



OPEN Impact of solid particle geometry, size, and intensity, coupled with fluid velocity, on erosion dynamics in elbow conduits

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Sand production poses a significant challenge because of erosion caused by solid particles in turbulent flows, particularly in elbows and fittings. This research explores the influence of solid particle geometry, size, intensity, elbow radius of curvature, and fluid velocity on erosion dynamics in elbows under vertical flow conditions via the CFD-DPM (discrete phase model) coupling method. The novelty of this study lies in its integrative approach, which involves simultaneously analyzing multiple interrelated parameters and validating predictions with detailed experimental data. This provides more realistic insights into erosion behavior and more practical guidelines for minimizing wear in industrial pipelines. The numerical results were verified through experimental investigation. The findings revealed that increasing the number of particles increased the erosion rate up to a certain point, after which erosion did not change. This can be attributed to surface saturation, particle shielding, and energy dissipation mechanisms. Larger particles cause more erosion, whereas smaller, rounded particles cause less erosion. Furthermore, high flow rates and lower elbow radii of curvature induce higher impact pressures, especially on outer elbow surfaces, intensifying erosion for larger particles. Therefore, this study identifies the combined effects of particle and flow parameters that critically influence elbow erosion, highlighting effective control strategies to prolong equipment life. Future work should focus on developing mitigation strategies and exploring alternative materials to reduce erosion under turbulent flow conditions.

Keywords Solid particles, Erosion, Elbow, CFD-DPM (discrete phase model) coupling, Multiphase flow

During production operations, sand or shale particles are released from oil and gas reservoirs. In a solid–fluid multiphase flow, these particles collide with the inner walls of pipes and stationary components such as elbows, valves, junctions, flowmeters, and reducers^{1–5}. Over time, such particle–wall interactions cause progressive localized material loss, potentially leading to severe failures in pipeline infrastructure^{4,6}. Additionally, the presence of sand particles in liquid-dominated flows can distort multiphase flow predictions, resulting in inefficient production control and further damage to piping infrastructure. Consequently, this can cause production downtime and various operational and maintenance problems, especially in the oil and gas industry^{7–9}.

In transport systems, the fluid velocity must exceed a critical threshold to maintain particle suspension and prevent sediment accumulation, which can clog pipes. However, excessively high velocities increase pump energy consumption and aggravate erosion damage, particularly in curved fittings such as elbows^{10,11}. When wells are drilled, sand, cuttings, and proppants are transported by the media, causing damage to fittings such as elbows, tees, chokes, and reducers. McLaury et al.¹² studied sand erosion in horizontal and vertical annular flow in pipes and reported that sand entrainment increased with increasing superficial gas velocity in the annular flow regime. Duarte et al.¹³ used the dynamic mesh deformation model to analyze material deformation due to erosion for jet impingement, elbow, and choke bean flows. To investigate the motion of particles and fluids, different numerical methods are used based on the system's size, each with its strengths, weaknesses, and applications, including microscopic modeling at the molecular scale¹⁴, kinetic theory at the mesoscopic scale^{15,16}, and continuum modeling at the macroscopic scale¹⁷. Currently, computational fluid dynamics (CFD) is widely used in numerous industrial fields and erosion research. CFD-DPM is a simulation method that focuses on dilute flow and is commonly used for modeling the behavior of particles in liquid–solid and gas–solid flows. It operates under the assumption that particle interactions can be disregarded, making it suitable for analyzing

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systems with low particle concentrations¹⁸. Wang et al.¹⁹ made an erosion model for long-radius elbows on the basis of CFD-DPM. Njobuenwu et al.²⁰ analyzed how particles interact with walls and used a Lagrangian particle tracking technique to estimate the erosion of a dilute flow in a 90° square cross-section elbow. Chen et al.² used CFD-DPM to investigate the erosion patterns in elbows caused by a dilute mixture of gas and solid particles²¹. Mazumder²² used CFD-DPM to examine how gas or liquid velocity affects erosion in a U-shaped elbow. Therefore, CFD-DPM has become a widely accepted and effective approach for simulating erosion in multiphase systems, particularly in pipe fittings such as elbows, where complex flow behavior and particle-wall interactions significantly influence wear patterns.

