

Hydrodynamic behavior of non-spherical particles in confined vertical flows: a resolved computational fluid dynamics-discrete element method study

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We investigate the sedimentation and vertical hydraulic transport of non-spherical poly-metallic nodules (PMNs) using resolved computational fluid dynamics-discrete element method (CFD-DEM) with multisphere particles spanning $98 < Re_p < 2904$. Shape effects induce 1.8-2.0 times drag enhancement relative to volume-equivalent spheres, arising from 50% larger frontal areas and wake asymmetry, reducing terminal velocities by 27-29%. Vertical transport exhibits velocity-driven transitions from intermittent settling to stable convection, as demonstrated by residence-time and drag-force statistics. While PMNs exhibit enhanced rotational-translational coupling and broader force fluctuations, the regime progression qualitatively resembles that of volume-equivalent spherical particles. Drag variance evolution reveals contrasting behavior: small particles ($d/D = 0.082$) show narrow distributions and wake suppression at higher velocities, while large particles ($d/D = 0.22$) exhibit non-monotonic variance. These findings elucidate shape-confinement interactions in vertical transport and establish bounds on the applicability of volume-equivalent spherical particles in reduced-order models.

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I. INTRODUCTION

The recovery of polymetallic nodules (PMNs) from abyssal plains relies on hydraulic systems to transport coarse non-spherical particles through vertical risers extending several kilometers^{1,2}. The efficiency of these systems depends on the ability to predict particle entrainment, suspension stability, and transport behavior under strong gravitational forcing and geometric confinement^{3–6}. In such risers, particles are often comparable in size to the riser diameter and interact strongly with both the carrier fluid and the confining walls, leading to complex multiphase flow behavior^{7–9}.

Hydraulic collection systems are favored in deep-sea mining for their operational efficiency and mechanical simplicity^{10,11}, yet their design rests on a multiphase flow problem whose governing physics, i.e., the transport of coarse, irregular, and strongly confined particles in dense slurries, remains incomplete^{12–16}. Two features distinguish PMN transport from canonical particle-laden flow: irregular particle morphology and strong geometric confinement. Unlike spheres, PMNs exhibit enhanced drag, shape-dependent lift, coupled rotational-translational motion, and altered settling dynamics^{17–19}, all of which directly affect transport efficiency, minimum suspension velocity, and energy consumption. Although shape effects have been characterized extensively in unconfined and weakly confined flows^{20–23}, their behavior in narrow risers with confinement ratios $d/D \geq 0.2$, representative of deep-sea mining systems, remains underexplored. This is a consequential gap: at such confinement ratios, it alters wake development and amplifies particle-wall momentum exchange, mechanisms absent or weak in unconfined studies.

Most numerical studies of hydraulic transport employ unresolved computational fluid dynamics-discrete element method (CFD-DEM), in which particle-fluid interactions are modeled using empirical drag correlations^{24,25}. Such correlations are calibrated against spherical particles or parameterized by scalar descriptors such as sphericity^{19,23,26,27}. This averaging is reasonable in dilute and unconfined flows where particles tumble freely, but it fails in confined flows: (1) it cannot represent orientation-dependent drag when wall proximity sustains preferred particle orientations, (2) it ignores the asymmetric, wall-deflected wakes responsible for shape-induced lift, and (3) it decouples translation from rotation, suppressing the very mechanism through which non-spherical particles redistribute momentum to the carrier fluid. The limitations are relevant in regimes where particle-fluid and particle-wall interactions dominate and may trigger flow instabilities, intermittent settling, and jamming^{28–30}.

These closure problems are addressed in resolved CFD-DEM, which compute particle-fluid interaction forces directly at the interface, without empirical drag laws^{31–33}. Integrating particle representations such as signed distance functions or multisphere approximations extends the approach's ability to model particles with arbitrary shapes^{7,34}. Resolved CFD-DEM is well suited for modeling confinement-driven phenomena, including shear jamming, wake-mediated interactions, and regime transitions in narrow geometries^{8,35}, with broader applicability to engineering-relevant solid-fluid problems^{36,37}. However, existing studies have largely focused on sedimentation, fluidized beds, or short-bend geometries; sustained vertical hydraulic transport of X-ray computed tomography (CT) derived non-spherical particles at high confinement ratios has not been systematically examined. This gap is the practical motivation for the present study.

Resolved CFD-DEM at industrial-scale riser dimensions remains computationally prohibitive: representing realistic PMN morphology for $\mathcal{O}(10^3 - 10^4)$ particles over kilometer-scale domains via SDF or multisphere approaches demands CPU runtime that preclude parametric design. Consequently, large-scale simulations routinely substitute volume-equivalent spheres, trading morphological fidelity for tractable runtimes. Whether this substitution preserves ensemble-level transport behavior or biases predictions of entrainment thresholds and pressure drop is unknown. Addressing this requires a controlled configuration that isolates shape-induced hydrodynamic effects from confounding collective phenomena such as dense-phase clustering and polydispersity, distinctions that are obscured in fully representative industrial simulations. We therefore adopt a controlled vertical transport configuration with moderate particle ensembles, enabling a direct comparison of CT reconstructed PMNs and volume-equivalent spheres under identical flow and confinement conditions.

In this work, we employ resolved CFD-DEM to investigate the hydrodynamic behavior of non-spherical PMNs in vertical pipes representative of deep-sea mining risers. The model couples the incompressible Navier-Stokes equations with Newton's equations of motion for discrete particles, whose irregular geometries are represented using multisphere approximations derived from CT scans. We systematically analyze the influence of particle-to-pipe diameter ratio, particle Reynolds number, and flow velocity on particle trajectories, residence time distributions, and drag force statistics. Residence time analysis characterizes the transition from settling-dominated to convection-dominated transport, enabling prediction of minimum suspension velocities^{38,39}, while drag force statistics reveal underlying force balance mechanisms. The objectives are twofold: first, to elucidate mechanisms by which particle shape influences drag,

wake dynamics, and rotational-translational coupling in confined vertical flows; and second, to assess whether ensemble-averaged transport metrics for non-spherical PMNs qualitatively converge toward those of volume-equivalent spheres, thereby establishing when spherical models are suitable for reduced-order simulations of large-scale hydraulic transport systems.

The remainder of this paper is structured as follows. **Section II** presents the mathematical formulation of the resolved CFD-DEM framework, detailing the Navier-Stokes equations for the fluid phase, Newton's equations for particle dynamics, the immersed boundary method for fluid-solid coupling, and the multisphere representation for complex geometries. **Section III** presents numerical verification through comparisons with benchmark experiments for spherical and non-spherical particle sedimentation, establishing the model's accuracy across the Stokes-to-intermediate Reynolds number regime. In addition, we have used the classical DKT problem to resolve multiple particle interactions using CFD-DEM framework. **Section IV** presents results in two parts: sedimentation analysis, which quantifies the effects of shape on drag coefficients and terminal velocities; and vertical transport simulations that analyze entrainment dynamics, residence time distributions, and drag force statistics as functions of flow velocity and confinement ratio. **Section V** summarizes key findings and discusses implications for hydraulic transport in deep-sea mining applications.

II. METHODOLOGY

We employ a resolved CFD-DEM framework to investigate the hydraulic transport of coarse, non-spherical PMNs in a vertical cylindrical pipe. The framework couples the Immersed Boundary (IB) method with CFD-DEM, integrating OpenFOAM for fluid dynamics simulation and LIGGGHTS for discrete particle tracking⁴⁰. This fully resolved, bidirectional coupling framework captures the complex multiphase interactions between fluid flow, particle transport, and sedimentation dynamics by resolving mesoscale physics at the solid-fluid interface through a Lagrangian-Eulerian formulation.

A. Discrete Element Method for Particle Dynamics

Individual particles are modeled within a Lagrangian framework using DEM, where Newton's second law governs each particle's motion for both translational and rotational dynamics

$$m_i \frac{d\mathbf{u}_i}{dt} = m_i \mathbf{g} + \sum_{j \neq i}^{N_c} \mathbf{F}_{c,ij} + \sum_k^{N_w} \mathbf{F}_{c,ik} + \mathbf{F}_{f,i}, \quad (1)$$

$$\mathbb{I}_i \frac{d\boldsymbol{\omega}_i}{dt} = \sum_{j \neq i}^{N_c} \mathbf{T}_{c,ij} + \sum_k^{N_w} \mathbf{T}_{c,ik}, \quad (2)$$

where m_i and $\mathbb{I}_i$ represent the mass and moment of inertia tensor of particle i , $\mathbf{u}_i$ and $\boldsymbol{\omega}_i$ denote linear and angular velocity vectors, $\mathbf{g}$ is the gravitational acceleration vector, $\mathbf{F}_{c,ij}$ and $\mathbf{T}_{c,ij}$ are contact forces and torques between particles i and j , $\mathbf{F}_{c,ik}$ and $\mathbf{T}_{c,ik}$ represent wall-particle interactions with wall k , and $\mathbf{F}_{f,i}$ is the particle-fluid interaction force computed via the IB method. The particle-particle and particle-wall contact forces are computed using the Hertz-Mindlin contact model with Coulomb friction (i.e., soft sphere model), which provides an accurate representation of non-linear deformation and energy dissipation during collisions between non-spherical particles^{41,42}. The contact detection algorithm efficiently handles complex particle geometries represented as multisphere assemblies.

