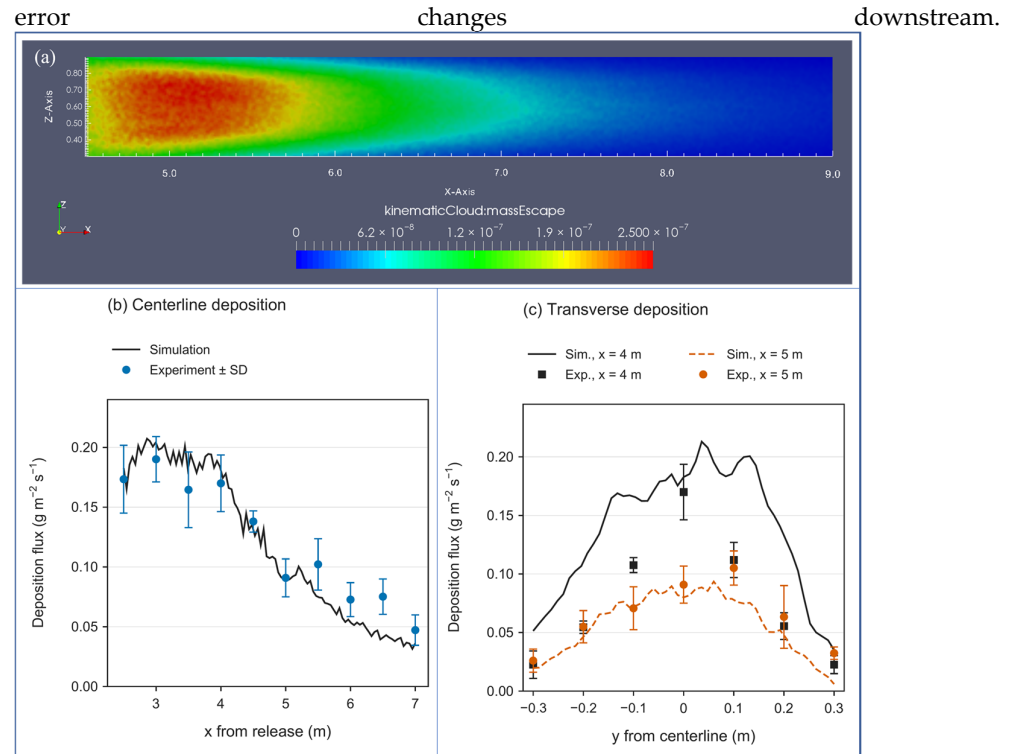


Figure 6. Deposition over the flat floor. (a) Accumulated deposited mass per computational boundary face (kg). (b) Streamwise variation in centerline deposition flux. (c) Spanwise deposition-flux distributions at $x = 4$ and 5 m. Symbols denote experimental run-wise means; error bars show $\pm$ one between-run sample standard deviation. Lines denote simulations. Between-run variability for the experimental centerline and transverse profiles is shown in Figure A3a,b.

