

Article

Mechanisms of Coarse Particle Transport in a Right-Angle Elbow Pipe: A Conjunctive PIV and CFD-DEM Study

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Abstract

The transport mechanism of non-spherical particles in complex pipelines, such as right-angle elbows, remains insufficiently understood, posing challenges to the efficiency optimization of industrial systems like deep-sea mining. This study investigates the fundamental mechanisms governing the upward transport of 1–15 mm non-spherical particles in a 100 mm right-angle bend by integrating Particle Image Velocimetry (PIV) experiments with coupled computational fluid dynamics and discrete element method (CFD-DEM) simulations. We systematically quantify the effects of key factors—flow velocity, particle size distribution, and shape factor (ranging from 0.4 to 1)—on flow asymmetry, particle dynamics, and transport efficiency. The results reveal a pronounced flow asymmetry, where the outer-side peak velocity is approximately twice that of the inner side, accompanied by a persistent separation vortex. Crucially, transport efficiency is governed by particle interactions: wide-grading blends achieve up to 12% higher conveying speed than narrow fractions at high flow rates. While spherical particles (shape factor, $SF = 1$) attain the highest axial velocity, particles with $SF \geq 0.8$ are identified as optimal, maintaining moderate rotation, concentrating in the central high-speed zone, and thereby combining high transport velocity with minimal wall contact. These findings elucidate the underlying particle–fluid interactions in bends and provide a quantitative basis for optimizing particle morphology in industrial hydraulic transport systems.

Keywords: hydraulic lifting; coarse particles; shape factor; complex solid–liquid two-phase flow study



Academic Editors: Angelo Luongo and Francesco Zirilli

Received: 12 January 2026

Revised: 22 February 2026

Accepted: 16 March 2026

Published: 17 March 2026

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1. Introduction

The hydraulic transport of coarse, non-spherical particles is a critical unit operation in numerous industries, from mineral processing to the hydraulic lifting of deep-sea polymetallic nodules—a particularly demanding application where system viability hinges on transport efficiency [1–3]. Across these fields, performance bottlenecks often occur at pipe fittings, especially right-angle (90°) bends. In these canonical geometries, complex secondary flows, intense particle–wall interactions, and significant energy losses conspire to govern overall system performance. A fundamental, mechanistic understanding of particle-laden flows in bends is therefore essential for advancing the design and optimization of robust transport systems.

Initial research on hydraulic lifting systems primarily focused on fundamental flow in straight pipelines (i.e., vertical and horizontal configurations), thereby establishing

a baseline understanding of particle trajectories, velocities, and concentration distributions [4–9]. Progress in understanding two-phase pipe flows has been driven by advances in both measurement and simulation. On the experimental side, Particle Image Velocimetry (PIV) has established itself as an indispensable tool for quantifying complex flow fields, providing unparalleled insight into fluid-phase dynamics and serving as a critical benchmark for model validation [10,11]. Building on these experimental capabilities, PIV has been extensively applied to characterize coarse particle transport behavior under varying flow conditions [12–14], as well as to analyze vorticity, turbulent kinetic energy, and the turbulence-enhancing effects of pipe inserts [15,16]. While straight-pipe studies provide essential foundational knowledge, practical deep-sea mining systems inevitably involve complex geometries. Consequently, research has progressively shifted toward investigating the influence of pipe configurations on conveying performance. Li et al. [17], for instance, demonstrated that Y-shaped pipelines outperform U-shaped designs in terms of transport efficiency, clogging mitigation, and wear resistance. Subsequent CFD-DEM studies have further optimized key operational parameters—such as flow velocity—for Y-shaped geometries, thereby complementing experimental efforts [18,19]. Among various fittings, the right-angle bend presents a particularly acute challenge due to pronounced inertial separation, intense secondary flows, and frequent particle–wall collisions. Early numerical investigations into bend and T-junction flows have predominantly focused on predicting macroscopic consequences such as erosion, blockage, and pressure drop [20–23]. For example, Chen integrated PIV with turbulence modeling to quantify pressure-loss characteristics in right-angle bends [22]. Notably, a common thread in many of these simulations is the predominant assumption of spherical particles [23,24]. Chen Wei, for instance, employed numerical simulations to systematically investigate wear in right-angle bends but focused on multi-sphere models of non-spherical particles, thereby failing to capture the full complexity of realistic, irregular shapes [24]. This simplification overlooks the critical role of particle shape—a key factor governing motion, rotation, and collision behavior. Although some studies have acknowledged shape effects, they are often confined to straight pipes [25]. For example, existing studies have examined diverse particle effects: some focus on how spherical, plate-like, and linear particles affect transport in vertical pipelines [26], while others compare the wear induced by rod-shaped versus triangular particles in similar sections [27]. Similarly, while studies have examined the influence of particle size and concentration using CFD-DEM [28,29], they have not systematically isolated the effect of the shape factor within the high-stress environment of a right-angle bend.

However, a critical technical gap persists when applying these findings to the design of deep-sea mining systems. First, while the importance of bends is recognized, a quantitative, mechanistic understanding of the coupled fluid–particle dynamics within right-angle bends—specifically regarding how they govern transport efficiency—remains lacking. Second, although particle shape is acknowledged as influential, existing studies have not systematically isolated and quantified the effect of shape factor (SF) across a continuous range (e.g., from disks to spheres) within the high-stress environment of a bend. Third, there is a dearth of studies that integrate high-fidelity experimental validation (like PIV) with high-resolution coupled CFD-DEM simulations to both visualize and fundamentally explain these complex interactions.

Therefore, the novelty and necessity of this work are twofold. (1) Methodologically, it establishes a robust, validated framework by uniquely coupling PIV experiments with CFD-DEM simulations to study bend flow, ensuring both observational insight and predictive capability. (2) Scientifically, it delivers the first systematic analysis that disentangles and quantifies the individual and synergistic effects of

flow velocity, particle size distribution, and—most critically—a continuous shape factor on transport efficiency and particle behavior in a right-angle bend. This allows us to identify not just qualitative trends but an optimal shape-factor range for operational efficiency.

To bridge this critical knowledge gap, this study systematically investigates the upward transport behavior of non-spherical particles (with shape factors ranging from 0.4 to 1) in a 100 mm right-angle bend. By integrating Particle Image Velocimetry (PIV) experiments with Computational Fluid Dynamics–Discrete Element Method (CFD–DEM) simulations, we quantitatively analyze the asymmetric flow field, particle motion behavior, and key influencing factors: specifically, flow velocity, particle size, and particle shape factor.

2. Experimental Setup and Methods

2.1. Experimental System Setup

The primary objective of this experimental study is to investigate the fundamental mechanisms governing the transport of coarse, non-spherical particles in a canonical right-angle bend geometry. The context of deep-sea polymetallic nodule mining serves as a key motivation and a relevant application scenario, but the work is not intended as a direct, scaled physical model of the full-scale mining system. Instead, we employ a well-controlled laboratory prototype to isolate and quantify the effects of key variables—flow velocity, particle size distribution, and shape factor—on transport efficiency and flow asymmetry.

The experimental system consists of three subsystems: pipeline transportation, control, and measurement, as illustrated in Figures 1 and 2. The pipeline transportation subsystem comprises a main transportation pipeline with a total length of 12 m and an inner diameter of 100 mm, along with a slurry pump. A 3 m-long transparent acrylic pipe is installed on the main pipeline to facilitate observation of particle movement. The slurry pump has a flow rate of 50 m³/h, a head of 15 m, and a power of 7.5 kW. The water inlet, positioned at the highest point of the system, works in conjunction with an air valve to inject water and simultaneously expel air, thereby maintaining a predominantly solid–liquid two-phase flow. The coordinated operation of the feed inlet and valves enables safe material feeding and discharging while aiding in air removal. The control subsystem includes a variable-frequency drive for pump speed regulation and a master control switch for the entire system, both wired into the central power cabinet. The measurement subsystem comprises an electromagnetic flowmeter, multiple pressure sensors, a slurry concentration meter, and a Particle Image Velocimetry (PIV) system. The PIV system is equipped with a dual-pulse laser, a synchronization controller, a high-speed camera, and a dedicated software suite (PIV/PTV, Beijing Cubic Sky Technology Development Co., Ltd., Beijing, China). PIV/PTV measurements follow the standard tracer particle approach: laser illumination captures the instantaneous velocity field generated by particle displacement in continuous frames, which is further processed to extract vorticity, streamlines, and isobars; particle tracking can also provide the trajectory and flow velocity of individual particles, making it a powerful tool for studying particle flow in right-angle bends.