B. Computational Fluid Dynamics Formulation

The continuous fluid phase is resolved using an Eulerian framework based on the incompressible Navier-Stokes equations within the fluid domain Ω_f , using eqs. (3) and (4)

$$\nabla \cdot \mathbf{u}_f = 0, \quad (3)$$

$$\frac{\partial \mathbf{u}_f}{\partial t} + (\mathbf{u}_f \cdot \nabla) \mathbf{u}_f = -\frac{1}{\rho_f} \nabla p + \nu \nabla^2 \mathbf{u}_f, \quad (4)$$

where $\mathbf{u}_f$ represents the fluid velocity field, p is the pressure, ρ_f is the fluid density, and $\nu = \mu_f / \rho_f$ is the kinematic viscosity with μ_f being the dynamic viscosity. The fluid velocity field is initialized as $\mathbf{u}_f(\mathbf{x}, t = 0) = \mathbf{u}_0(\mathbf{x})$ in Ω_f , with Dirichlet boundary conditions $\mathbf{u}_f = \mathbf{u}_\Gamma$ imposed at domain boundaries Γ . At the fluid-solid interface Γ_s , the no-slip condition enforces velocity continuity

$$\mathbf{u}_f = \mathbf{u}_s \quad \text{on} \quad \Gamma_s, \quad (5)$$

where $\mathbf{u}_s$ represents the local solid velocity. The fluid stress tensor is defined as $\boldsymbol{\sigma} = -p\mathbb{1} + \mu_f(\nabla \mathbf{u}_f + (\nabla \mathbf{u}_f)^T)$, and the surface traction at the interface is $\mathbf{t} = \boldsymbol{\sigma} \cdot \mathbf{n}$ with $\mathbf{n}$ being the outward unit

normal vector. The governing equations are discretized using OpenFOAM's finite-volume method with second-order spatial accuracy, and temporal integration employs the Pressure-Implicit with Splitting of Operators (PISO) algorithm for robust pressure-velocity coupling⁷.

C. Immersed Boundary Method for Fluid-Solid Coupling

The immersed boundary method provides direct solid-fluid coupling by resolving the interface Γ_s without empirical drag correlations, offering significant advantages over the unresolved CFD-DEM framework in terms of accuracy and physical fidelity⁸. The no-slip condition (eq. (5)) is enforced through a direct forcing approach that modifies the momentum equation. The total hydrodynamic force acting on particle i is computed by integrating the fluid stress over the particle surface

$$\mathbf{F}_{f,i} = \int_{\Gamma_{s,i}} \boldsymbol{\sigma} \cdot \mathbf{n} dA \approx \sum_{c \in V_{\Omega_{s,i}}} (-\nabla p + \mu_f \nabla^2 \mathbf{u}_f)_c V_c, \quad (6)$$

where $V_{\Omega_{s,i}}$ represents the set of fluid cells overlapping with solid domain $\Omega_{s,i}$, V_c is the volume of cell c , and the summation extends over all fluid cells influenced by particle i . This formulation captures pressure (buoyancy), viscous drag, and added mass effects without requiring empirical closure relations^{8,34}. Void fraction weighting ensures accurate force distribution across the fluid-solid interface, accounting for partial cell occupancy by solid particles.

To ensure accurate resolution of boundary layers around complex particle geometries, the computational grid satisfies the criterion $\Delta x/D < 0.1$, where Δx is the characteristic grid spacing and D is the characteristic particle dimension⁷. This resolution requirement ensures that the viscous boundary layer and near-wall velocity gradients are properly captured for non-spherical particles across the range of Re_p investigated. The coupling between CFD and DEM solver occurs at a coupling interval of 10 timesteps, with fluid forces from eq. (6) passed to the DEM solver. The updated particle positions and velocities are communicated back to the CFD domain. This bidirectional feedback maintains momentum conservation across the fluid-solid interface while preserving numerical stability through appropriate time step restrictions based on the Courant-Friedrichs-Lewy (Courant number) condition and particle collision time scales.

D. Particle Representation

Complex particle geometries are represented using the multisphere approach, where non-spherical particles are constructed as rigid assemblies of overlapping spherical sub-particles, see Fig. 1a. This approach is computationally efficient while retaining high geometric fidelity, capturing the essential features influencing particle-fluid interactions and collision dynamics. The void fraction field visualization, see Fig. 1b, demonstrates the approach's capability to resolve complex particle-fluid interfaces within the Eulerian CFD grid.

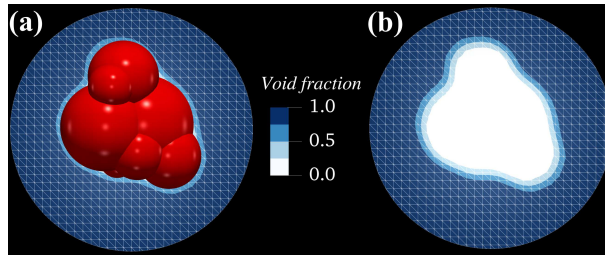


FIG. 1: Multisphere representation of non-spherical particles in the resolved CFD-DEM framework. (a) Example geometry constructed from 14 overlapping sub-spheres capturing an irregular shape. (b) Corresponding void fraction field, with white denoting solid and blue fluid, resolving the fluid-solid interface on the Eulerian grid for hydrodynamic force evaluation via the IB method without empirical drag laws.

III. NUMERICAL VERIFICATION

A. Single Sphere Settling

The computational framework is verified against experimental data and numerical benchmarks through simulations of a single spherical particle settling in quiescent fluid. We compare our results with the experimental measurements of Ten Cate *et al.*⁴³ and numerical predictions from Lattice Boltzmann Method-DEM (LBM-DEM)⁴³ and CFD-DEM simulations³⁴ to assess the accuracy of terminal velocity predictions.

The numerical verification configuration follows the experimental setup of Ten Cate *et al.*⁴³, where a submerged sphere with diameter $d = 15\text{ mm}$ and density $\rho_s = 1120\text{ kg m}^{-3}$ undergoes

free sedimentation within a confined domain of dimensions $100 \times 100 \times 160 \text{ mm}^3$. The particle is initially released from a height of 120 mm. Two test cases with different fluid properties are investigated, as summarized in Table I, with particles' Reynolds number ($Re_p = \rho_f u_t d / \mu_f$) in the Stokes regime and intermediate regime where inertial effects become significant. The computational domain is discretized into 1,600,000 hexahedral cells, with a particle diameter-to-cell ratio of $d/\Delta x = 15$, ensuring adequate boundary-layer resolution around the particle. Dynamic mesh refinement is applied locally at the particle-fluid interface to maintain accuracy during particle motion. For this particular case, we are not interested in the collision dynamics, but rather in settling behavior. The time integration employs $\Delta t_{\text{DEM}} = 1 \times 10^{-5} \text{ s}$ for particle dynamics and $\Delta t_{\text{CFD}} = 1 \times 10^{-4} \text{ s}$ for fluid flow, with the Courant number maintained below 0.1 for numerical stability⁸. Convergence is monitored through pressure and velocity residuals, with a tolerance of 10^{-6} .

Fig. 2 presents the temporal evolution of particle velocity for the two verification cases, where solid lines represent the CFD-DEM predictions and markers denote experimental measurements from Ten Cate *et al.*⁴³. The two cases probe distinct hydrodynamic regimes: Case 1 at $Re_p = 1.4$ corresponds to viscous-dominated Stokes flow, while Case 2 at $Re_p = 29.8$ corresponds to the intermediate regime where inertial effects are not negligible, and a wake forms behind the particle. The simulated trajectories capture the full settling history in both cases, including the initial acceleration phase, the approach to terminal velocity, and the deceleration upon bottom approach. The acceleration time scale differ, reflecting the different balance between viscous drag and particle inertia: Case 1 reaches terminal velocity within $\sim 0.8 \text{ s}$, while Case 2 requires $\sim 1.2 \text{ s}$, consistent with the higher Re_p and lower fluid viscosity. The CFD-DEM predictions accurately reproduce both time scales. The terminal velocities ($u_t = 0.036 \text{ m s}^{-1}$ for Case 1 and 0.12 m s^{-1} for Case 2) are recovered to within 6% of the experimental values, with the normalized maximum velocity u_{max}/u_t likewise captured within 6% (Table I). The deceleration phase as the particle approaches the bottom wall is well reproduced, indicating that near-wall hydrodynamic interactions are correctly resolved by the IB method, even without empirical wall-correction terms.

The flow field snapshots (Figs. S1 and S2 in Supplementary material (SM)) demonstrate the transition from viscous-dominated to inertia-dominated settling as Re_p increases. Case 1 exhibits the symmetric streamline pattern characteristic of Stokes flow, with the disturbance decaying smoothly into the far field and no wake formation, consistent with the analytical Stokes solution

TABLE I: Verification metrics comparing CFD-DEM predictions with experimental data from Ten Cate *et al.*⁴³. Terminal velocity u_t is the experimental terminal velocity; $u_{\max}/u_t$ is reported from the present simulations; Re_p is computed from the simulated u_t .