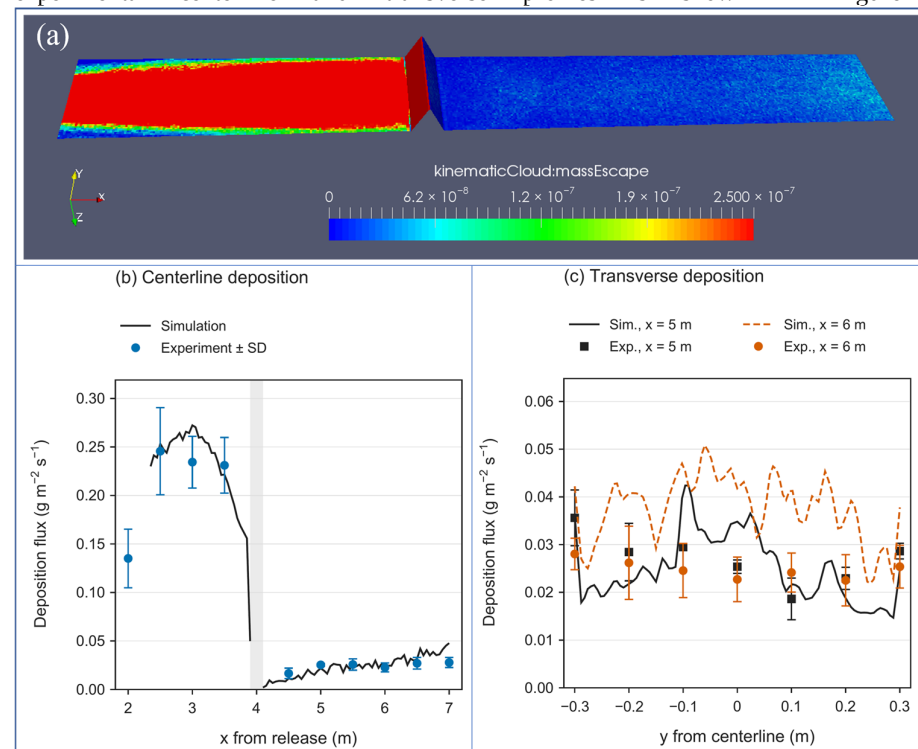


Figure 7. Deposition over the steep ridge. (a) Accumulated deposited mass per computational boundary face (kg). (b) Streamwise variation in centerline deposition flux; the crest is at $x = 4$ m. The

gray band in (b) marks the streamwise extent of the ridge base ($x = 3.9\text{--}4.1$ m). (c) Spanwise deposition-flux distributions at $x = 5$ and 6 m. Symbols denote experimental run-wise means; error bars show $\pm$ one between-run sample standard deviation. Lines denote simulations. Between-run variability for the experimental ridge-centerline profile is shown in Figure A3c.

3.4. Deposition over the Ridge

The ridge produces a marked difference between the approach and the lee (Figure 7). Figure 7a records particle impacts on the approach floor and ridge surfaces under the prescribed capture condition; the normalized centerline deposition contrast is evaluated in Figure 7b. The centerline flux rises on the approach and decreases sharply near the crest at $x = 4$ m (Figure 7b). The approach-region maximum also lies near the flat-floor landing region (Figure 6b). The baseline landing distribution and ridge-induced flow deflection together affect deposition before the crest; the abrupt crest-to-lee decrease reflects the change in terrain. The matched-station statistics are reported in Table A2 and Figure A3d.

Particle inertia can contribute to the windward–lee contrast. Rapid upward deflection of the airflow along the windward slope, combined with finite particle response, can promote streamline crossing and interception by the rising surface [15–18]. This interpretation considers the simulated airflow, particle motion, and deposition together, with non-linear drag included in the trajectory calculation. The approach-region deposition also reflects the source landing distribution observed over the flat floor.

Deposition remains low in the lee but shows an overall downstream recovery. Particle exchange between the flow above the wake and the lee region may contribute to this pattern. However, cross-layer particle fluxes and trajectory-based exchange statistics were not quantified, so shear-layer exchange remains a possible contributing mechanism whose relative importance cannot be determined from the present results. To quantify ridge-associated changes relative to the flat-floor reference, the ridge-to-flat deposition-flux ratio was calculated at shared centerline floor locations (Figures 6b and 7b). Ratios were calculated separately for measurements and simulations, with numerical fluxes linearly interpolated to the measurement positions. At $x = 2.5, 3.0$, and 3.5 m, the measured ratios were 1.41, 1.23, and 1.40, respectively, indicating local enhancement of approximately 23–41% over the flat-floor values. The corresponding simulated ratios were 1.39, 1.34, and 1.20. Thus, the ridge increased deposition within an upstream region that already contained a landing maximum in the flat-floor case. Figure A2 shows the individual aperture measurements.

At $x = 4.5$ m, the measured ridge-to-flat ratio was 0.119, corresponding to an 88.1% reduction in local deposition flux. Although measured deposition increased overall farther downstream, the ratio at $x = 7.0$ m was only 0.597, leaving a 40.3% deficit relative to the flat floor. The downstream increase therefore represents partial recovery within the sampled region. The simulated ratios at $x = 4.5$ and 7.0 m were 0.087 and 1.32, respectively: the calculation reproduced strong near-lee suppression but overestimated recovery at the farthest comparison station. The transverse profiles at $x = 5$ and 6 m also show low measured deposition (Figure 7c). The simulated flux varies more strongly across the sampled width, particularly at $x = 6$ m, indicating remaining discrepancies in the local deposition distribution. The transverse fluctuations may reflect both spatially heterogeneous particle transport and finite computational sampling. The comparison supports interpretation of the broader deposition pattern, while the accuracy of local transverse fluxes remains limited. For the ridge centerline profile, the RMSE was $0.0151 \text{ g m}^{-2} \text{ s}^{-1}$ across nine matched locations, corresponding to an NRMSE of 9.8%. For the transverse profiles at $x = 5$ and 6 m, each comprising seven measurement locations, the RMSEs were 0.00649 and $0.0161 \text{ g m}^{-2} \text{ s}^{-1}$, respectively, with NRMSEs of 20.1% and 35.1%. At $x = 6$ m, all seven transverse locations are overpredicted, with an MAE and mean bias of $0.01577 \text{ g m}^{-2} \text{ s}^{-1}$ (Table A1).