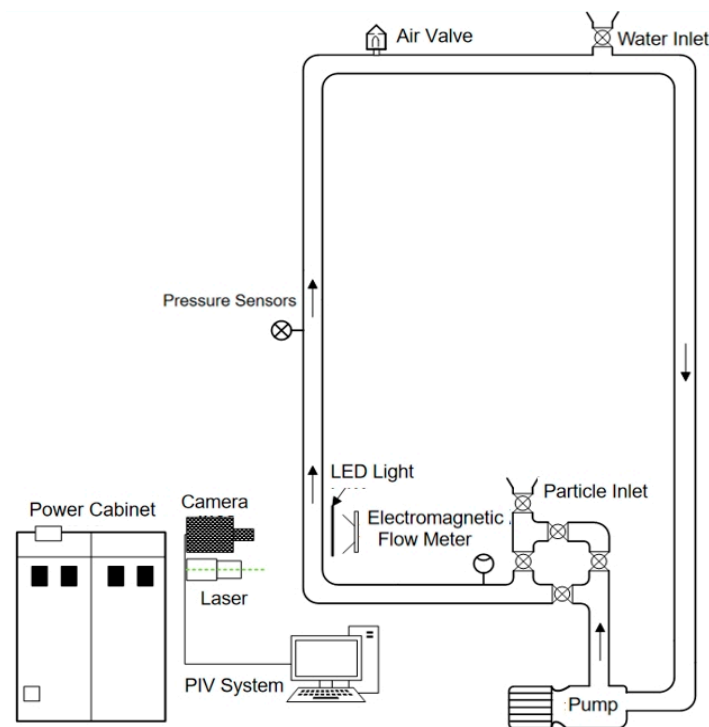


Figure 1. Schematic diagram of the hydraulic conveying test system.

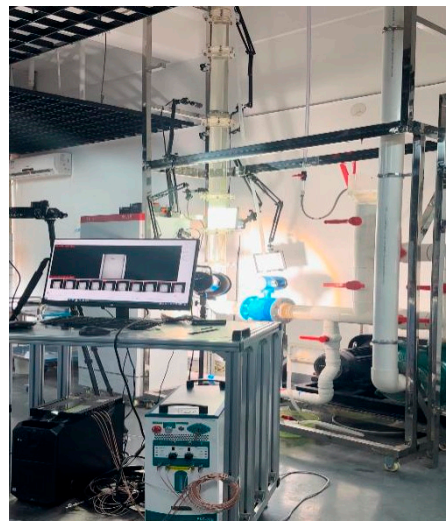


Figure 2. Photograph of the hydraulic conveying test system.

2.2. Experimental Methods

The experiments were designed to isolate the fundamental fluid–particle interactions within the bend. To this end, deliberate idealizations were made in the choice of materials and parameters, justified by the principle of dynamic similarity to ensure the relevance of the revealed mechanisms to industrial conditions. The fluid medium in the experiment was clear water. This idealization eliminates complexities such as corrosion and non-Newtonian rheology, allowing us to isolate the inertial and turbulent interactions dominant in high-Reynolds-number flows relevant to industrial transport. The solid phase consisted of quartz sand particles with a density of 2650 kg/m^3 , a density comparable to many crushed minerals. This ensures dynamic similarity in terms of the key dimensionless Stokes number, which governs particle response to fluid turbulence. The particle size range of 1–15 mm was selected to reflect practical size limits while preventing blockages

in the laboratory-scale pipe. Because direct measurement of the cross-sectional velocity distribution inside the pipe was impractical, we inferred the fluid velocity field from the motion of tracer particles that exhibited excellent flow-following behavior. To this end, we employed hollow silica microspheres (5–20 μm in diameter) as tracer particles. Their small size and low density ensured that their volumetric and mass contributions to the flow were negligible. Before each experiment, we completely filled the loop with water and repeatedly vented to eliminate residual air bubbles. After completing these preparatory steps, we started the slurry pump and set the desired flow rate via the frequency inverter. The system was allowed to stabilize until the pump reached and maintained the specified frequency. Steady-state flow was then quantitatively confirmed when the readings from the electromagnetic flowmeter and pressure sensors varied by less than $\pm 5\%$ over a continuous period of 10 s, indicating the dissipation of transient startup effects. Once the steady state was reached, the camera recorded images of both tracer and solid particles. We then used PIV software (MicroVec v3.6.2) to extract particle velocities and the fluid velocity field.

To quantitatively demonstrate the dynamic similarity between our laboratory-scale experiment and real deep-sea mining conditions, Table 1 presents a comparison of the key dimensionless numbers governing the flow and particle transport regimes.

Table 1. Comparison of key dimensionless numbers between laboratory-scale experiment and typical deep-sea mining conditions.

Parameter	Value	Laboratory	Deep-Sea Mining
Flow regime	Reynolds number, Re	1.05×10^5 – 2.28×10^5	1.0×10^5 – 5.0×10^6
Particle inertia	Stokes number, Stk	1.9–761	1.5–17,000
Gravity/inertia	Froude number, Fr	1.31–2.32	1.6–3.3
Particle/fluid density	Density ratio, ρ_p/ρ_f	2.65	2.5–3.0

This comparison demonstrates that, despite differences in absolute scale, the dimensionless parameter space of our experiments overlaps significantly with that of full-scale deep-sea mining systems—particularly in the particle size range of 1–15 mm that is the focus of this study. The flow is fully turbulent in both systems, particle inertia responses are dynamically similar for the relevant size fractions, and gravitational effects are comparably scaled. Therefore, the mechanistic insights obtained from this laboratory investigation are transferable to industrial practice within the studied parameter range.

2.3. Simulation Model

This study employed a coupled ANSYS Fluent (ANSYS 2022R1)–Rocky approach to simulate the transport of coarse particles in pipelines. The simulation geometry replicates the experimental pipeline at a 1:1 scale and incorporates a pump assembly, as shown in Figure 3. We specified the pump parameters based on experimental data (Table 2).

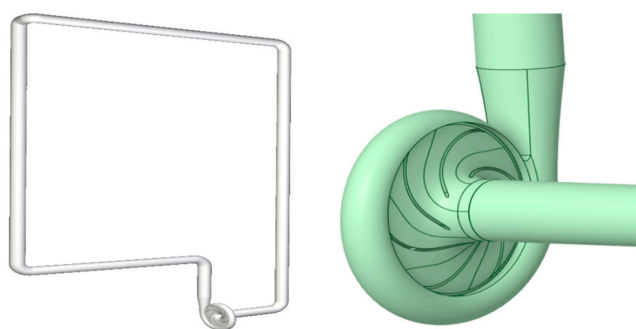


Figure 3. Cont.

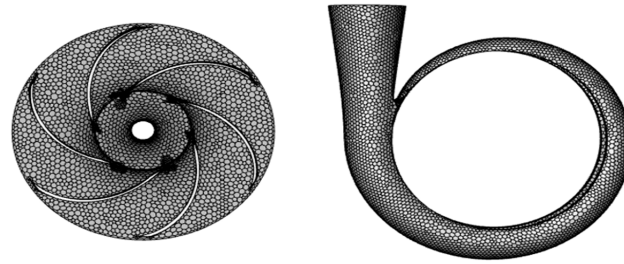


Figure 3. Schematic diagram of the complete model structure.

Table 2. Pump parameters.

Parameter	Value
Allowable Stress	15 MPa
Safety Factor	1.15
Minimum Shaft Diameter	24.97 mm
Total Inlet Pressure	1 bar
Hub Diameter	25 mm
Suction Diameter	100 mm
Impeller Diameter	274 mm
Outlet Width	30 mm
Inlet Volume Flow	100 m ³ /h

2.3.1. Governing Equations and Coupling Framework

The fluid phase (slurry) was solved using an Eulerian approach in Fluent by solving the volume-averaged Navier–Stokes equations. The conservation of mass and momentum for the incompressible fluid is given by the following:

$$\frac{\partial(\varepsilon_f \rho_f)}{\partial t} + \nabla \cdot (\varepsilon_f \rho_f u_f) = 0 \quad (1)$$

$$\frac{\partial(\varepsilon_f \rho_f)}{\partial t} + \nabla \cdot (\varepsilon_f \rho_f u_f) = -\varepsilon_f \nabla p + \nabla \cdot (\varepsilon_f \tau_f) + \varepsilon_f \rho_f g + S_p \quad (2)$$

where ε_f is the fluid volume fraction, ρ_f is the fluid density, u_f is the fluid velocity, p is the pressure, τ_f is the viscous stress tensor, g is gravity, and S_p is the momentum exchange source term due to particle–fluid interaction. This key source term is calculated as $S_p = -\frac{1}{V_{cell}} \sum F_{f-p}$, where F_{f-p} is the force exerted by the fluid on a particle (see Section 2.3.2). The SST k- ω turbulence model was employed.