Case	$\rho_f(\text{kg m}^{-3})$	$\mu_f(\text{Pa} \cdot \text{s})$	$u_t(\text{ms}^{-1})^a$	$u_{\max}/u_t$	Re_p
Case 1	970	0.373	0.038	0.95	1.4
Case 2	960	0.058	0.128	0.94	29.8

^a Experimental terminal velocity from Ten Cate *et al.*⁴³

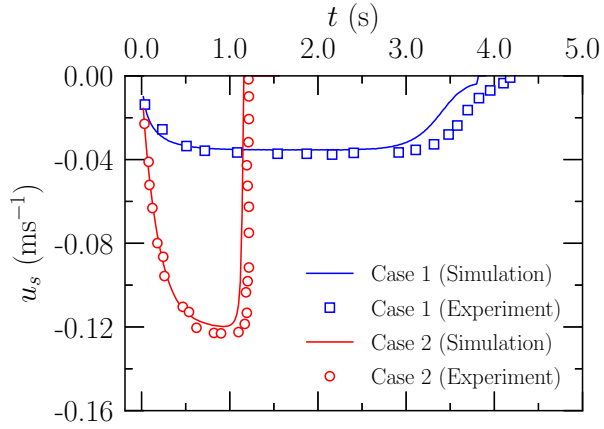


FIG. 2: Temporal evolution of settling velocity for verification cases comparing CFD-DEM predictions (solid lines) with experimental measurements from Ten Cate *et al.*⁴³ (symbols). The simulations capture both the acceleration phase and the approach to terminal velocity, with an accuracy of 6%, verifying the IB method for hydrodynamic force calculation across the transitional Reynolds number regime.

for creeping flow past a sphere. Case 2 instead shows flow separation behind the particle and a recirculating wake region extending approximately one particle diameter downstream, with a corresponding pressure deficit that contributes to the drag component absent in Case 1. The transition from viscous-dominated to inertia-dominated settling is therefore evident in both the velocity history and the flow-fields, and the agreement with the experimental benchmarks of Ten Cate *et al.*⁴³ verifies the numerical method across the range $1 < Re_p < 50$ (see movie M1 in the SM).

B. Drafting, Kissing and Tumbling

The CFD-DEM capacity to resolve hydrodynamic interactions between multiple particles is verified through simulations of two settling spheres in quiescent fluid, following the benchmark configuration of Glowinski *et al.*⁴⁴. The computational domain is a vertical rectangular box (10 mm $\times$ 10 mm $\times$ 40 mm). Two identical spheres are released vertically, initially separated, and their settling velocities are tracked as they approach, collide, and tumble. Fig. 3 compares the settling velocity evolution of the two spherical particles with the direct numerical simulations (DNS) from Sharma and Patankar⁴⁵, revealing three characteristic phases of particle-particle interactions:

1. **Initial Settling Regime** ($t < 0.14$ s): The particles settle at identical velocities as the trailing particle remains beyond the wake of the leading particle. Each particle experiences drag from the undisturbed far-field flow, producing independent settling dynamics with a velocity difference of $< 5\%$.
2. **Drafting—Wake Entrainment Regime** ($0.14 \text{ s} < t < 0.35 \text{ s}$): The trailing particle enters the leading particle's low-pressure wake, where fluid velocity is elevated relative to the far-field. This reduces the drag force on the trailing particle, causing it to accelerate and rapidly close the gap.
3. **Kissing—Contact and Tumbling Dynamics** ($t \geq 0.35 \text{ s}$): At $t = 0.35 \text{ s}$, the particles come in contact, known as the kissing phase. The Hertz-Mindlin contact model calculates normal and tangential contact forces, leading to particle tumbling and momentum exchange.

Quantitative comparison from the CFD-DEM shows good agreement with DNS benchmarks: maximum velocity deviation $< 5\%$ throughout all phases, accurate prediction of collision time (0.35 s, within 5% of DNS), and correct post-collision behavior. The verification confirms that the IB method accurately resolves: (1) long-range wake-mediated hydrodynamic interactions, (2) transition from independent to coupled settling, (3) contact collision dynamics, and (4) momentum transfer during tumbling. Flow field snapshots in Fig. S4 in SM show particle positions and velocity contours at representative times of ($t = 0.0 \text{ s}, 0.14 \text{ s}, 0.35 \text{ s}, 0.7 \text{ s}$), illustrating the progressive wake entrainment mechanism and collision-induced flow reorganization (see movie M2 in the SM).

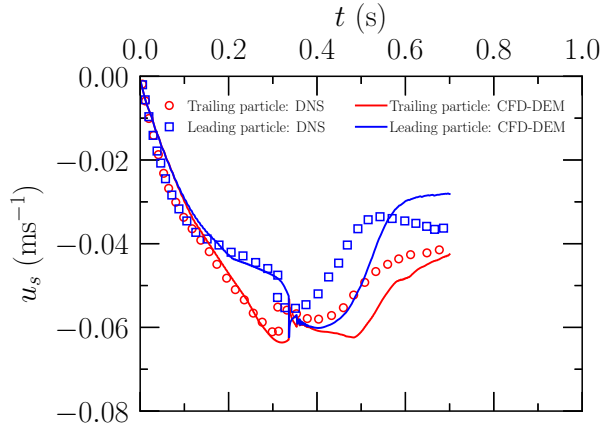


FIG. 3: Settling velocity evolution for the two-particle drafting-kissing-tumbling benchmark. CFD-DEM results (solid) agree well with DNS from Sharma and Patankar⁴⁵ (symbols). The three phases are captured: drafting ($0.14\text{ s} < t < 0.35\text{ s}$), kissing ($t \approx 0.35\text{ s}$), and tumbling ($t > 0.35\text{ s}$). Velocity deviations remain below 5% during drafting and kissing, confirming accurate multi-particle hydrodynamic interactions.

C. Non-spherical Particle Settling

The framework's suitability in handling complex particle morphologies is assessed through a sedimentation simulation of an idealized spherical particle, approximated using a multisphere approach. The test particle comprises 206 overlapping sub-spheres arranged to approximate a spherical geometry while maintaining identical density ($\rho_s = 1120\text{ kg m}^{-3}$) and volume, as the reference sphere from Case 2 ($d = 15\text{ mm}$). The configuration enables a direct comparison of the hydrodynamic behavior of a spherical particle with that of a non-spherical proxy under identical physical conditions. The computational setup maintains consistency with the verification case 2; fluid properties $\rho_f = 960\text{ kg m}^{-3}$ and $\mu_f = 0.058\text{ Pa}\cdot\text{s}$, rectangular domain dimensions $100 \times 100 \times 160\text{ mm}^3$, and particle is released from the same initial position. The mesh resolution is enhanced to $d/\Delta x = 16$ to ensure adequate representation of the irregular particle surface. Time step remain unchanged at $\Delta t_{\text{DEM}} = 1 \times 10^{-5}\text{ s}$ and $\Delta t_{\text{CFD}} = 1 \times 10^{-4}\text{ s}$ to maintain temporal accuracy and numerical stability.

Fig. 4 compares the settling velocity evolution for spherical and multisphere particles. The mul-

tisphere particle exhibits terminal velocity $u_t = 0.12 \text{ m s}^{-1}$, representing $\leq 6\%$ decrease relative to the sphere ($u_t = 0.128 \text{ m s}^{-1}$). Despite the irregular surface geometry, particles exhibit quantitatively similar acceleration dynamics, with a smooth, monotonic approach to terminal velocity over $t \approx 0.8 \text{ s}$. The subtle velocity decrease for the multisphere particle reflects enhanced drag due to its increased surface area, which is greater than that of the equivalent sphere. The flow field around the multisphere particle is qualitatively similar to that of the smooth sphere at the same Re_p , exhibiting flow separation and a recirculating wake, characteristic of inertia-dominated flow (Fig. S3 in SM). The irregular surface introduces additional finer-scale distortions in the near-wall velocity contours, particularly downstream of surface protrusions where local velocity gradients intensify. These features reflect the particle's geometry but do not significantly alter the global force balance or settling dynamics in this intermediate Reynolds number regime. The close agreement between spherical and multisphere terminal velocities (within 6%) validates two critical aspects of the computational framework: (1) the multisphere approximation accurately represents the hydrodynamic resistance of irregular particles while maintaining computational efficiency, and (2) the IB method accurately resolves fluid-solid interactions around complex geometries with accuracy comparable to smooth surfaces. This verification establishes confidence in the numerical framework that distinguishes the non-spherical simulations from the spherical baseline: the multisphere representation and the IB force integration over complex geometries. Because the resolved CFD-DEM framework computes hydrodynamic forces by directly integrating the fluid stress tensor over the particle volume, the accuracy of this integration—rather than agreement with empirical drag correlations—constitutes the appropriate verification target.

Remark: We note that established non-spherical drag correlations (e.g., Haider and Levenspiel¹⁷, Hölzer and Sommerfeld¹⁹) are calibrated for geometrically regular shapes parameterized by well-defined sphericity values, and their applicability to the highly irregular, non-convex PMN morphologies considered here is itself uncertain. The present verification strategy, therefore, focuses on validating the numerical framework at the level of the governing equations, providing a robust basis for PMN transport investigations.

IV. RESULTS AND DISCUSSION

We systematically investigate the hydrodynamic behavior of non-spherical PMNs in confined vertical flows, which is directly relevant to hydraulic lifting systems used in deep-sea mining risers.