Microscale erosion behavior is influenced by a combination of factors, including particle concentration, size, shape, velocity, and flow geometry. These variables control how energy is distributed during particle-wall impacts, which ultimately governs whether the material is removed through cutting, plastic deformation, or fracture. By capturing these localized physical processes more effectively, incorporating discrete particle tracking and rebound models in CFD simulations improves the accuracy of erosion predictions. Recent experimental and numerical investigations have provided detailed insights into how individual particles contribute to erosion. The particle concentration—often described by the number of impacts per unit area over time—plays a key role in the cumulative erosion rate. Simulations based on CFD-DEM and PD-DEM frameworks have shown that higher particle intensities increase energy transfer to the wall, accelerating surface damage²³. Han et al. (2024) noted that under dense loading, particles may cluster near surfaces, initially enhancing erosion, although prolonged interactions can create shielding effects that reduce direct impact. The particle size is another critical parameter affecting the impact momentum and stress concentration. Larger particles carry greater kinetic energy and are more likely to induce deep surface damage, particularly in brittle materials. Walayat et al.²³ reported that increasing the particle diameter leads to elevated peak stresses at the contact point, whereas Chen and Zhang²⁴ experimentally reported that larger alumina grains produced wider deformation zones and deeper subsurface cracking. Ai et al.²⁵ studied coarse particle erosion mechanisms, revealing that finer particle fractions cushion wear effects, whereas larger pipe diameters disperse particle impacts, further complicating erosion patterns in turbulent multiphase flows. The geometry of the flow path—especially in elbows—also affects erosion severity. Elbows with smaller elbow radius of curvature ratios (lower r/D) force sharper directional changes, increasing the likelihood of high-angle impacts along the outer bend. These geometric effects cause particles to concentrate in regions such as 45° from the inlet, where both the velocity and impact angle favor maximum erosion. Ren et al.²⁶ demonstrated that local surface features, such as dimples or slight geometric variations, further influence the landing positions and erosive force of particles. Wang et al.²⁷ focused on flow path effects and reported that erosion tends to increase with increasing diameter ratio up to a threshold, after which it significantly decreases. The maximum erosion rate initially decreases sharply with increasing length, then stabilizes and becomes less influenced by further length changes²⁷. In addition, the particle shape influences how particles interact with the flow and the surface. Compared with spherical particles, irregular or angular particles generate greater contact forces and display more complex rebound behavior. Rawat et al.²⁸ studied how fly ash slurries erode pipes and fittings, reporting the most severe erosion at a 45° impact angle. They also showed that particle shape dynamically alters the impact angle and erosion distribution due to flow deflection, which is a key geometric influence. Ben-Ami et al.²⁹ developed a model based on experiments and theory for shape-dependent energy transfer, further emphasizing the importance of the particle morphology³⁰. Wan et al.³¹ reported that disk-like particles experience repeated collisions due to their tumbling motion, leading to more intense erosion. Yu et al.³² confirmed that angular grains cause more cutting and gouging, especially at shallow impact angles, whereas smoother particles tend to produce more uniform surface wear through plowing or fatigue. Yasser et al.³³ demonstrated that nonspherical and angular particles significantly increase localized erosion on the outer bend due to sharper impact angles, highlighting the critical role of particle geometry in erosive wear. Finally, impact velocity is a dominant factor in determining erosion severity. Hassani-Gangaraj et al.³⁴, using high-speed nanosecond imaging, identified three impact regimes: elastic rebound at low velocities, bonding and plastic deformation at moderate velocities, and localized melting and fragmentation at high velocities. These transitions underscore the existence of a critical velocity threshold that separates mild wear from severe erosion, an essential consideration in designing erosion-resistant systems.