The particle phase was tracked using a Lagrangian Discrete Element Method (DEM) in Rocky. The motion of each particle is governed by:

$$m_p \frac{dV_p}{dt} = F_{f-g} + F_c + m_p g \quad (3)$$

where m_p and V_p are the particle mass and velocity, F_c is the contact force, and g is gravity. A two-way transient coupling was implemented: Fluent passed fluid fields to Rocky, which calculated particle forces and returned the momentum sink S_p to Fluent at each coupling time step, thereby solving the system in an unsteady manner to capture dynamic interactions.

2.3.2. Particle Force Models and Collision Dynamics

The fluid–particle force F_{f-p} includes drag, pressure gradient, virtual mass, and lift forces. The drag force was modeled using the Di Felice correlation for dense flows:

$$F_{drag} = \frac{1}{2} C_d \rho_f A_p |u_f - V_p| (u_f - v_p) \varepsilon_f^{-\chi} \quad (4)$$

where C_d is the drag coefficient, A_p is the projected particle area, and χ is an empirical constant.

Pressure Gradient Force (F_p):

$$F_p = -V_p \nabla p \quad (5)$$

Virtual Mass Force (F_{vm}): $F_{vm} = C_{vm} \rho_f V_p (\frac{Du_f}{Dt} - \frac{dv_p}{dt})$, where C_{vm} is the virtual mass coefficient.

Lift Force (F_l) is calculated using established lift models within Rocky to account for shear-induced lift.

Particle–particle and particle–wall interactions were modeled using the Hertz–Mindlin (no-slip) contact model. The contact force $F_c = F_n + F_t$ comprises:

Normal Force:

$$F_n = (K_n \delta_n^{3/2} + C_n \dot{\delta}_n) n \quad (6)$$

where $K_n = \frac{4}{3} E^* \sqrt{R^*}$ is the normal stiffness, C_n is the normal damping coefficient, δ_n is the normal overlap, $\dot{\delta}_n$ is its rate, and n is the unit normal vector at the contact point.

Tangential Force:

$$F_t = -\min(\mu_s |F_n|, |K_t \delta_t + C_t \dot{\delta}_t|) \frac{\delta_t}{|\delta_t|} \quad (7)$$

where $K_t = 8G^* \sqrt{R^* \delta_n}$ is the tangential stiffness, C_t is the tangential damping coefficient, δ_t is the tangential displacement vector, $\dot{\delta}_t$ is the tangential relative velocity, and μ_s is the static friction coefficient. The pipe wall material was defined with a density of 1190 kg/m³, a Poisson's ratio of 0.3, and a Young's modulus of 1×10^{11} Pa.

2.3.3. Computational Setup

For the computational domain, we generated a polyhedral mesh. A grid independence study was conducted by evaluating three mesh resolutions: coarse (1 million cells), medium (1.65 million cells), and fine (3 million cells). Key flow parameters, such as the average turbulent kinetic energy in the bend and the outlet velocity, were monitored. The differences between the medium and fine mesh results were less than 2%, confirming that further refinement would not significantly impact the solution. Consequently, the medium-resolution mesh, comprising 287,024 nodes and 1,648,623 elements, was selected for all subsequent simulations to balance accuracy and computational cost.

To accurately model the pump's operation, we designated the impeller, front shroud, and back shroud as rotating boundaries, while treating the volute and pipe walls as stationary no-slip walls. This ensured a zero relative velocity between the fluid and these stationary surfaces. We applied the SIMPLE algorithm for pressure–velocity coupling. The internal CFD (Fluent) time step was set to 0.0001 s to satisfy the Courant condition ($CFL < 1$) and ensure numerical stability for the flow solution. The critical system evolution time step, defined as the coupling interval for data exchange with the DEM solver (Rocky), was determined through a sensitivity analysis. Three coupling intervals (0.05 s, 0.1 s, and 0.2 s) were tested for the most dynamic case. The quasi-steady-state solid mass flow rate was used as the comparison metric. The results obtained with a coupling interval of 0.1 s showed a deviation of less than 3% from those using the shorter 0.05 s interval, while

significantly reducing computational time. Thus, a coupling interval of 0.1 s was selected for all simulations.

In Rocky, we generated particles with a density of 2650 kg/m³ and diameters ranging from 1 mm to 15 mm. To simulate the irregular shapes of natural particles, we created ten distinct particle models within the software. To facilitate the study of the influence of particle shape on the flow characteristics, the particle shape factor was defined using the method in reference [30], and the formula is as follows:

$$SF = \frac{c}{\sqrt{ab}} \quad (8)$$

In the formula, a , b , and c represent three mutually perpendicular axis lengths, and c is the shortest axis length.

All particle properties other than shape were kept constant; the key parameters are summarized in Table 3.

Table 3. Partial particle parameters.

	1	2	3	4	5
SF	0.4064	0.6025	0.6468	0.7146	0.7863
Geometry					
	6	7	8	9	10
SF	0.8	0.8154	0.9833	0.99	1
Geometry					

3. Experimental Validation

3.1. Flow Rate Matching

To ensure strict one-to-one correspondence between pump performance in the simulation and the experimental conditions, a linear relationship between volumetric flow rate and pump frequency was established experimentally and reproduced numerically. In the experimental stage, the fluid velocity was varied by adjusting the pump frequency. Ten frequencies were randomly selected; once steady flow was achieved at each step, the electromagnetic flowmeter reading was logged. Figure 4 presents the linear relationships between flow rate and pump frequency (experiment) and between flow rate and pump rotational speed (simulation). Linear interpolation was then used to identify the exact speeds that match the experimental flow rates. Consequently, the model pump speed can be set directly from experimental conditions, ensuring fidelity to reality and enhancing the accuracy of subsequent particle transport simulations, thus providing a validated basis for comparison with experimental data.

3.2. Validation

3.2.1. Pressure Validation

To isolate the fluid dynamics from the complicating effects of particle motion and to obtain a clean benchmark for model validation, pressure measurements were first conducted using clean water only. This approach eliminates pressure fluctuations caused by particle–wall and particle–sensor interactions. Three pressure transmitters (A1, A2, A3) were installed at equal intervals along the vertical pipe section downstream of the right-angle bend, with A1 closest to the bend exit and A3 farthest upstream. Experiments were performed at three bulk flow velocities, and the corresponding steady-state pressures were

recorded at each transmitter. Identical flow conditions were replicated in the CFD-DEM simulations, and pressure values were extracted at the same spatial locations for direct comparison. As shown in Figure 5, the simulated pressures are in excellent agreement with the experimental measurements across all three velocities and monitoring points. The pressure decreases monotonically from A1 to A3 in both experiment and simulation. The maximum relative error observed across all measurements is approximately 6%. Overall, the small and consistent errors confirm that the CFD-DEM model reliably predicts the fluid pressure field in the absence of particles, providing a solid foundation for the subsequent validation of particle-laden flow behavior.

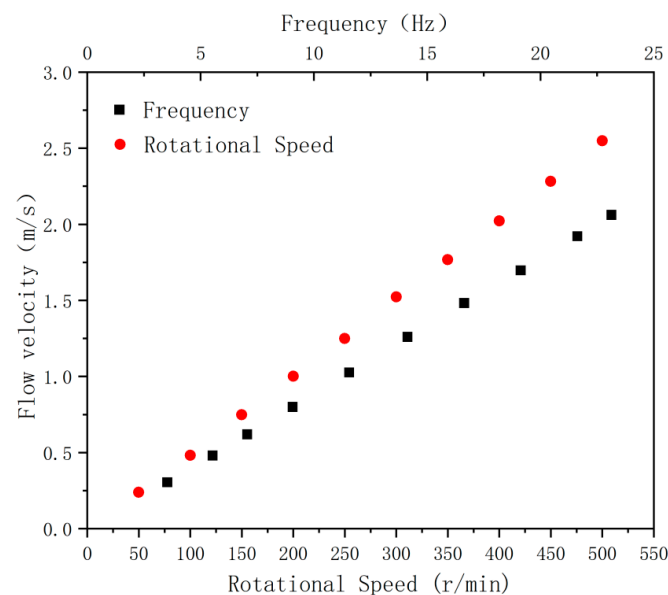


Figure 4. Relationship between pump rotational speed and flow velocity (simulation), and between pump frequency and flow velocity (experiment).