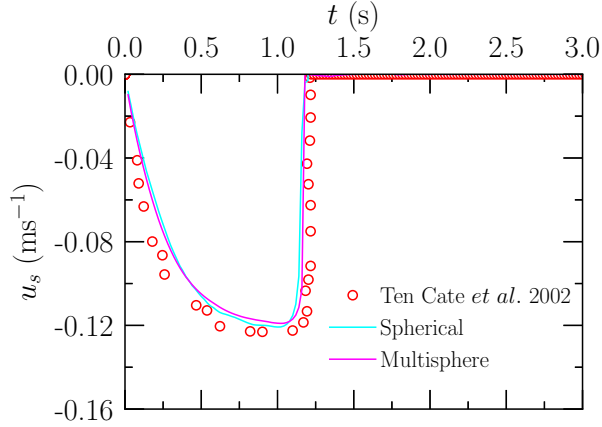


FIG. 4: Settling velocity comparison between spherical and multisphere particles verifying the multisphere approximation. A 206 sub-sphere assembly approximates a sphere with identical density ($\rho_s = 1120 \text{ kg m}^{-3}$), volume, and mass (Case 2), settling in silicon oil ($\rho_f = 960 \text{ kg m}^{-3}$, $\mu_f = 0.058 \text{ Pa} \cdot \text{s}$). Experimental data from Ten Cate *et al.*⁴³ (red open symbols) and numerical results for the sphere (cyan solid line) and multisphere (magenta solid line) agree closely, with terminal velocity differences within 6%.

The analysis is structured in two parts. First, sedimentation in quiescent fluid is examined to quantify shape-induced drag enhancement and establish reference settling velocities for irregular PMNs relative to volume-equivalent spheres. These results provide calibration data for drag models commonly used in riser-scale simulations. Second, vertical hydraulic transport is analyzed using residence-time statistics and drag-force distributions to identify entrainment behavior and transport stability as flow velocity increases.

All transport simulations are performed with 40 particles to provide statistically meaningful ensemble measures while preserving fully resolved particle-fluid interactions. This particle number captures particle-to-particle variability without introducing collective effects such as sustained clustering or plug formation, which are beyond the scope of the present study. Statistical convergence of the drag-force distribution $P(\hat{f})$ is verified by comparing ensemble sizes of $N_p = 20, 40$, and 80 for the large sphere case at $u_f = 3.0u_t$ (Fig. S5 in the SM); all the distributions agree closely in both peak location and tail behavior, confirming that $N_p = 40$ is sufficient for the first- and second-order statistics reported here. Continuous particle injection is not considered here; instead,

the focus is on isolating the intrinsic hydrodynamic response of PMNs under controlled confinement. This approach enables clear physical interpretation and directly supports the reduced-order modeling strategies for riser-scale transport.

A. Settling Analysis

Fig. 5 illustrates the complex and irregular morphology of PMNs represented using a multisphere approximation based on high-resolution CT scans. This approach employs 28 and 45 sub-spheres for PMNs with effective diameters of $d_{\text{eff}} = 20\text{mm}$ and $d_{\text{eff}} = 54\text{mm}$, respectively, where d_{eff} represents the diameter of the minimum circumscribed sphere that fully encloses the PMN. The volume-equivalent sphere diameter $d_v = (6V_p/\pi)^{1/3}$, where V_p is the PMN volume, yields $d_v = 16.4\text{mm}$ and $d_v = 44\text{mm}$ for the small and large PMN, respectively. The ratio $(d_v/d_{\text{eff}})^3 \approx 0.55$ indicates that PMNs occupy only 55% of their circumscribed volume, reflecting their irregular, non-convex morphology with surface protrusions and concavities characteristic of natural PMNs. The multisphere representations in Fig. 5b and d show the PMN geometries superimposed with their volume-equivalent spheres, demonstrating that the irregular PMN surfaces extend significantly beyond the volume-equivalent sphere while remaining contained within the circumscribed sphere envelope. This geometric distinction is crucial for understanding hydrodynamic behavior, as the effective frontal area and surface morphology of PMNs differ substantially from volume-equivalent spheres.

Fig. 6 compares the temporal evolution of settling velocities for PMNs and their volume-equivalent spherical particles in fluid. The numerical simulations are performed within a cylindrical computational domain with diameter $D = 200\text{mm}$ and length $L = 1200\text{mm}$. The mesh is constructed with resolution requirements based on the particle characteristic dimension: for PMNs, we use $d_{\text{eff}}/\Delta x \geq 8$ to resolve surface irregularities and wake structures; for volume-equivalent spheres, we use $d_v/\Delta x \geq 8$. This ensures at least 8 grid cells across the particle dimension in all cases. Both PMNs and spherical particles have density $\rho_p = 2000\text{kgm}^{-3}$ and identical volumes. They are released from rest at the domain centerline at height $z = 1000\text{mm}$ in quiescent fluid with density $\rho_f = 1000\text{kgm}^{-3}$ and dynamic viscosity $\mu_f = 0.05\text{Pa}\cdot\text{s}$. The terminal velocity u_t is determined from the steady-state settling velocity achieved after initial transients decay. Table II lists the details of the settling characteristic for the PMNs and volume-equivalent spheres. The elastic properties prescribed for the simulations are $v_p = 0.2$ and $Y_p = 1\text{GPa}$. This yields a time

step of $\Delta t_{\text{DEM}} = 5 \times 10^{-6}$ s ($\approx 10\%$ of the Rayleigh time step for smaller spheres sets the time step, eq. (7)) and $\Delta t_{\text{CFD}} = 5 \times 10^{-5}$ s to maintain temporal accuracy and numerical stability.

$$t_{\text{DEM}} = \frac{0.5\pi d_p}{0.163v_p + 0.8766} \times \sqrt{\frac{2\rho_p(1+v_p)}{Y_p}}, \quad (7)$$

where d_p and ρ_p are the particle diameter and density, respectively. v_p and Y_p are the elastic properties.

TABLE II: Comparison of settling characteristics for PMNs and volume-equivalent spheres

Particle	d_v (mm)	d_{eff} (mm)	u_t (ms ⁻¹)	Re_p	C_D
Small sphere	16.4	16.4	0.42	138	1.21
Small PMN	16.4	20.0	0.30	98	2.38
Large sphere	44.0	44.0	1.1	968	0.48
Large PMN	44.0	54.0	0.80	704	0.9

Note: Re_p based on d_v ; C_D based on $A_{\text{proj}} = \pi d_v^2/4$

Fig. 6 reveals that PMNs settle significantly slower than volume-equivalent spheres despite identical mass and buoyancy. The small PMN reaches terminal velocity $u_t^{\text{PMN}} = 0.30 \text{ ms}^{-1}$ compared to $u_t^{\text{sphere}} = 0.42 \text{ ms}^{-1}$ (29% reduction), while the large PMN achieves $u_t^{\text{PMN}} = 0.8 \text{ ms}^{-1}$ versus $u_t^{\text{sphere}} = 1.1 \text{ ms}^{-1}$ (27% reduction). These velocity differences are purely shape effects and correspond to Re_p of 98 and 138 (small PMN and sphere) and 704 and 968 (large PMN and sphere). The drag coefficient, defined from terminal force balance as $C_D = 4(\rho_p - \rho_f)gd_v/(3\rho_f u_t^2)$ using the projected area $A_{\text{proj}} = \pi d_v^2/4$, yields $C_D^{\text{PMN}} = 2.38$ and 0.9 compared to $C_D^{\text{sphere}} = 1.21$ and 0.48 for small and large particles, respectively—representing 2.0 and 1.8 times enhancements⁴⁶. This drag increase reflects two distinct contributions that are inherently coupled for freely settling non-spherical particles. The first is the larger instantaneous projected area—the PMNs rotate during settling—where the frontal area varies continuously with orientation. The maximum orientational projected area exceeds the volume-equivalent value $\pi d_v^2/4$ by a factor of approximately $(d_{\text{eff}}/d_v)^2 \approx 1.5$, accounting for a substantial portion of the observed C_D enhancement. The second contribution arises from morphology-induced effects that persist independently of projected-area differences: asymmetric wake structures generated by surface protrusions and concavities (see Fig. 7), orientation-dependent pressure differences along the irregular surface, and rotational-translational coupling that continuously alters the angle of attack. Accounting for the projected-area difference through normalized drag coefficients $C_D^{\text{norm}} = C_D^{\text{PMN}}(d_v/d_{\text{eff}})^2$ yields values still

20–30% above spherical equivalents, confirming that these morphological effects contribute substantially beyond the geometric area increase alone.

The use of the volume-equivalent projected area $\pi d_v^2/4$ as the reference in the definition of C_D is a deliberate choice: it is orientation-invariant and enables direct comparison with volume-equivalent spheres, which is key to the settling analysis. The orientation-dependent contribution to drag is thus absorbed into the reported C_D^{PMN} values. For applications requiring orientation-resolved drag models, the instantaneous projected area must be tracked alongside particle angular dynamics, an approach that is beyond the scope of the present study but naturally accommodated within the resolved CFD-DEM framework. Fig. 8 shows the temporal evolution of vertical drag force during sedimentation, revealing distinct transient dynamics. The drag force initially increases during particle acceleration as the relative fluid-particle velocity and unsteady inertial effects develop. The drag forces reach steady-state values of $F_d = (\rho_p - \rho_f)V_p g \approx 0.023 \text{ N}$ (small) and 0.43 N (large), confirming force balance to within 5%. Notably, the PMNs and spheres experience identical terminal drag forces since they have equal volumes and densities—the 27–29% lower settling velocities of PMNs arise because their enhanced drag coefficients allow them to generate the required hydrodynamic resistance at reduced slip velocities. The sharp decrease in F_d after $t \approx 2.8 \text{ s}$ for the small PMN indicates bottom contact, where wall reaction forces partially support the particle weight.