Although these recent investigations corroborate the critical importance of simultaneously considering particle size, shape, intensity, fluid velocity, and elbow geometry for accurate erosion modeling and practical mitigation strategies, the combined effects of these parameters have not been systematically quantified and validated under realistic gas–solid upward flow conditions. In this work, we investigate the erosion of a right-angled elbow subjected to particle-laden gas flow via an enhanced CFD-DPM framework that integrates particle shape classification, size scaling, impact frequency, and rebound dynamics. The model's accuracy and robustness are rigorously validated against recent experimental data, ensuring its practical reliability. By systematically analyzing the combined influence of the particle geometry, size, intensity, fluid velocity, and elbow radius of curvature, this study provides a significant enhancement to existing models and complements previous research efforts. Our comprehensive multiparameter approach advances the predictive capabilities of CFD-DPM simulations for realistic industrial erosion scenarios, offering valuable insights for erosion mitigation and pipeline design.

Materials and methods

The computational model employed three coupled frameworks: (1) a continuous gas phase governed by the Navier–Stokes equations; (2) a discrete particle phase tracked through Newtonian mechanics; and (3) erosion mechanisms analyzed via particle–wall interaction models. Using an Eulerian–Lagrangian formulation, the gas phase was solved as a continuum, while individual particles were simulated through discrete phase modeling

(DPM). The following sections systematically present the governing equations, numerical implementation strategies and validation, and mesh convergence analysis.

CFD-DPM modeling

In the CFD-DPM, the fluid phase is treated as a continuous medium. The motion of the fluid phase is governed by the volume-averaged Navier-Stokes (VANS) equations, which are typically known as the continuity and momentum conservation equations as follows^{35,36}:

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

$$\frac{\partial (\epsilon_f \rho_f u_f)}{\partial t} + \nabla \cdot (\epsilon_f \rho_f u_f u_f) = -\nabla p + s_p + \nabla \cdot \tau + \epsilon_f \rho_f g \quad (2)$$

In this context, ϵ_f represents the void fraction, ρ_f signifies the fluid density, u_f represents the average velocity of the fluid unit, p denotes the pressure common to both phases, τ represents the viscous stress tensor, and s_p refers to a source term arising from the interaction between the particles and the volumetric fluid.

The locally averaged Navier-Stokes equations describe the flow as a continuous phase. The discrete phase consists of particles that follow Newton's laws of motion and may collide with each other or with the boundaries during their movement. These particles are treated as discrete phases, and their motion is controlled via the Lagrangian method. The momentum balance equation is given by:

$$\frac{du_p}{dt} = -\frac{\nabla p}{\rho_p} + F_D (u_f - u_p) + \frac{(\rho_p - \rho_f)}{\rho_p} g - \frac{\nabla \cdot \bar{\tau}_s}{\rho_p} + a_{other} \quad (3)$$

In this context, u_p represents the particle velocity, ρ_p denotes the particle density, and $\bar{\tau}_s$ is the solid stress tensor resulting from particle-particle interactions as predicted by the kinetic theory of granular flow. The term $F_D (u_f - u_p)$ describes the particle acceleration due to the drag force, whereas $-\frac{\nabla p}{\rho_p}$ represents the acceleration of the particles caused by the pressure gradient. The term a_{other} accounts for acceleration due to external forces, including the virtual mass force, Saffman lift force, electrostatic force, etc. The solid stress tensor and drag coefficient are computed in the Eulerian coordinate system. Since particle collisions are considered, this governing equation is also known as the dense discrete phase model (DDPM). When the volume fraction of solid particles is less than 10%, the last two terms of Eq. (3) can be neglected, simplifying it to the discrete phase model, which is appropriate for dilute conditions.