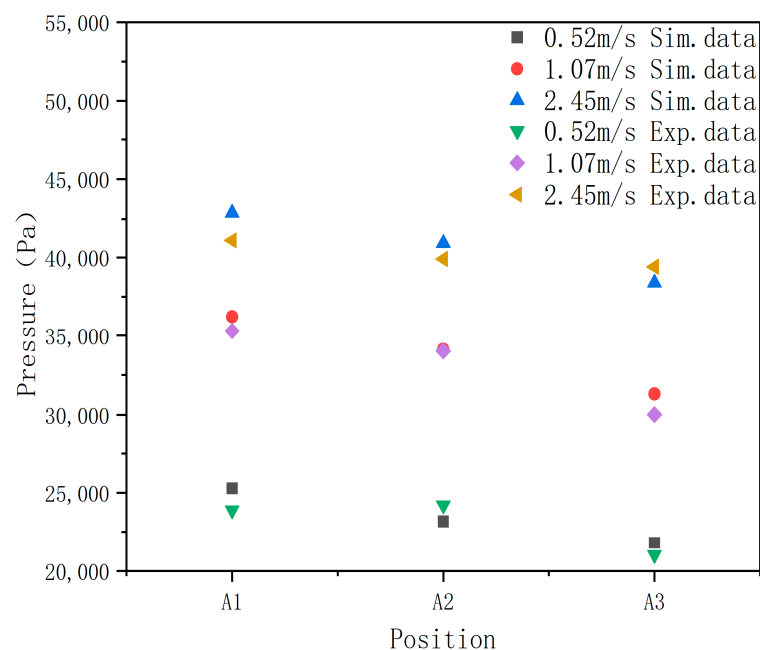


Figure 5. Comparison of experimental and simulated pressures at three monitoring points under different flow velocities under single-phase flow conditions.

3.2.2. Particle Motion Validation

Experimental and numerical setups for three representative cases—single spherical particles, single non-spherical particles, and spherical particle clusters—were conducted at three matched flow rates (pump frequencies: 14.13, 16.63, 21.63 Hz; corresponding simulated pump speeds: 250, 300, 400 r/min). In the experiments, a high-speed camera recorded particle images, and a tracking algorithm computed instantaneous velocities. In the simulations, spherical ($\rho = 2560 \text{ kg/m}^3$, $d = 10 \text{ mm}$) and polyhedral particles ($\rho = 2650 \text{ kg/m}^3$, equivalent $d = 10 \text{ mm}$) were tracked at planes identical to the experimental field of view. Ensemble averaging over repeated samples was applied to both datasets to eliminate random errors.

Qualitative validation is achieved by comparing characteristic trajectories. Figures 6 and 7 present direct comparisons for representative single spherical and non-spherical particles, respectively. The spherical particle (Figure 6) exhibits smooth, congruent paths in both experiment and simulation, with limited lateral displacement. The non-spherical particle (Figure 7) shows that the simulation successfully reproduces the experimental behavior of pronounced flipping and complex, fluctuating paths. Furthermore, to illustrate the complex phenomenon that the model aims to capture, Figure 8 presents the experimental trajectory of a spherical particle swarm, highlighting the increased randomness and dispersion due to inter-particle collisions.

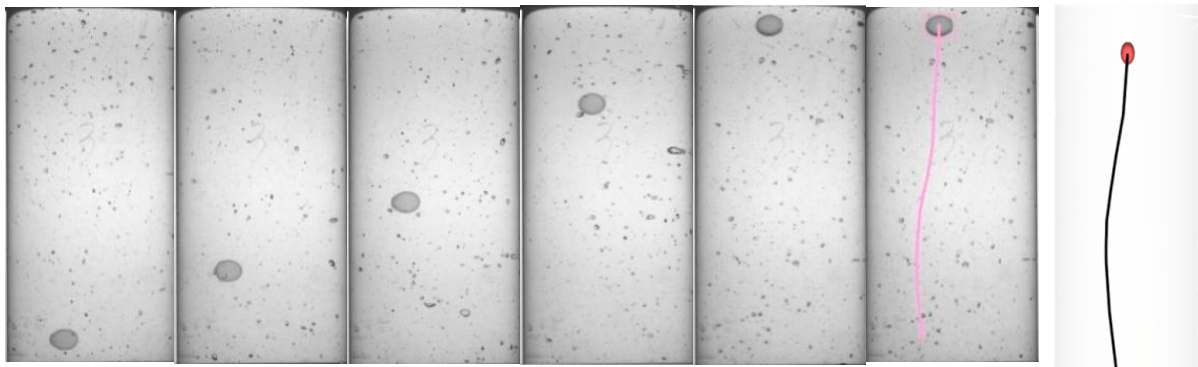


Figure 6. Trajectory of a single spherical particle. The black lines in the figure on the far right represent the particle trajectories in the simulation.

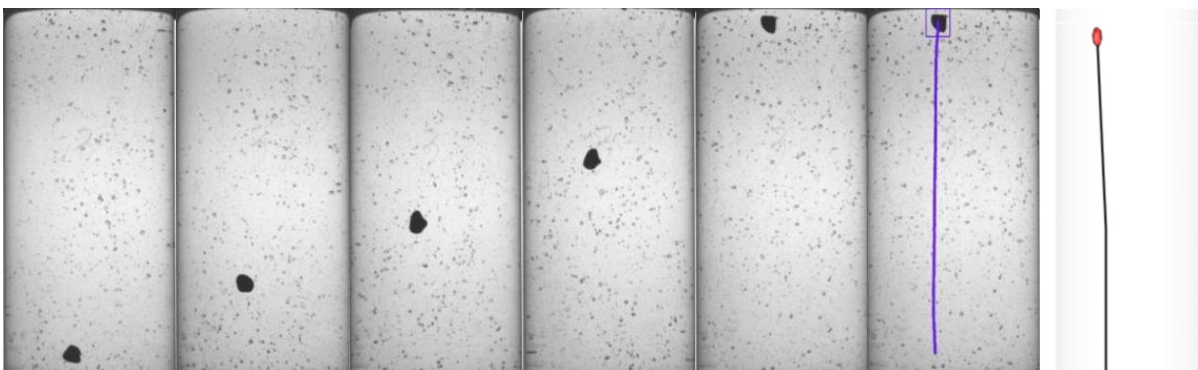


Figure 7. Trajectory of a single non-spherical particle. The black lines in the figure on the far right represent the particle trajectories in the simulation.

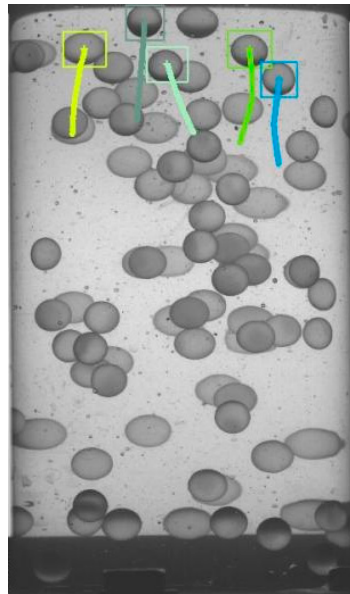


Figure 8. Trajectory of spherical particle swarm.

Quantitative validation is based on the comparison of ensemble-averaged particle velocities. Figure 9 plots the particle mean velocity against the local liquid velocity for all cases. The results show excellent agreement: with increasing liquid velocity, particle mean velocity rises monotonically while slip velocity decreases. Spherical clusters travel approximately 8% faster than a single sphere, and non-spherical single particles move about 5% faster than spherical ones at the same liquid velocity. Quantitative error analysis across all data points yields a Mean Absolute Percentage Error (MAPE) of 3.03% and a coefficient of determination (R^2) of 0.998, with a maximum observed deviation of 5%.

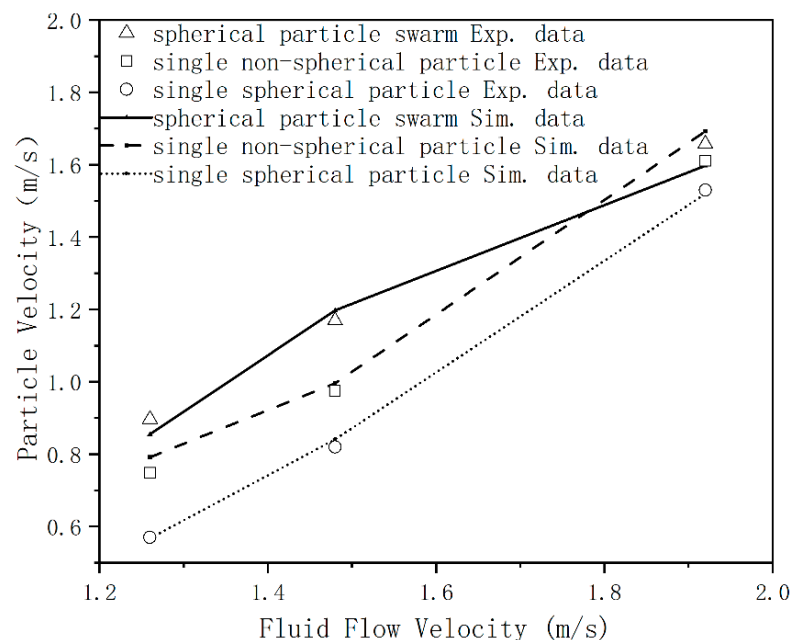


Figure 9. Comparison of experimental and simulated velocities for three particle groups.