B. Vertical transport

To investigate PMN entrainment in vertical risers, we simulate the transport of mono-sized spherical particles and PMNs ($d_v = 16.4 \text{ mm}$ and 44 mm) through a vertical cylindrical pipe with diameter $D = 200 \text{ mm}$ and length $L = 1200 \text{ mm}$ at three fluid velocities: $u_f = 1.0u_t$, $2.0u_t$, and $3.0u_t$, where u_t is the terminal settling velocity. Table III lists the Re_p values. Particles are initially distributed randomly in the lower section of the pipe ($0 < z < 200 \text{ mm}$) and allowed to reach quasi-steady transport conditions. The local hydrodynamic regime around individual particles is more appropriately characterized by the Re_p , which spans 98–2904, with the confinement ratio $d/D = 0.082$ and 0.22 further modulating wake behavior. We analyze transport characteristics through residence time distributions $P(t_r)$ and normalized drag force distributions $P(\hat{f})$, where t_r is the time required for a particle to traverse one meter vertically and $\hat{f} = F_d/(\rho_p - \rho_f)V_p g$ is the ratio of instantaneous vertical drag to submerged particle weight.

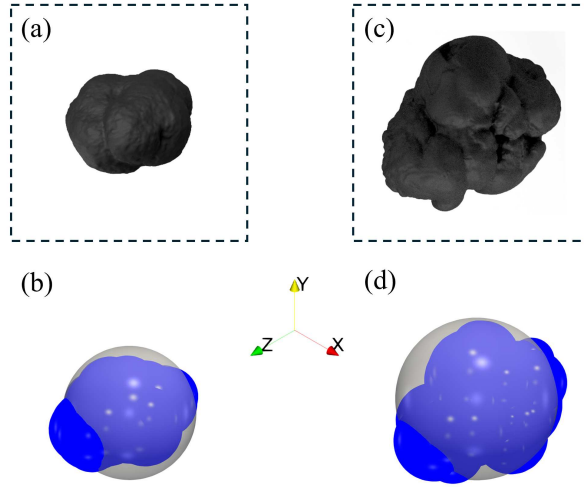


FIG. 5: PMN morphology and multisphere approximations. (a) & (c) CT-reconstructed PMN surfaces showing irregular geometry. (b) & (d) Corresponding multisphere models (blue; 28 and 45 sub-spheres) with effective diameters ($d_{\text{eff}} = 20\text{ mm}$ and 54 mm), overlaid on volume-equivalent spheres (grey; $d_v = 16.4\text{ mm}$ and 44 mm). The volume ratio $((d_v/d_{\text{eff}})^3 \approx 0.55)$ reflects the non-convex morphology.

1. Residence Time Analysis

Fig. 9 presents the probability distributions of residence time (t_r) for spherical and non-spherical particles at varying flow velocities. The distributions characterize the transition from intermittent, settling-dominated transport at low velocities to steady, convection-dominated entrainment at high velocities. In Fig. 9a and c, the small spherical particles and PMNs, respectively, exhibit broad distributions with extended tails at $u_f = 1.0u_t$ and $u_f = 2.0u_t$, indicating high variability in individual particle transport velocities. For spheres, the standard deviation decreases from $\sigma_{tr} = 1.55\text{ s}$ at $1.0u_t$ to $\sigma = 0.06\text{ s}$ at $3.0u_t$. At $1.0u_t$, the small PMNs exhibit marginal suspension states—particles oscillate near the inlet without achieving consistent upward motion. This is illustrated in particle trajectory visualizations (see Fig. 10e and Fig. 11e), where small PMNs remain confined to the lower pipe section at low velocity, exhibiting continuous rotational motion without net vertical displacement. Large spherical particles, Fig. 9b, show systematic variance reduction from $\sigma = 0.19\text{ s}$

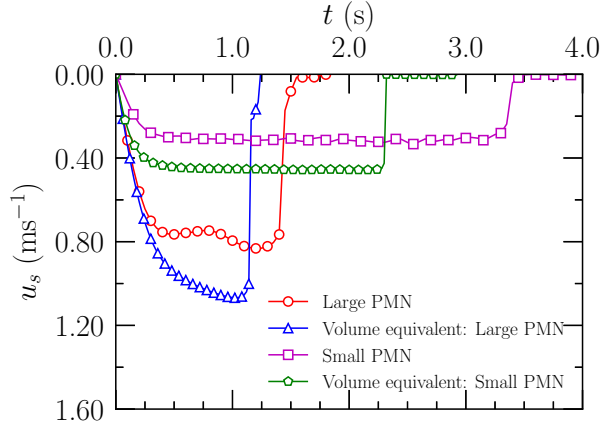


FIG. 6: Temporal evolution of settling velocity for PMNs and volume-equivalent spherical particles. PMNs (squares and circles) reach terminal velocities 27–29% lower than volume-equivalent spheres (triangles and pentagons) despite identical mass and volume, reflecting enhanced drag coefficients due to increased surface area.

TABLE III: Particles' Reynolds numbers (Re_p) for spherical particles and PMNs during vertical transport at varying fluid velocities. Terminal velocities u_t from sedimentation analysis with $\rho_f = 1000 \text{ kg m}^{-3}$ and $\mu_f = 0.05 \text{ Pa} \cdot \text{s}$.

Particle Type	d_v (mm)	u_t (ms^{-1})	$Re_p = \rho_f u_t d_v / \mu_f$		
			$u_f = 1.0u_t$	$u_f = 2.0u_t$	$u_f = 3.0u_t$
Small sphere	16.4	0.42	138	276	414
Small PMN	16.4	0.30	98	196	294
Large sphere	44.0	1.10	968	1936	2904
Large PMN	44.0	0.80	704	1408	2112

Note: Re_p calculated using volume-equivalent diameter d_v and fluid velocity u_f .

to 0.02 s as the fluid velocity increases. Large PMNs, Fig. 9d, exhibit broader distributions at all velocities compared to spherical particles, with more pronounced tails at $2.0u_t$ and $3.0u_t$.

The mean residence times (μ_r) for all particles follow the expected inverse relationship $\mu_r \propto 1/(u_f - u_t)$, with measured values of $\mu_r = 6.87 \text{ s}$, 1.85 s , and 1.04 s for small spherical particles at $1.0u_t$, $2.0u_t$, and $3.0u_t$, respectively. Table IV delineates the μ_r and σ_r for various particle groups.

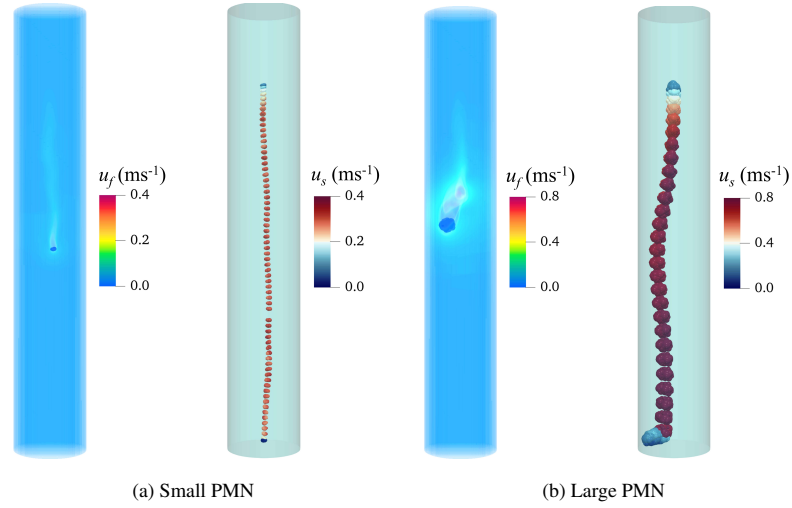


FIG. 7: Instantaneous flow fields and particle trajectories during sedimentation of PMNs in a quiescent fluid. (a) Small PMN at terminal velocity; (b) large PMN. Fluid velocity magnitude contours (left) show asymmetric wakes induced by particle geometry. Three-dimensional trajectories (right), colored by solid velocity magnitude, exhibit vertical settling with coupled rotation.

Particle configuration snapshots in Fig. 10 reveal the spatial distributions underlying these statistical behaviors. At $1.0u_t$, small spherical particles, Fig. 10a exhibit pronounced vertical dispersion with particles spanning the half pipe length, consistent with the broad residence time distribution and intermittent settling events. The small PMNs (see Fig. 10e) remain in a state of marginal suspension near the pipe inlet, exhibiting oscillatory motion without net upward transport—the imposed fluid velocity matches the terminal settling velocity, providing hovering equilibrium in which the time-mean drag balances submerged weight without sustained net upward transport. Particles undergo continuous rotational adjustments and lateral excursions, but accumulate no measurable axial displacement over the simulation window, which is insufficient to overcome gravitational settling, resulting in a dynamic equilibrium in which the particles hover with continuous rotational adjustments. Large particles, Fig. 10c and g, show less dispersion due to higher inertia, which reduces susceptibility to local flow fluctuations.