The low measured flux contributes to the large NRMSE, but does not remove the underlying positive bias. Along the ridge centerline, the simulation underpredicts deposition at $x = 4.5\text{--}5.5$ m and overpredicts it at $x = 6\text{--}7$ m. At $x = 7$ m, the calculated and measured fluxes are 0.0478 and $0.0282\text{ g m}^{-2}\text{ s}^{-1}$. The simulation therefore captures the broad downstream recovery trend but overestimates its magnitude at the farthest station.

4. Conclusions

An existing Eulerian–Lagrangian framework was applied to particle transport and deposition over a flat floor and a 0.20 m triangular ridge under the investigated wind-tunnel conditions. The following conclusions are supported by the present comparisons.

The flat-floor deposition maximum occurs approximately 3 m downstream of release. The enhanced deposition ahead of the ridge overlaps this baseline settling region and should not be attributed solely to terrain forcing.

Comparison at matched experimental stations quantifies terrain-associated redistribution. Ridge-to-flat deposition ratios are 1.42 , 1.23 and 1.40 at $x = 2.5$, 3.0 and 3.5 m, respectively. The ratio decreases to 0.12 at $x = 4.5$ m and subsequently increases to 0.59 at $x = 7.0$ m, indicating enhanced approach-floor deposition and reduced lee-side deposition.

The model reproduces the main streamwise deposition pattern, with mean-normalized RMSE values of 8.6% and 9.8% for the flat-floor and ridge cases. Transverse predictions show larger discrepancies, including values of 40.8% at $x = 4$ m over the flat floor and 35.1% at $x = 6$ m in the ridge case. Agreement therefore depends on the location and profile considered.

The present results cover one particle-size range, incoming wind speed, release condition, and ridge shape. Predictions of local flux could be improved by using release-velocity distributions, testing near-wall and wake resolution and sampling convergence, and examining surface capture and rebound. Measurements across particle sizes, ridge slopes, and wind speeds, with denser sampling in the wake, would help quantify the extent of windward interception and lee-side recovery.

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Appendix A. Reprocessed Experimental Measurements

The experimental plots below use the retained weighing and mean air-speed records. The deposition statistics are based on the original analyzed run sets and the recorded collection durations.

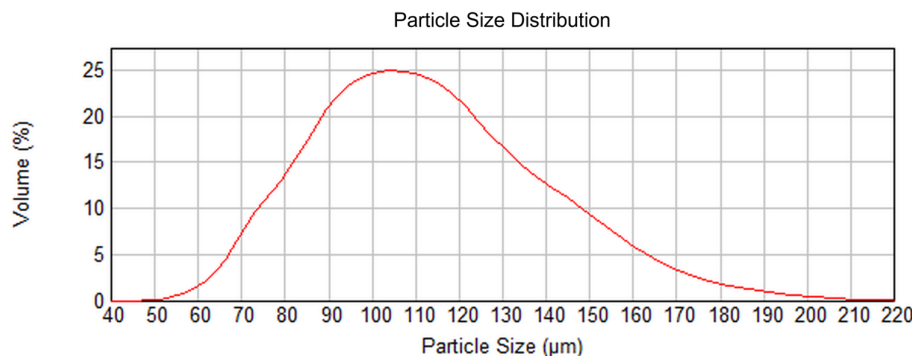


Figure A1. Measured volume-based particle-size distribution of the alumina used in the experiments. The vertical axis represents volume percentage. The nominal particle size is approximately 100 μm .