The combined qualitative and quantitative evidence confirms that the coupled model accurately reproduces particle transport dynamics in right-angle bends, providing a reliable basis for the subsequent mechanism analysis.

4. Results and Discussion

4.1. Flow Field at the Bend

Figure 10 presents the axial velocity contours at the exit section of the right-angle bend for four pump frequencies with water as the working fluid. The velocity field exhibits a pronounced left-high/right-low pattern: a high-speed zone adjacent to the left wall decreases toward the lower-right corner, where a vortex forms [15]. As pump speed increases, both the peak velocity and the left-right velocity difference expand. This distribution arises from the sudden geometric change at the bend, flow decelerates along the inner wall due to wall constraint, while the outer region retains higher momentum; flow separation along the inner surface generates a vortex and pronounced velocity non-uniformity. Velocity variations induce corresponding pressure changes: higher pressure on the inner wall and lower on the outer wall. At higher pump frequency (21 Hz), the rapid velocity change at the corner is accompanied by noticeable noise and pipe vibration, indicating water-hammer and additional energy loss.

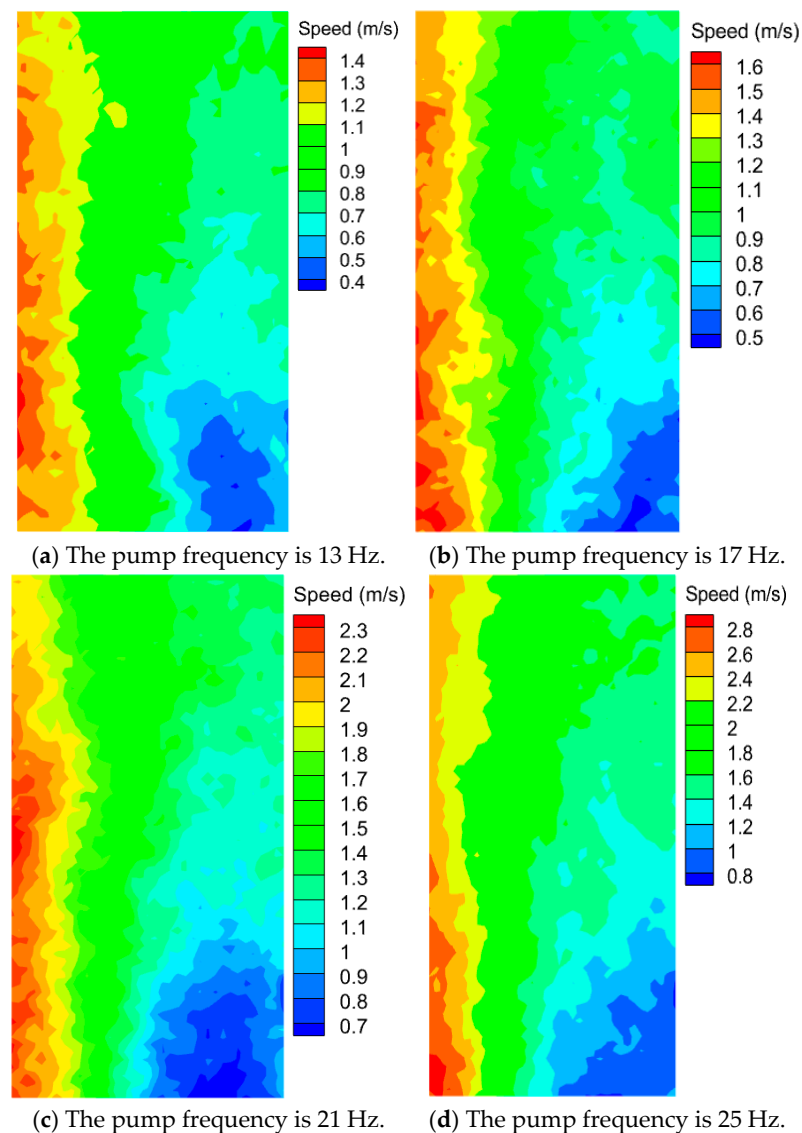


Figure 10. Velocity cloud map of the pipe section.

Figure 11 presents the two-dimensional velocity distributions in the bend region, obtained through Particle Image Velocimetry (PIV) measurements at various pump frequencies. The results indicate that while the total flow rate through the bend increases

linearly with pump frequency, the bend effect induces a highly asymmetric velocity distribution. Specifically, the peak velocity on the left (outer) side increases from 1.2 m/s at 13 Hz to 2.9 m/s at 29 Hz, whereas the velocity in the low-speed zone on the right (inner) side only rises from approximately 0.8 m/s to 1.8 m/s. It can be concluded that although the velocity ratio between the two sides remains approximately 2:1 across the tested frequency range, the resulting absolute velocity difference (i.e., the lateral velocity gradient) caused by the increasing pump frequency expands linearly from 0.4 m/s to 1.1 m/s. This enhanced lateral velocity gradient drives more fluid into the inner corner, thereby intensifying the separation vortex. This work demonstrates that increasing the pump frequency not only raises the overall flow rate linearly but also significantly amplifies the velocity gradient at the bend exit. These findings establish a crucial hydrodynamic basis for subsequent analysis of particle classification and transport efficiency.

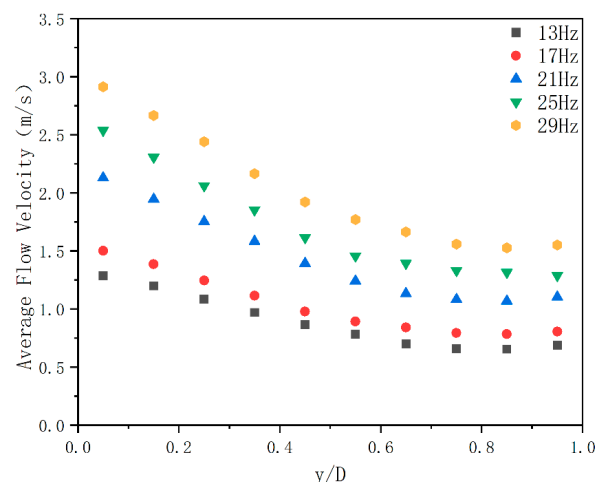


Figure 11. Average fluid velocity distribution across the pipe section at different pump frequencies. (y/D indicates that the horizontal coordinate is the relative position of the particle's location from the left side of the tube).

4.2. Effect of Particle Size Distribution on Transport Efficiency

In this study, transport efficiency is quantitatively defined as the average axial velocity of a particle group measured at the outlet cross-section of the bend under a given pump frequency. This metric directly reflects the system's throughput capacity for a specific particle ensemble, where a higher average axial velocity indicates a shorter transport time and thus higher efficiency.

To investigate the effect of particle size distribution on transport efficiency, the actual ore, following crushing, exhibits a complex system characterized by a wide particle size distribution, non-spherical shapes, and intense collisions. Its transport behavior differs significantly from that of idealized spherical particles of uniform size. In this study, a 1–15 mm quartz-sand blend was prepared by volume fraction: fine (1–5 mm, 25%), medium (5–10 mm, 35%), and coarse (10–15 mm, 40%). PIV was employed to simultaneously capture flow fields and particle velocities. The motion characteristics of narrow-gradation groups (6–8 mm and 8–10 mm) were systematically compared to reveal the true behavior of particle size differences at the outlet of a right-angle elbow.