At $3.0u_t$, all particle types achieve spatially homogeneous distributions with minimal vertical dispersion, confirming efficient entrainment and stable transport (see Fig. 10b, d, f, and h). The ab-

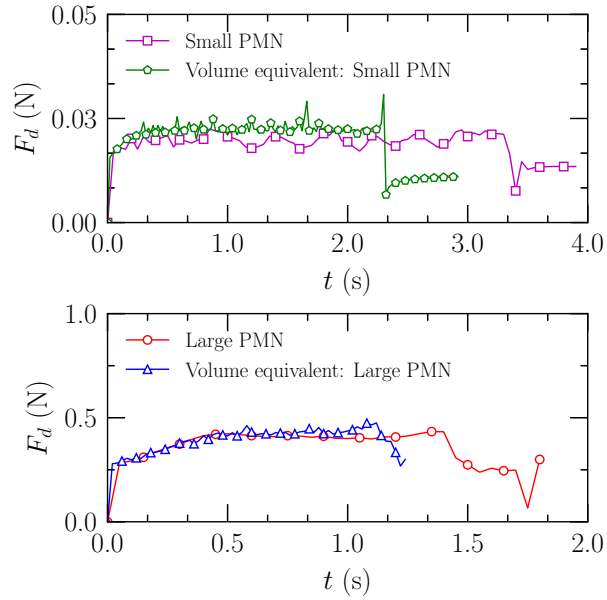


FIG. 8: Temporal evolution of vertical drag force during sedimentation for PMNs and volume-equivalent spheres. Small particles reach steady-state drag force $F_d \approx 0.023$ N (top). Large particles achieve $F_d \approx 0.43$ N (bottom).

sence of extended residence time tails at this velocity indicates that all particles maintain consistent upward motion without settling reversals. Flow field visualizations show that small PMNs develop subtle asymmetric wakes and helical trajectories with variable angular velocity even at high velocities, Fig. 10f, while large PMNs exhibit no spatially coherent wake structures in instantaneous streamline plots, despite angular velocity 80 rad s^{-1} , indicative of strong rotational-translational coupling, Fig. 10h. Individual particle trajectories in Fig. 11 provide a direct visualization of these transport regimes. Small spherical particles (Fig. 11a and b) transition from oscillatory motion with lateral wandering at $1.0u_t$ to nearly rectilinear trajectories at $3.0u_t$. However, the Small PMNs (Fig. 11e) remain in marginal suspension at low velocity. Large PMNs, Fig. 11g and h, exhibit enhanced rotational motion, with PMNs achieving significantly higher angular velocities, reflecting shape-induced torques and coupled translational-rotational dynamics.

TABLE IV: Mean residence time (μ_{tr}) and standard deviation (σ_{tr}) for spherical particles and PMNs during vertical transport at varying fluid velocities.

Particle	μ_{tr} (s)			σ_{tr} (s)		
	$1.0u_t$	$2.0u_t$	$3.0u_t$	$1.0u_t$	$2.0u_t$	$3.0u_t$
Small sphere	6.87	1.85	1.04	1.55	0.18	0.06
Small PMN	—	3.51	1.62	—	0.75	0.11
Large sphere	1.48	0.52	0.33	0.19	0.04	0.02
Large PMN	2.11	0.89	0.51	0.39	0.10	0.06

Note: Small PMNs remain in a suspended state at $1.0u_t$.

2. Drag Force Analysis

Fig. 12a and b illustrate the probability distributions of the normalized axial drag force, $\hat{f} = F_d/(\rho_p - \rho_f)V_p g$, providing insight into the force balance mechanisms governing particle suspension. The distributions are obtained by sampling $\hat{f}$ for each particle at every output step and aggregating the resulting realizations across the ensemble and realization window. It characterizes the fluctuating drag experienced by individual particles during transport, rather than their ensemble- or time-averaged mean. Across all fluid velocities examined, the mean normalized drag force remains approximately near one ($\langle \hat{f} \rangle \approx 1$), confirming that drag effectively balances particle weight under steady-state conditions. Particles continuously adjust their slip velocity to maintain this equilibrium, regardless of the imposed fluid velocity. This behavior aligns with classical multiphase flow theory, where terminal velocity defines the threshold for suspension, and higher entrainment velocities enhance stability without significantly altering the mean force balance. While gravitational and hydrodynamic forces remain dynamically balanced on average, the distinction between different operating conditions arises from the shape of the distributions, which encapsulate the fluctuating components of the drag force and their dependence on turbulence, inertia, and confinement. The evolution of drag-force statistics can be directly interpreted in light of the resolved flow fields shown in Fig. 10. For the smaller spherical particles, at $u_f = u_t$, the flow exhibits clear local velocity deficits and moderate streamline curvature around individual particles, indicating the presence of short, attached wakes, see Fig. 10a. In this regime, the particle inertia is moderate ($St \approx 1.26$), placing the particles in a transitional response regime where they partially track the carrier flow while retaining a measurable lag to the velocity fluctuations. The Stokes

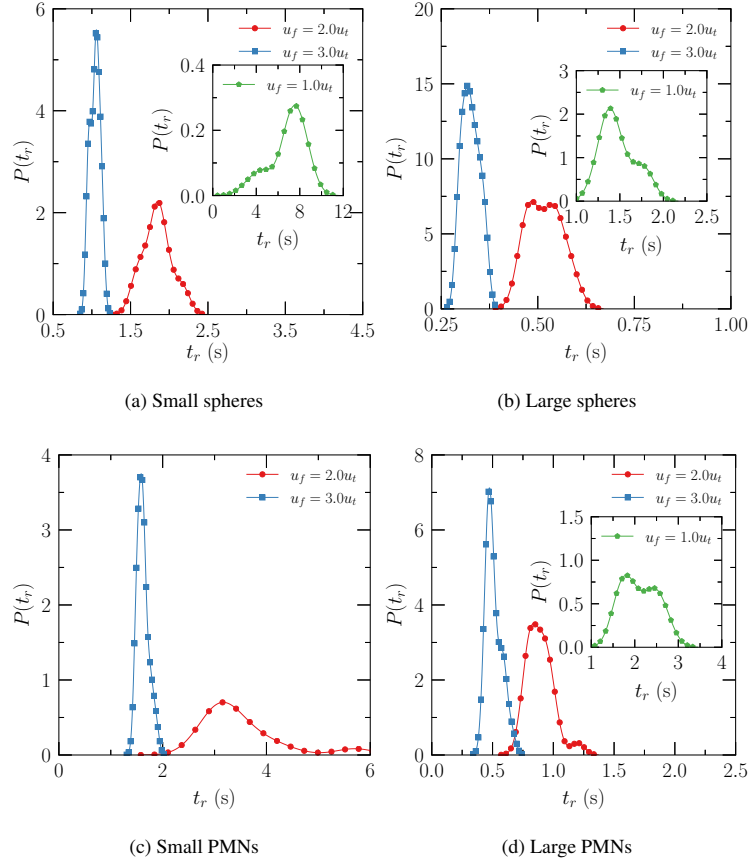


FIG. 9: Probability distributions of residence time (t_r) at $u_f = 1.0u_t$, $2.0u_t$, and $3.0u_t$. Panels (a-d) show small spheres, large spheres, small PMNs, and large PMNs, respectively. Distributions narrow with increasing velocity, transitioning from broad, variance-dominated profiles at low flow rates (insets) to sharp, convection-dominated distributions at high rates. Note: Small PMNs remain suspended at ($u_f = 1.0u_t$) without net upward transport.

number St is defined as

$$St = \frac{\rho_p d_p^2 u_f}{18 \mu_f D}. \quad (8)$$

As a result, drag fluctuations remain weak, and the corresponding force distribution is narrow, Fig. 12a. As the flow velocity increases to $u_f = 3u_t$, the streamline patterns appear straighter

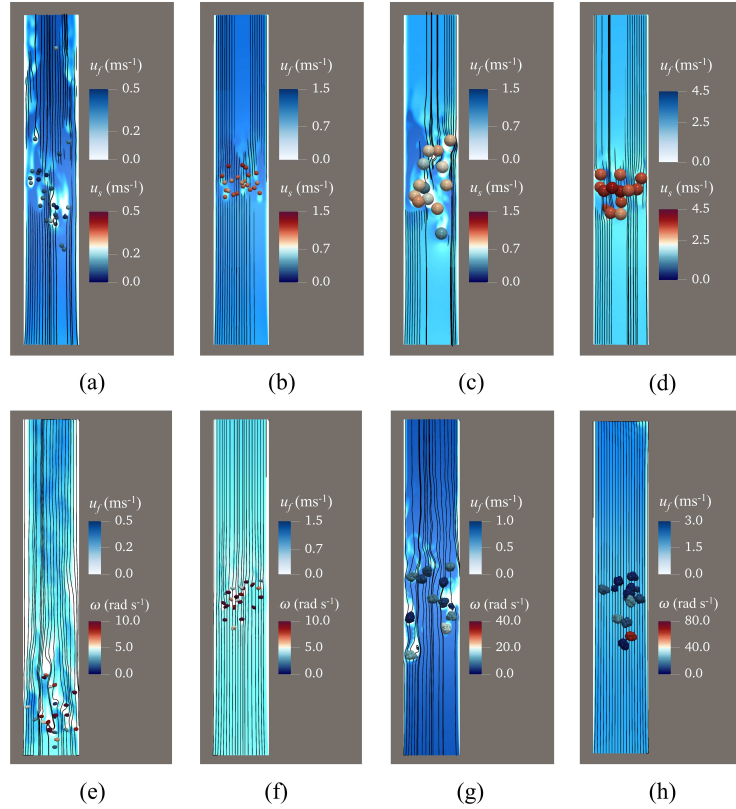


FIG. 10: Particle configurations and flow fields during vertical transport. Spheres (a-d) and PMNs (e-h) for small ($d_v = 16.4$ mm) and large ($d_v = 44$ mm) particles at ($u_f = 1.0u_t$) and ($3.0u_t$). Lower velocity cases exhibit greater dispersion and irregular trajectories, whereas higher velocity cases show more homogeneous, vertically aligned transport. PMNs generate asymmetric wakes and sustained rotation, with large PMNs reaching angular velocities up to 80 rad s^{-1} and intermittent wall interactions (see Movies M3 and M4 in the SM). Fluid velocity is colored by magnitude with streamlines shown as tubes (left); particle trajectories are colored by translational velocity (top right) and angular velocity (bottom right).