In the coupling, the analysis of fluid and particle governing equations is integrated into the discrete phase model program. Before the equations are solved, the void fraction is determined based on the particle positions and the geometry of the finite volume grid elements. The particle momentum equation is subsequently solved. The source term resulting from the interaction between the fluid volume and particles is crucial for solving the coupling. This source term is computed and stored in user-defined memory to avoid additional computational loops, as the user-defined source function is invoked by the solver at the cell level. Following this, the fluid governing equation is solved, and the collision dynamics are calculated. After the fluid region is updated, the next time step is initiated. Building on this (Fig. 1), Wu et al.³⁷ enhanced discrete phase model calculations under dense conditions by refining the user-defined functions and proposed a comprehensive numerical strategy to achieve high computational efficiency and mass conservation.

Erosion modeling

After obtaining steady-state flow field solutions, particle-induced erosion was estimated via widely accepted erosion and rebound models available in the literature. The CFD solver calculates each particle's velocity, impact angle, and impact location as it travels through the computational domain. Based on these kinematic parameters, the local erosion rate (expressed in kg/m²·s) was computed through a user-defined function (UDF) incorporating multiple erosion models.

The UDF framework integrates several well-established erosion models previously developed and validated by the Erosion/Corrosion Research Center (E/CRC) at The University of Tulsa. Specifically, the Arabnejad et al.³⁸, Veritas³⁹, Oka et al.^{40,41}, and Zhang et al.⁴² models were embedded into the UDF structure. However, for the present study, only the Arabnejad et al.³⁸ model was applied to predict erosion rates due to its suitability for gas-solid erosion scenarios and its consideration of both cutting and deformation mechanisms.

In the Arabnejad et al.³⁸ model, the total erosion rate is computed as the sum of the cutting (Vol_C) and deformation (Vol_D) volume removal mechanisms. The degree of cutting erosion is a function of the particle velocity, impact angle, and material deformation properties, described as follows:

$$Vol_C = \begin{cases} \frac{U^2 \sin \theta [2K \cos \theta - \sin \theta]}{2K^2} & \text{for } \theta \leq \tan^{-1} K \\ \frac{U^2 \cos^2 \theta}{2} & \text{for } \theta > \tan^{-1} K \end{cases} \quad (4)$$

Deformation erosion is estimated based on the particle's normal velocity component exceeding a threshold velocity, as given below:

$$Vol_D = \frac{1}{2} (U \sin \theta - U_{tsh})^2 \quad (5)$$

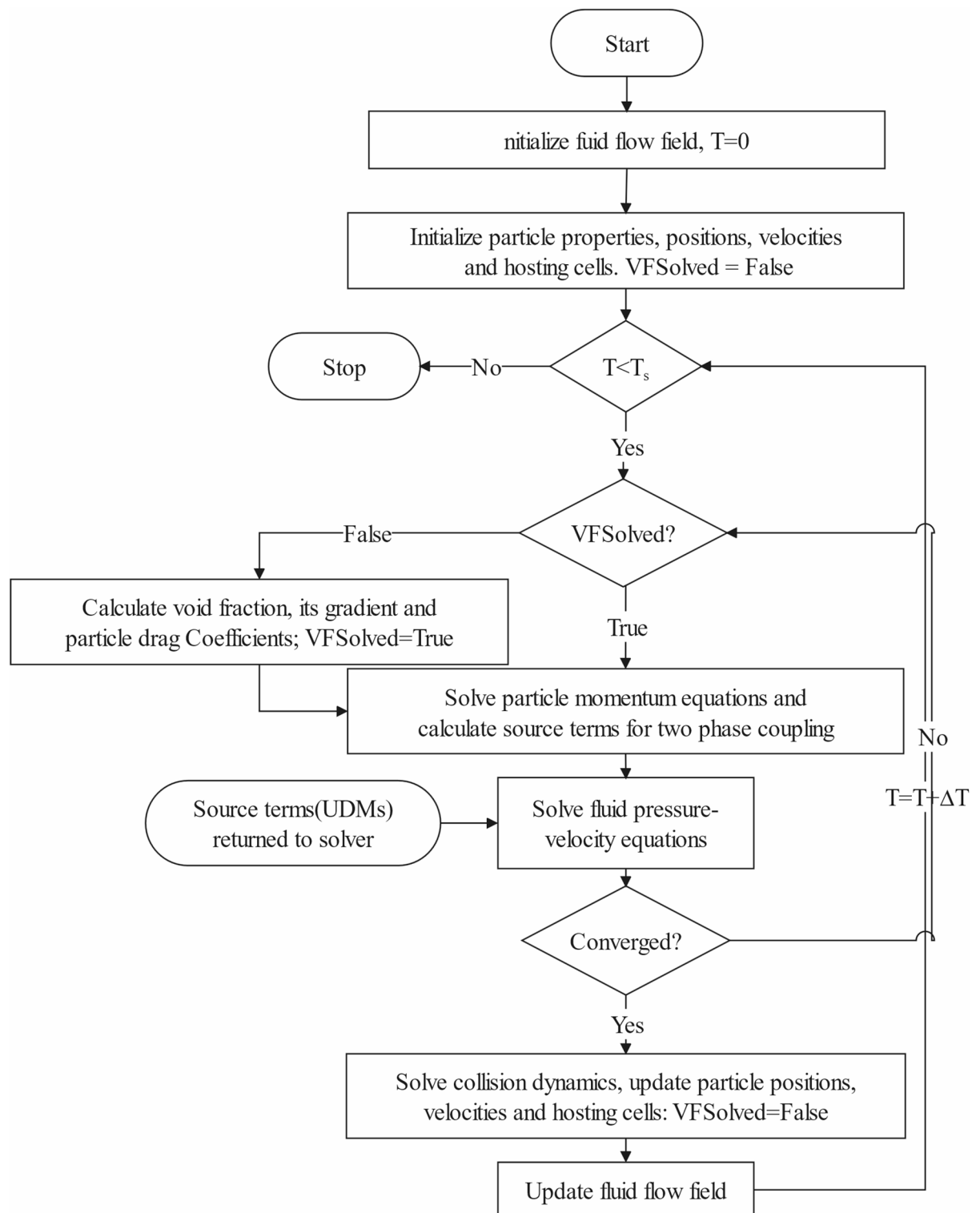


Fig. 1. Diagram of the CFD-DPM methodology.

The final erosion rate (ER) is calculated by summing these contributions, weighted by the material-dependent constants C_C and C_D , as:

$$ER = F_s (C_C Vol_C + C_D Vol_D) \quad (6)$$

In these equations, K represents the deformation parameter, which is assigned a constant value of 0.4 and depends on both the target material response and the particle shape. The threshold velocity U_{tsh} and the sharpness factor

F_s also influence erosion calculations. According to McLaury et al.⁴³, F_s reflects particle angularity, with values of 0.2 for rounded particles, 0.53 for semirounded particles, and 1.0 for sharp angular particles. Given that angular quartz sand was employed for both particle size groups in this study, F_s was set to 1.0.

The postimpact behavior of particles, specifically their rebound characteristics, was modeled via the rebound model proposed by Haider et al.^{44,45}. This rebound model considers both normal and tangential restitution effects during particle-wall collisions, which influence the secondary trajectories and subsequent impact locations of rebounding particles. Although alternative erosion models^{39–42} are widely used in erosion studies, they were not applied in the present work. Through the combined application of flow field simulations, discrete particle tracking, and detailed erosion and rebound models, the present methodology provides a robust framework for accurately predicting erosion patterns and rates under complex gas–solid flow conditions.