Figures 12–14 present cross-sectional mean velocities for the 1–15 mm blend, 6–8 mm, and 8–10 mm sands, respectively. At 15 Hz, fine particles (1–5 mm) exhibit the highest velocity and accumulate in the left-side high-speed zone. Medium and large particles exhibit similar velocities, collectively forming a distribution characterized by high velocities on the left and low velocities on the right, consistent with the flow field in a curved pipe. At 20 Hz, medium-particle velocity increases rapidly and converges

with that of fines, while coarse-particle velocity remains almost unchanged—indicating that fluid kinetic energy is sufficient to overcome medium-grain inertia but not yet that of coarse grains. At frequencies of 25 Hz and 30 Hz, the velocity of larger particles abruptly increases, enabling them to overtake medium and small particles in the low-velocity zone on the right as their inertial advantage becomes apparent. At 25 Hz, the average velocity of the wide-gradation aggregate group increased by approximately 6% compared to the 6–8 mm single-size fraction, and by approximately 12% at 30 Hz. Therefore, at high frequencies, the conveying efficiency of wide-graded aggregates is markedly superior to that of narrow-graded aggregates. Although 6–8 mm particles move slightly faster than 8–10 mm under the same conditions, both mono-fractions lag behind the 5–10 mm segment of the wide blend, confirming that a larger size difference yields higher efficiency.

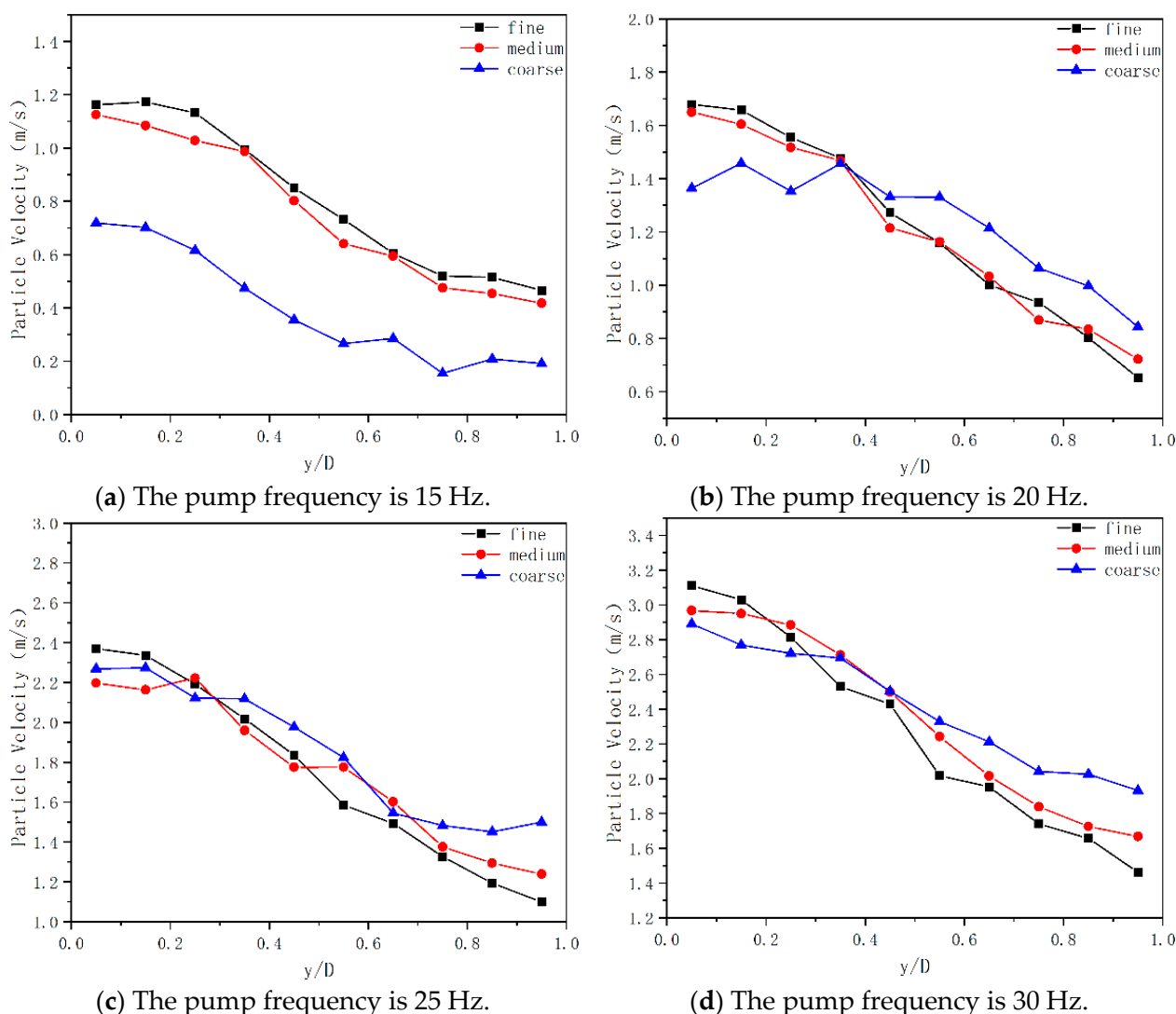


Figure 12. Particle velocity distributions (1–15 mm) at different pump frequencies.

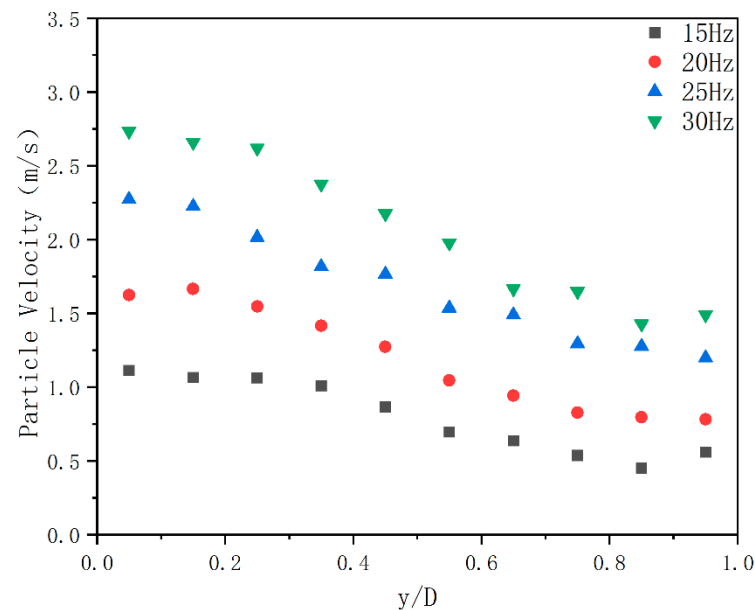


Figure 13. Particle velocity distributions (6–8 mm) at different pump frequencies.

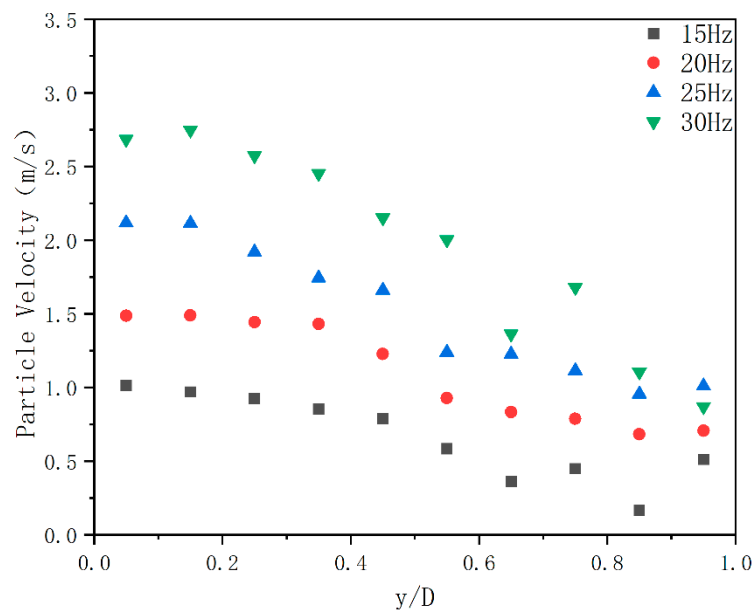


Figure 14. Particle velocity distributions (8–10 mm) at different pump frequencies.

4.3. Shape-Factor Influence on Velocity and Rotation

To clarify how non-spherical particles behave at the bend, 8–10 mm blends were simulated over 0.89–2.69 m/s and validated against PIV data. Figure 15 shows the relationship between particle mean velocity and shape factor at different flow rates. At 0.89 m/s, velocity differences among various shapes are insignificant. As velocity increases, spherical particles (shape factor = 1) maintain the highest velocity, while disk-like particles (shape factor = 0.4) exhibit the lowest velocity with irregular fluctuations, resulting from additional drag, collisions, and wall friction caused by geometric asymmetry. Figure 16 further illustrates the rotational angular velocity distribution. At 0.89 m/s, all particles have low rotational speeds, with columnar particles (shape factor = 0.71) showing the highest value. With increasing velocity, overall rotation increases significantly: columnar particles reach the maximum rotational angular velocity of 215 rad/s, whereas spherical particles and disk-like particles remain low and change little. Comparison shows that high

rotation does not bring high axial velocity. Instead, energy dissipation reduces axial speed. Particles with shape factors ≥ 0.8 maintain moderate rotation and are concentrated in the central high-speed zone, combining high velocity with low wall contact.