and individual wake structures become less visually distinct, Fig. 10b. This does not imply the absence of wake dynamics. Instead, the increase in Re_p leads to wake structures that are rapidly convected downstream, while axial shear and inter-particle interactions inhibit the formation of

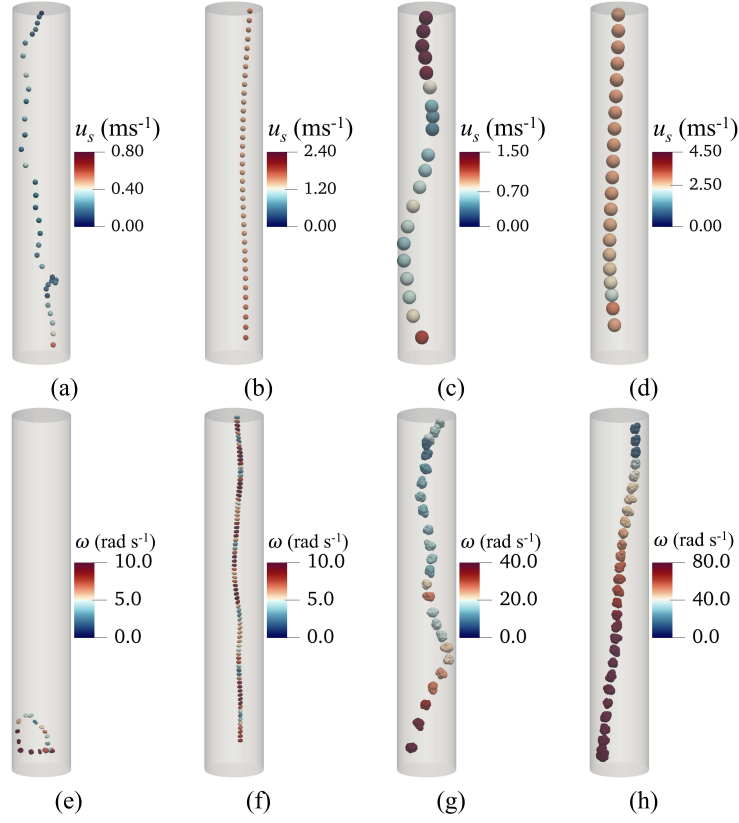


FIG. 11: Particle trajectories of a representative particle during vertical hydraulic transport, colored by instantaneous translational velocity (u_s) or angular velocity (ω). Panels (a-d) show spheres and (e-h) PMNs for small and large particles at $u_f = 1.0u_t$ and $3.0u_t$. Lower-velocity cases exhibit greater lateral dispersion and fluctuations, whereas higher-velocity cases show vertically aligned, convection-dominated transport. PMNs display stronger rotation than volume-equivalent spheres.

spatially coherent recirculation zones⁴⁷. In this regime, wake-induced disturbances persist but are temporally short-lived and not spatially localized, resulting in a modest broadening of the drag-force distribution without significant intermittency.

A qualitatively different behavior is observed for the larger spherical particles ($d_v = 44\text{ mm}$).

At $u_f = u_t$, the flow field reveals strong streamline distortion and a pronounced velocity deficit downstream of the particle cluster. The wake remains coherent and visibly asymmetric due to lateral confinement by the pipe wall ($d_v/D = 0.22$), but adjusts quasi-steadily to particle motion. Such confinement-induced wake asymmetry and deflection are well documented for bluff bodies in pipes and channels^{48,49}. Despite the higher particle inertia ($St \approx 23.7$), the quasi-steady wake adjustment yields relatively narrow distributions of drag force, see Fig. 12b. At $u_f = 3u_t$, the instantaneous flow visualizations show predominantly axial streamlines with no clearly identifiable recirculation Fig. 10d. This apparent suppression of wake structures does not indicate steady drag conditions. At high inertia ($St \approx 71$) and elevated Re_p , wake dynamics transition to a regime dominated by rapid downstream convection, confinement-induced suppression of lateral wake expansion, and strong interactions with neighboring particles and the confining wall⁴⁸. Under these conditions, the particle response time becomes comparable to the characteristic time scales of wake evolution, resulting in history-dependent drag forces that are not uniquely determined by the instantaneous slip velocity^{50,51}. Consequently, drag fluctuations become intermittent and heavy-tailed, even though wake structures are not readily apparent in instantaneous streamline plots.

The persistence of wake unsteadiness at high u_f is confirmed quantitatively by the streamwise velocity fluctuation intensity $I = u'_{rms}/u_f$, computed from fluid probes on the pipe centerline at $z = 0.1$ m, $z = 0.6$ m and $z = 1$ m. For the large-sphere case ($d/D = 0.22$), I grows from $\approx 11\%$ at mid-pipe to $\approx 23\%$ near the exit at $u_f = u_t$, indicating that wake disturbances accumulate downstream when the convective time scale is long. At $u_f = 3u_t$, $I \approx 13\%$ at both locations, indicating a statistically homogeneous fluctuating state in which disturbances advect out of the domain rather than accumulating, while u'_{rms} in absolute terms remains substantial. The transition from spatially developing (z -dependent) to spatially developed (uniform) fluctuation intensity parallels the residence time narrowing, and indicates that wake unsteadiness persists at high u_f even where instantaneous streamline plots show predominantly axial flow. Several factors contribute to this apparent contrast between the streamline visualizations and the fluctuation statistics, including the short convective time of the wake, confinement-induced suppression of lateral wake expansion, and inter-particle wake interference. The fluctuation intensities reported here arise predominantly from particle-induced disturbances rather than from classical wall-bounded turbulence in the absence of particles (see Fig. S6 in the SM). Probe measurements at z show that the u_z relaxes to the imposed value once particles have advected out.

The drag force distribution for small PMNs in Fig. 12c exhibits behavior quantitatively simi-

lar to that of spherical particles, with sharp peaks centered around $\hat{f} \approx 1.1 - 1.3$ across all flow velocities. This indicates that, for small particles, geometric irregularity plays a secondary role relative to inertia and confinement. Owing to their low effective inertia and rapid rotational dynamics, small PMNs remain strongly coupled to the carrier flow, such that orientation-dependent variations in projected area are rapidly averaged out and drag fluctuations are primarily governed by local flow variability. In contrast, the drag-force distributions for large PMNs, Fig. 12d, exhibit distinct features associated with orientation-dependent forcing. At $1.0u_t$, the distribution is relatively narrow but shifted toward higher values, with a peak at $\hat{f} \approx 1.5$ and a tail extending to $\hat{f} \approx 2.0$, reflecting enhanced form drag associated with non-spherical geometry. As the flow velocity increases to $2.0u_t$ and $3.0u_t$, the distributions broaden and shift toward $\hat{f} \approx 1.7$, accompanied by extended high-drag tails. At $3.0u_t$, the distribution becomes more sharply peaked than at intermediate velocities, yet remains substantially broader than that of spherical particles and retains a long tail extending to $\hat{f} \approx 4.0$.

The contribution of the orientation-dependent projected area to these distributions deserves explicit consideration. Although $\hat{f}$ is normalized by submerged weight and therefore does not contain A_{proj} explicitly, the instantaneous drag force F_d is sensitive to the time-varying orientation of non-spherical particles. This orientation-dependent forcing is directly resolved in the present simulations, as the CFD-DEM framework integrates the fluid stress over the instantaneous particle volume and does not invoke any orientation-dependent drag closure or explicit parameterization. The orientation modulation observed in $P(\hat{f})$ is therefore an emergent feature of the resolved solid-fluid coupling. For the PMN morphologies considered here, A_{proj} varies between bounds set by the volume-equivalent and circumscribed spheres, with $(d_{\text{eff}}/d_v)^2 \approx 1.5$ representing the ratio of the maximum instantaneous value to the orientation-averaged value. Whether this orientation modulation manifests in $P(\hat{f})$ depends on the ratio of the rotational time scale to the wake-shedding and transit time scales, which is controlled by the particle Stokes number. For small PMNs ($St \approx 0.9$ at u_t), the projected-area variability is geometrically bounded, and the resulting orientation-induced force fluctuations are small, comparable to carrier flow-driven fluctuations. Consequently, orientation modulation does not produce a distinguishable broadening, which remains quantitatively similar to that of small spheres (Fig. 12c). For large PMNs at higher flow velocity ($St \approx 51.6$), the rotational time scales are comparable to wake evolution time scales. The angular velocities reaching 80 rad s^{-1} (Fig. 11h) sample a wide range of projected areas without complete averaging. The resulting orientation-dependent forcing is transmitted into the instantaneous drag force,

broadening $P(\hat{f})$ and generating the extended tails (see Fig. 12d). This mechanism operates in addition to, and is distinguishable from, the wake-history effect governing large spheres or PMNs: large spheres exhibit broadening without orientation modulation, whereas large PMNs exhibit both contributions superimposed.