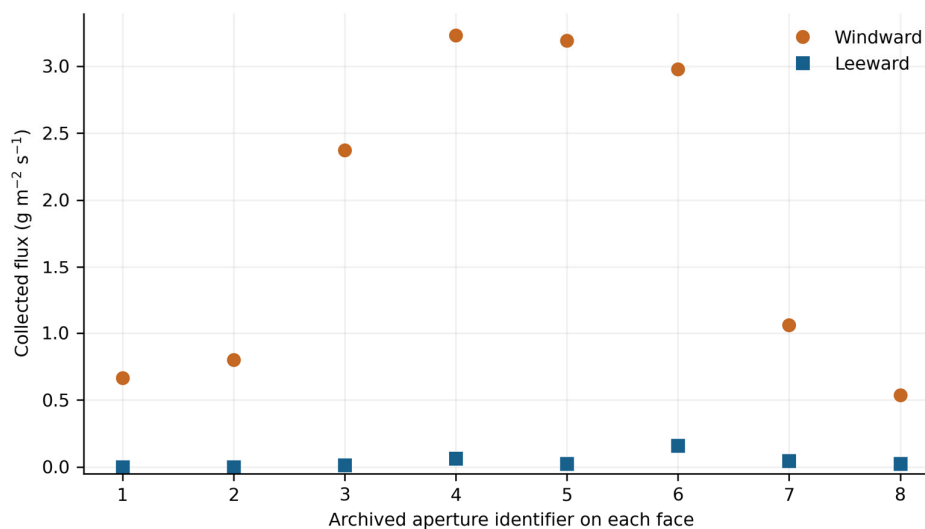


Figure A2. Ridge-aperture collection accumulated over 75 min through eight 8 mm openings on each face. The record corresponds to model A, nominally 100 μm alumina, a nominal wind speed of 10 m s^{-1} , and a feeding rate of 42.663 g min^{-1} . Flux is normalized by actual opening area. Horizontal labels are the archived aperture identifiers, not a continuous spatial coordinate; the same identifier on opposite faces is not asserted to be a matched physical point. The observations are spatial samples from one cumulative record. No repeat-run error bars or whole-face retention

efficiencies are inferred.

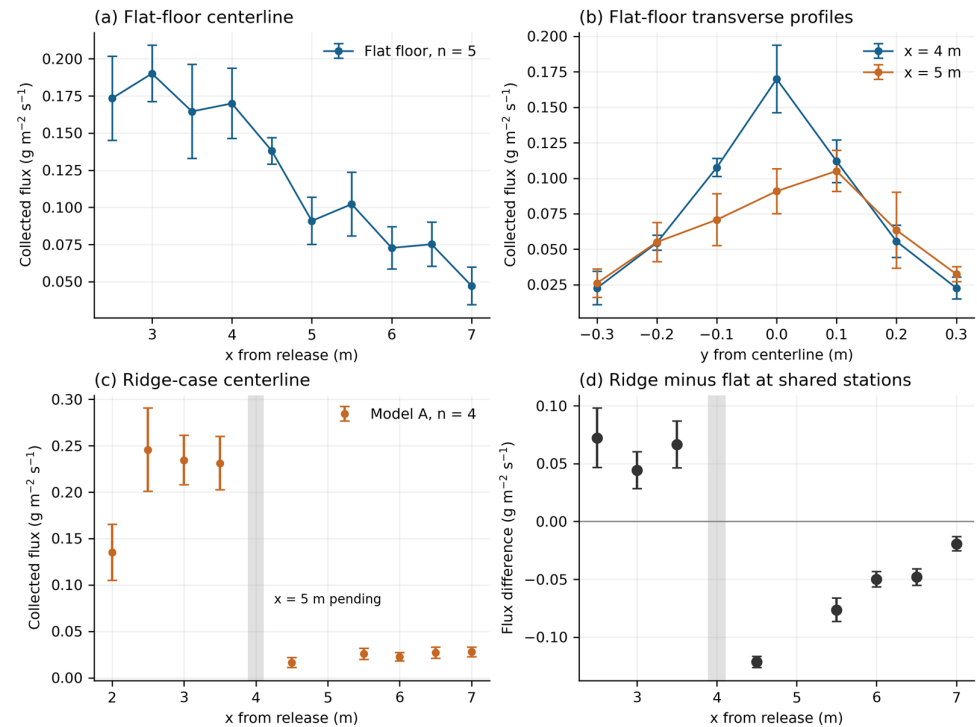


Figure A3. Experimental floor deposition. (a) Flat-floor centerline profile. (b) Flat-floor transverse profiles at $x = 4$ and 5 m. (c) Ridge-case centerline profile. (d) Ridge-minus-flat difference in mean deposition flux at shared centerline stations. Each run is normalized by the total collector opening area and its recorded collection duration. Points in (a–c) show arithmetic means across the retained independent runs (3–5 per station); error bars show the between-run sample standard deviation. Error bars in (d) show the standard error of the difference for independent run sets. The gray bands in (c) and (d) mark the streamwise extent of the ridge base ($x = 3.9$ – 4.1 m). The horizontal zero-reference line in (d) indicates equal mean deposition fluxes for the ridge and flat-floor cases.