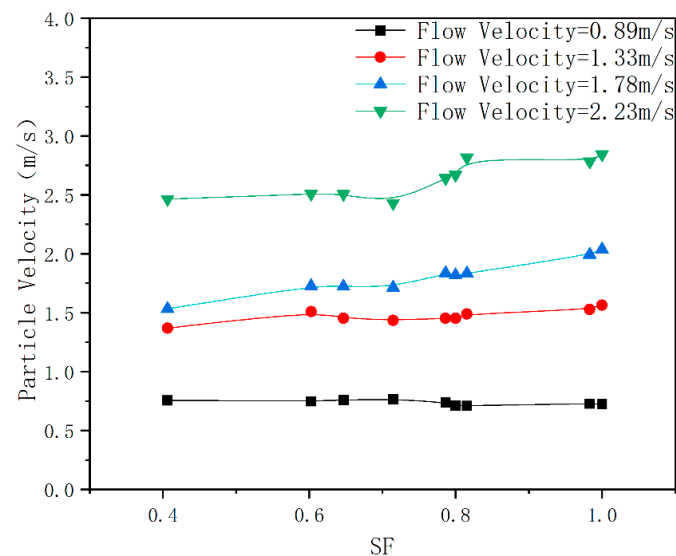


Figure 15. Relationship between particle velocity and shape factor at different flow velocities.

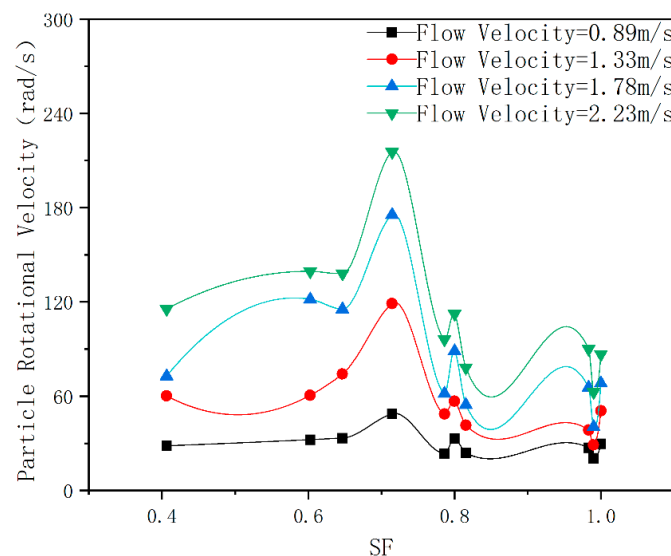


Figure 16. Relationship between particle rotational velocity and shape factor at different flow velocities.

4.4. Spatial Distribution and Slip Velocity

To clarify the influence of shape factor on spatial distribution and motion behavior, simulations were used to observe the distribution characteristics of non-spherical particle swarms at the exit section of the right-angle bend. Figures 17 and 18 present the axial velocity distributions of 8–10 mm and 1–15 mm particles at 260 r/min, respectively. In both figures, particle velocity decreases monotonically from left to right; the left high-speed zone is densely populated with particles, while the right low-speed zone is sparsely populated. Due to their larger inertia, coarse particles mainly accumulate in the center of the pipe, whereas fine particles are more likely to contact the left wall and experience velocity drops in the wall-adjacent region. Because of friction between particles and the pipe wall, particle velocity is lower near the left wall. Under the same operating conditions, comparison of the

two particle groups also shows that the wide-grading swarm (1–15 mm) achieves a faster lifting speed.

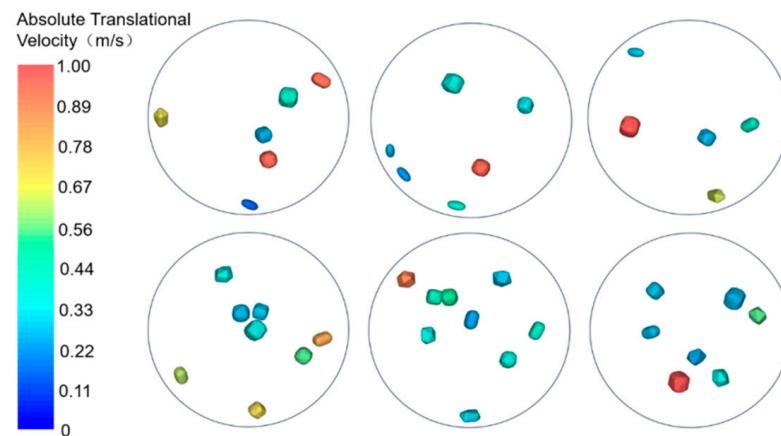


Figure 17. Spatial distribution and velocity of 8–10 mm non-spherical particles.

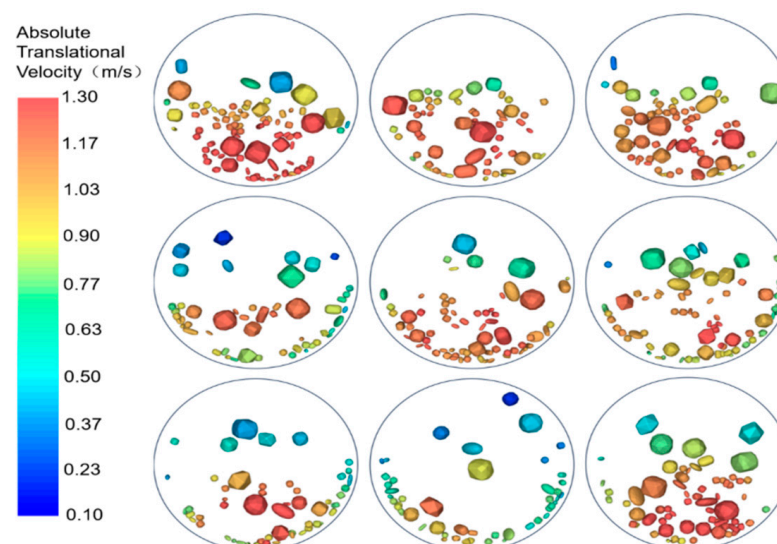


Figure 18. Spatial distribution and velocity of 1–15 mm non-spherical particles.

Analyzing the influence of shape factor on particle motion is crucial, as it not only helps to understand particle transport characteristics more accurately but also provides a reference for optimizing the transport process. In this simulation of the 8–10 mm non-spherical particle swarm, since all particles have equivalent diameters within 8–10 mm, size effects are temporarily ignored, and the analysis focuses on ten different shape-factor particle models to explore the influence of shape factor on particle motion. Figure 19 presents the absolute rotational angular velocity distribution of 8–10 mm non-spherical particles at 440 r/min. From Figure 19, it can be seen that there are significant differences in distribution and rotation characteristics among particles with different shape factors. The ten particle models are divided into three categories based on shape and shape factor. First, disk-like particles have the most special motion trajectory in the pipe. These particles tend to move along the left pipe wall, and their rotation speed is almost zero. This phenomenon is mainly due to their flat structure, which allows them to move along the pipe wall with fluid inertia in the right-angle bend, and still adhere to the wall for lifting afterwards. Moreover, since the fluid cannot provide sufficient torque to cause them to roll or deviate, their motion state is difficult to change. Second, columnar particles are more dispersed in the pipe and exhibit a wide range of rotational speeds. As shown in the spatial distribution

(Figure 19), instantaneous rotational speeds can reach up to 300 rad/s for individual particles under this condition (440 r/min, corresponding to 2.23 m/s). It is important to note that this represents the upper extreme observed in the spatial distribution, whereas the maximum ensemble-averaged rotational speed for this particle type under comparable flow conditions was reported as 215 rad/s in Section 4.3. Compared with disk-shaped particles, columnar particles are more likely to roll and rotate under the action of the flow field because their structure is more susceptible to fluid rotational forces, thus increasing the rotation speed. Therefore, the motion trajectory of such particles is more complex and changeable. Third, nearly spherical and non-spherical particles are mainly distributed in the center of the pipe, and there are large fluctuations in rotation speed. Only a few particles can reach 300 rad/s, but most particles have a rotation speed of about 150 rad/s. Due to their relatively symmetrical shape, even with a large rotation speed, their rotation has little impact on the overall motion trajectory, mainly manifested as self-rotation during particle lifting without obvious deviation or rolling. Further analysis of particle motion speed shows that when the shape factor is greater than or equal to 0.8, the particle motion speed is larger, the average speed is close to 2 m/s, and these particles are mainly distributed in the center of the pipe. Particles with shape factors between 0.6 and 0.8 appear more around the pipe but do not cling to the wall, and their motion speed is relatively low, about 1.3 m/s. In contrast, disk-shaped particles have the lowest motion speed, and most of them move close to the pipe wall. Due to their flat structure and large contact area with the pipe wall, the flow field cannot provide sufficient rotational force to detach them from the wall, resulting in particles sliding and friction along the wall, and the transport speed is obviously very low.