CFD-DPM model validation

The validation of the numerical model was conducted based on experimental erosion behavior in gas–solid two-phase flows under industrially relevant conditions. In the experiment, gas–solid erosion tests were carried out in a closed-loop tower-boom facility (Fig. 2)⁴⁶, where a mixture of quartz sand and air was circulated through a vertical stainless steel 316 elbow with an internal diameter of 76.2 mm (3 inches) and an elbow radius of curvature ratio of $r/D = 1.5$. The test section included a long entrance length of approximately 223 pipe diameters to ensure fully developed flow conditions prior to entering the elbow. Angular quartz sand particles with a diameter of 300 μm and a density of 2650 kg/m^3 were introduced into the airflow at a concentration of 1 wt%. The gas velocities in the experiments reached 23 m/s. Erosion damage was evaluated via ultrasonic thickness (UT) measurements at various locations along the elbow, allowing both quantitative erosion rates and spatial erosion patterns to be measured (Table 1).

Following the experiment, the present numerical model was validated via the same experimental configuration and erosion measurements. The CFD simulations employed COMSOL Multiphysics 6.3, solving the governing Navier–Stokes equations for gas flow, coupled with discrete particle tracking via the discrete random walk (DRW) model. Erosion rates were predicted via the Arabnejad et al.³⁸ model, which accounts for both the cutting and deformation mechanisms. Particle rebound was modeled via the Haider et al.⁴⁵ rebound model⁴⁵, which incorporates normal and tangential restitution effects during particle-wall collisions. The boundary conditions, particle properties, and flow parameters used in the simulations were identical to those used in the experiments, ensuring consistent conditions for validation. Therefore, fully developed gas velocity profiles were applied at the inlet, atmospheric pressure was specified at the outlet, and no-slip conditions were applied at all solid boundaries.

High-resolution ultrasonic thickness measurements conducted on a 76.2 mm inner diameter stainless steel elbow under gas–solid flow conditions revealed that, for 300 μm angular quartz sand particles transported at a superficial gas velocity of 23 m/s, the maximum erosion occurred near 47° along the outer elbow curvature. At this location, the measured erosion rate reached 80.3 mm/year ($2.04 \times 10^{-5} \text{ kg}/\text{m}^2\cdot\text{s}$), reflecting the zone of highest particle impact energy concentration. In the current study, the CFD–DPM simulation replicated these