Across all velocities, small spheres and small PMNs maintain narrow, peaked distributions, whereas pronounced differences between spherical and non-spherical particles emerge for the larger size class. Large spherical particles exhibit a monotonic broadening of the drag distribution with increasing velocity, consistent with wake unsteadiness modified by confinement. For large PMNs, drag variability is further amplified by orientation-dependent forcing, which introduces an additional source of intermittency beyond wake dynamics alone. At $1.0u_t$, large PMNs experience irregular translational and rotational motion, including intermittent settling, wall-proximity events, and re-entrainment, leading to strong drag fluctuations. Flow-field visualizations in Fig. 10g reveal complex three-dimensional wake structures with multiple separation points arising from the non-convex particle morphology. Particle trajectory snapshots (see Fig. 11) confirm irregular lateral motion and variable angular velocity with intermittent wall-proximity events at low velocities, indicative of short-lived radial excursions. At higher velocities, increased angular velocity promotes more rapid reorientation and sustained transport upward through a more uniform mean flow, suppressing large radial excursions while promoting more persistent near-wall localization.

To quantify wall-proximity behavior, we define the instantaneous near-wall fraction $\phi_w(t) = \frac{1}{N_p} \sum_i I(\delta_i(t) < 0.1 d_v)$, where $\delta_i = R - r_i - d_v/2$ is the gap between the surface of particle i and the pipe wall, R is the pipe radius, and r_i is the radial distance of the particle center from the pipe axis. For consistency in defining the surface-wall separation, this metric is evaluated for spherical particles, although trajectory visualizations indicate qualitatively similar radial dynamics for non-spherical counterparts. Time-averaged over the stationary transport window, $\langle \phi_w \rangle$ increases from 0.13 at $u_f = 1.0u_t$ to 0.24 at $u_f = 3.0u_t$, indicating that the near-wall layer is sustained at both velocities but becomes denser at higher flow rates.

V. SUMMARY AND CONCLUSIONS

This study employed a fully resolved CFD-DEM approach to investigate the hydrodynamic behavior of non-spherical polymetallic nodules (PMNs) during sedimentation and vertical hydraulic transport in confined risers, which are relevant to deep-sea mining operations. Particle-fluid inter-

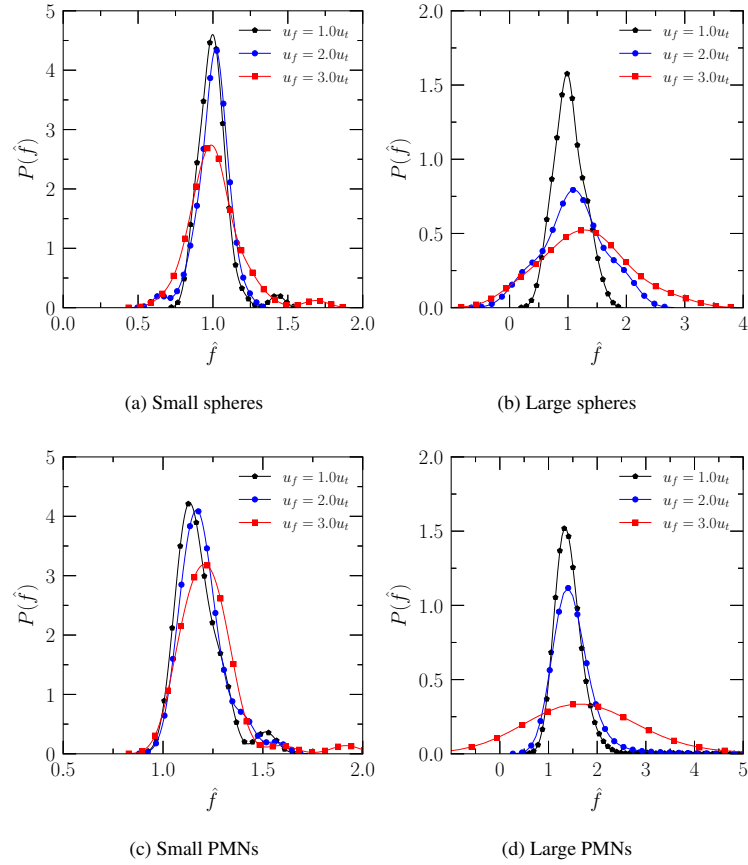


FIG. 12: Probability distributions of the normalized drag force ($\hat{f} = F_d/(\rho_p - \rho_f)V_p g$) for spherical and non-spherical particles at $u_f = 1.0u_t$, $2.0u_t$, and $3.0u_t$. Panels (a-d) show small spheres, large spheres, small PMNs, and large PMNs, respectively. Small particles exhibit narrow, weakly varying distributions across velocities, whereas large spheres show progressive broadening with increasing u_f , reflecting enhanced wake unsteadiness. Large PMNs display broader, skewed distributions with pronounced high-drag tails, highlighting intermittent, orientation-dependent forcing.

actions are explicitly resolved without empirical drag closures. The simulations provide mechanistic insight into how particle shape, confinement, and flow velocity collectively govern settling dynamics, residence time statistics, and fluctuations in drag force across low to moderate Re_p . The

key findings are outlined below.

1. Shape-induced drag enhancement governs PMN sedimentation, leading to reduced terminal velocities without altering the terminal force balance. Sedimentation simulations demonstrate that PMNs settle 27-29% slower than volume-equivalent spheres, irrespective of having the same mass and buoyancy. This reduction arises from an increase in the drag coefficient and morphology-induced wake asymmetry. Remarkably, the PMNs and spheres experience identical terminal drag forces equal to their submerged weight. The reduced settling velocity of PMNs reflects that the irregular particles generate the required hydrodynamic resistance at lower slip velocities, rather than an alteration in the equilibrium force balance.
2. The residence time distributions (t_r) highlight a velocity-driven transition from intermittent to convection-dominated transport, particularly showing that non-spherical particles experience delayed entrainment. At low flow velocities, the spherical particles and PMNs display broad t_r indicative of intermittent motion and partial settling, with small PMNs remaining marginally suspended and exhibiting oscillatory trajectories. As flow velocity increases, these distributions narrow and peak, signifying a shift to stable convection-dominated transport. The PMNs demonstrate larger mean residence times and variances compared to spherical particles under similar flow conditions, which is attributable to the greater drag ($\hat{f} > 1$) and rotational-translational coupling that contribute to the delayed entrainment.
3. Drag force statistics are significantly influenced by particle morphology and confinement, with non-spherical particles amplifying unsteady force fluctuations. The mean normalized drag force fluctuates around $\hat{f} = 1 - 1.5$ across configurations, indicating a steady transport equilibrium between hydrodynamic drag and submerged weight. Distinct transport regimes are characterized by variations in drag fluctuations. Small particles exhibit narrow distributions in drag fluctuations, which aligns with their rapid response to flow changes and low Stokes number dynamics. In contrast, large particles exhibit monotonic broadening of $P(\hat{f})$ with increasing u_f , consistent with wake-history effects. Large PMNs exhibit broadening $P(\hat{f})$ reflecting the competition between orientation-dependent forcing and increasingly homogeneous wake fluctuations. For small PMNs, rapid reorientation effectively averages out projected-area fluctuations, and the distributions remain comparable to those of equivalent spheres.

While PMNs exhibit 40-90% longer residence times and 2 times higher drag coefficients compared to volume-equivalent spheres, the underlying transport physics remains qualitatively simi-

lar. Both particle types undergo the same progression from a settling-dominated regime, through a transitional regime, to a convection-dominated regime as flow velocity increases. This suggests that first-order transport behavior can be captured using volume-equivalent spherical particles with appropriately calibrated drag laws, though quantitative predictions require shape-specific corrections. Future work will extend this framework to polydisperse systems with continuous particle injection and quantify pressure drop and transport efficiency under realistic operating conditions. The elevated drag coefficient has direct implications for pressure drop: at fixed input solid concentration for deep sea mining risers, the submerged weight $(\rho_p - \rho_f)g\phi_s$ is shape-independent, but the 27–29% lower settling velocity raises solid fraction (ϕ_s) at a given feed rate and increases the minimum input fluid velocity due to solid-fluid and solid-solid interactions. The results presented in this work apply to the Re_p ranges corresponding to dilute ensembles and are intended as calibration input for reduced-order models. Extrapolation of the results to dense slurries characterized by hindered settling, plug flow, and clustering is beyond the scope of the present study. Furthermore, the direct experimental validation of drag coefficients for CT-reconstructed PMN geometries, through controlled settling experiments with simultaneous orientation tracking, would provide complementary verification of the resolved simulations and enable assessment of the applicability of existing non-spherical drag correlations to highly irregular natural particle morphologies.

VI. SUPPLEMENTARY MATERIAL

The supplementary material (SM) contains flow and velocity snapshots of a sphere settling in a quiescent fluid, the Drafting, Kissing, and Tumbling stages, and high-resolution movies that complement the data and analyses presented in the manuscript. Moreover, the statistical convergence for the ensemble size and the intensity of fluctuations for the drag force analysis are also presented. Detailed movie captions are provided below.

- M1: A sphere settling in the viscous fluid: transition from a Stokes regime ($Re_p = 1.4$) to an intermediate regime ($Re_p = 29.8$), where inertial effects become significant.
- M2: Particle positions and fluid velocity magnitude contours during particle sedimentation, illustrating the drafting-kissing-tumbling phenomenon.
- M3: Particle configurations and stream lines during vertical transport of polycrystalline nodules entrained in a carrier fluid where $u_f = 0.8 \text{ m s}^{-1}$ (i.e., 1.0 times terminal velocity u_t) and ω

is the angular velocity.

M4: Particle configurations and stream lines during vertical transport of polymetallic nodules entrained in a carrier fluid where $u_f = 2.4 \text{ m s}^{-1}$ (i.e., 3.0 times terminal velocity u_t) and ω is the angular velocity.

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DATA AVAILABILITY

Data will be available on reasonable request.

CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

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