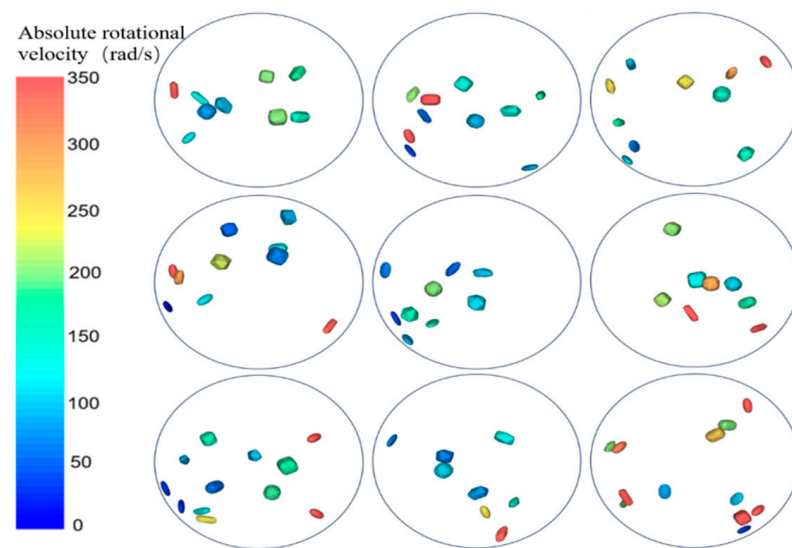


Figure 19. Spatial distribution and rotational velocity of 8–10 mm non-spherical particles.

4.5. Limitations

This study provides mechanistic insights into the transport of non-spherical particles in right-angle bends by integrating controlled experiments with validated CFD-DEM simulations. The key findings—the linear growth of the velocity gradient, the efficiency advantage of wide-grading blends, and the identification of an optimal shape factor range ($SF \geq 0.8$)—collectively advance the understanding of solid–liquid flow in complex geometries. These results have direct implications for optimizing industrial hydraulic systems, such as those in deep-sea mining, by guiding feedstock preparation to enhance efficiency and reduce wear.

However, several limitations should be acknowledged to properly scope the applicability of our conclusions:

1. The use of clean water and quartz sand, while essential for isolating fundamental inertial interactions, means the effects of seawater chemistry, slurry rheology, and true polymetallic nodule morphology are not captured. Our conclusions on optimal shape factor are thus most directly applicable to granular systems with similar density and in Newtonian fluids.
2. The experiments were conducted in a laboratory-scale pipe ($D = 100$ mm) with a limited range of flow velocities and particle concentrations. While dynamic similarity in key dimensionless numbers was sought, extrapolating the quantitative results to vastly different scales or much higher solid concentrations requires further validation.
3. The validation in this study focused on ensemble-averaged particle velocity, as it is the most robust metric obtainable from both PIV/PTV and simulations and directly governs transport efficiency. We acknowledge that other quantities—such as particle concentration, spatial distribution, rotation, and wall pressure—were not validated due to instrumentation limitations. Reliable measurement of these parameters in coarse-particle bend flows requires advanced techniques (e.g., ECT for concentration, stereoscopic PIV for rotation, differential pressure transducers) that were beyond the scope of the current facility. While our velocity-focused validation is consistent with established practice in CFD-DEM studies, we fully recognize that upgrading our experimental capabilities to include these measurements is a critical direction for future work.

Future work should focus on the following: (1) quantifying the deviations from the present idealizations through experiments with real ore particles and slurry; (2) extending the analysis to higher solid concentrations where particle–particle interactions dominate; and (3) upgrading the experimental facility to enable direct validation of particle concentration, spatial distribution, rotational motion, and pressure drop, thereby further strengthening the predictive capability of the coupled CFD-DEM framework.

5. Conclusions

This study integrates PIV experiments with validated CFD-DEM simulations to elucidate the fundamental mechanisms governing the transport of coarse, non-spherical particles in a right-angle bend. The main conclusions, supported by quantitative evidence, are as follows:

1. The flow field in the bend exhibits pronounced asymmetry, characterized by a consistently higher velocity on the outer (left) side compared to the inner (right) side, where a distinct separation vortex forms. The velocity ratio between the two sides remains relatively constant across pump frequencies, yet the absolute velocity disparity (lateral gradient) increases linearly. This growing gradient, from 0.4 to 1.1 m/s, intensifies the inner-wall vortex at higher frequencies.
2. Particle size distribution is a key determinant of system efficiency. Wide-grading blends achieve a statistically significant efficiency gain over narrow fractions (up to 12% higher conveying speed at 30 Hz). This is attributed to a synergistic effect: fine particles enhance flow initiation at low inertia, while coarse particles maintain higher solids concentration as velocity increases, optimizing overall momentum transfer.
3. Particle shape factor critically modulates the trade-off between translational and rotational motion. While spherical particles ($SF = 1$) achieve the highest axial velocity, an optimal shape range ($SF \geq 0.8$) is identified. Particles within this range sustain moderate rotation, preferentially concentrate in the central high-speed zone, and

thereby maximize transport efficiency while minimizing wall contact and abrasive wear risk.

4. Particle shape is the predominant factor determining the achievable axial velocity (i.e., transport efficiency as defined in Section 4.2) and the wear patterns in the bend. While spherical particles ($SF = 1$) achieve the highest axial velocity with minimal rotation, extreme shapes incur penalties. Disk-like particles ($SF \leq 0.4$) exhibit low, fluctuating velocities, sliding along the wall with weak rotation, which directly contributes to abrasive wear. Columnar particles ($SF = 0.71$) develop intense rotation (300 rad/s, as observed in the spatial analysis at 440 r/min) that dissipates energy, limiting their translational speed. An optimal shape range emerges: particles with $SF \geq 0.8$. They maintain moderate rotation, preferentially concentrate in the central high-speed zone (see Section 4.4), and exhibit the lowest slip velocity. Therefore, to optimize system performance, the feedstock should maximize the proportion of near-spherical particles ($SF \geq 0.8$) and minimize highly flat disks ($SF \leq 0.4$).

In conclusion, this study systematically investigates the transport of coarse, non-spherical particles in a right-angle bend. By integrating PIV experiments with CFD-DEM simulations, we quantify the asymmetric flow field and elucidate how particle shape factor governs key behaviors: from velocity and rotation to spatial distribution. The identification of an optimal shape factor range ($SF \geq 0.8$) that maximizes transport efficiency while minimizing wall contact provides a concrete criterion for feedstock optimization. While further research is needed on polydisperse mixtures, this work establishes a fundamental framework and delivers critical insights for designing efficient and wear-resistant deep-sea mining pipeline systems.

Author Contributions: Conceptualization, Y.H. and Y.S.; methodology, Y.H.; validation, Y.H. and Y.S.; formal analysis, Y.S. and Y.H.; investigation, Y.H. and Y.S.; data curation, Y.H.; writing—original draft preparation, Y.S.; writing—review and editing, Y.H. and Y.S.; visualization, Y.H. and Y.S.; supervision, Y.H. and Y.S.; project administration, Y.S.; funding acquisition, Y.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was supported by the following projects: 1. A project funded by the National Natural Science Foundation of China. Project Approval Number: 52231012. Project Name: Research on Design Theory and Key Mechanical Issues of Fully Flexible Vertical Pipe Transportation System for Deep-sea Mining. 2. National Key Research and Development Program. Project Number: 2021YFC2801500. Project Name: Research on a New Mining Model for Deep-Sea Polymetallic Nodules and Its Principle Prototype. 3. Major Science and Technology Programs of Hainan Province. Project Number: ZDJKJ2021027. Project Name: Development and Utilization of Deep-Sea Rare Metal Mineral Resources.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors want to thank the editor and anonymous reviewers for their valuable suggestions for improving this paper. The authors sincerely thank the professors for their guidance during this research.

Conflicts of Interest: The authors declare no conflicts of interest.

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