Table A1. Quantitative errors in the deposition-flux comparisons shown in Figures 6 and 7. MAE, mean bias, and RMSE are in g m⁻² s⁻¹. n denotes the number of matched sampling locations.

Configuration and Profile	n	MAE	Mean Bias	RMSE	NRMSE (%)
Flat floor, centerline	10	0.01531	−0.00474	0.01793	8.6
Flat floor, transverse at $x = 4$ m	7	0.04601	+0.04601	0.05280	40.8
Flat floor, transverse at $x = 5$ m	7	0.01385	−0.01341	0.01660	21.2
Ridge, centerline	9	0.01039	+0.00590	0.01507	9.8
Ridge, transverse at $x = 5$ m	7	0.00552	+0.00131	0.00649	20.1
Ridge, transverse at $x = 6$ m	7	0.01577	+0.01577	0.01609	35.1

Table A2. Mean floor-collection fluxes at unflagged shared centerline stations. ΔJ is model A minus flat floor, and SE is the standard error of the difference for independent run sets. Flux, SD, and SE are in g m⁻² s⁻¹.

x (m)	Flat Floor Mean $\pm$ SD	Model A Mean $\pm$ SD	$\Delta J \pm SE$	Ratio
2.5	0.1734 $\pm$ 0.0284	0.2456 $\pm$ 0.0448	+0.0722 $\pm$ 0.0258	1.42
3.0	0.1901 $\pm$ 0.0190	0.2344 $\pm$ 0.0267	+0.0443 $\pm$ 0.0158	1.23
3.5	0.1646 $\pm$ 0.0316	0.2311 $\pm$ 0.0287	+0.0665 $\pm$ 0.0202	1.40

4.5	0.1380 ± 0.0089	0.0166 ± 0.0054	-0.1215 ± 0.0048	0.12
5.5	0.1022 ± 0.0215	0.0258 ± 0.0058	-0.0764 ± 0.0100	0.25
6.0	0.0727 ± 0.0142	0.0227 ± 0.0046	-0.0500 ± 0.0068	0.31
6.5	0.0752 ± 0.0148	0.0270 ± 0.0060	-0.0481 ± 0.0073	0.36
7.0	0.0472 ± 0.0127	0.0278 ± 0.0052	-0.0193 ± 0.0062	0.59

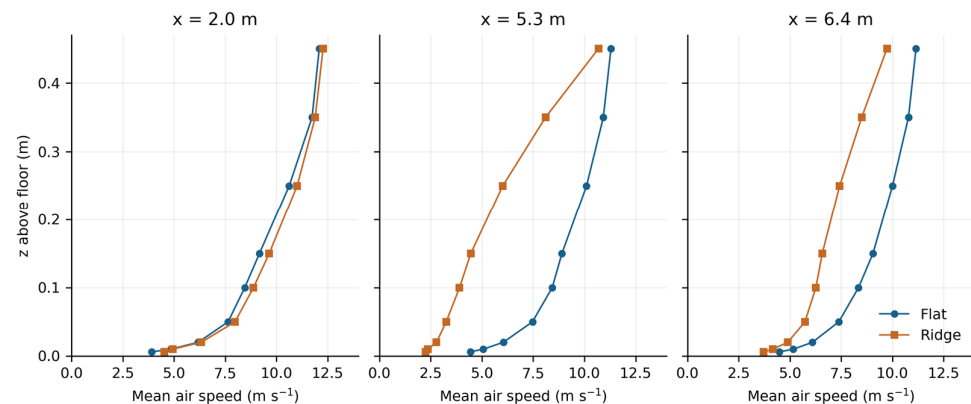


Figure A4. Recovered experimental mean air-speed profiles at $x = 2.0, 5.3$ and 6.4 m for the flat-floor and model-A configurations. The displayed values are the workbook columns labeled as the average of the two probe readings. Heights are relative to the floor at these stations. These experimental profiles document the approach and lee-side speed distributions; no matched numerical validation error or reverse-flow sign is inferred.

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