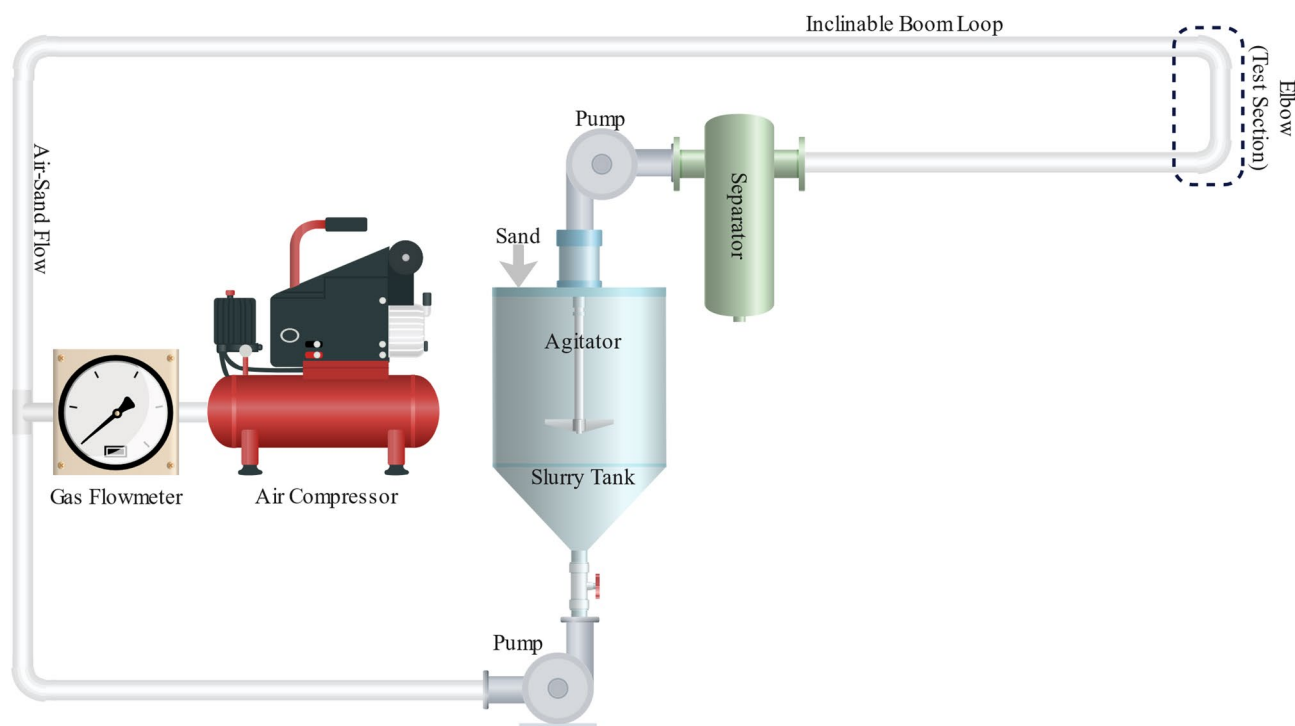


Fig. 2. Diagram showing the configuration of the experimental setup.

Parameter	Value/description
Pipe internal diameter (D)	76.2 mm (3 inch)
Elbow geometry	r/D = 1.5 (short-radius elbow)
Material	Stainless Steel 316
Sand particle size	300 μm (angular quartz sand)
Sand particle density	2650 kg/m ³
Sand concentration	1 wt%
Flow medium	Gas (air only)
Superficial gas velocity	23 m/s
Test duration	120 min
Operating pressure	Atmospheric
Temperature	Ambient
Measurement techniques	Ultrasonic thickness (UT) measurements
Elbow orientation	Vertical
Entrance length	L/D ≈ 223 (fully developed flow)
CFD software	COMSOL multiphysics 6.3
Turbulence model	Discrete random walk (DRW) for particles
Erosion model	Arabnejad et al. ³⁸ erosion model
Rebound model	Haider et al. ⁴⁵ rebound model

Table 1. Experimental and simulation parameters.

flow conditions using identical particle size, density, concentration, flow velocity, and elbow geometry. The numerical model predicted the erosion peak at approximately 45°, with a maximum erosion rate of 84 mm/year (2.13×10^{-5} kg/m²·s), yielding a deviation of less than 5% from the experimental benchmark (Fig. 3). This high level of agreement confirms the predictive capability of the model in capturing the location and severity of erosive damage under realistic conditions.

Beyond reproducing the peak erosion rate, the simulation also closely mirrored the angular erosion distribution observed experimentally. UT transducers were positioned at multiple circumferential angles—such as 15°, 47°, 75°, and 90°—enabling a detailed mapping of erosion intensity along the elbow surface. The experimental data exhibited a characteristic trend: erosion progressively increased from the inlet, peaked between 45° and 47°, and gradually declined toward 60° and beyond. This behavior is strongly governed by the particle impact angle, which critically influences the dominant erosion mechanism. In ductile materials like stainless steel 316, the cutting wear mechanism becomes most effective at oblique impact angles, typically in the 30°–45° range. At these angles, particles strike the surface with both normal and tangential components of velocity, leading to significant shearing, plowing, and material removal. At shallower or steeper angles, either the kinetic energy transfer is insufficient, or particles rebound rather than penetrate, resulting in reduced erosion.

The numerical model reproduced this angular pattern with high fidelity. The predicted erosion profile demonstrated a similar rise in intensity from 15° to 45°, followed by a tapering trend as angles approached 60°–90°, matching the experimental profile shape. This validates the model’s ability to resolve not only pointwise erosion severity but also the full spatial evolution of wear along the curved geometry. Together, the strong agreement in both maximum erosion rate and its angular distribution confirms the accuracy and robustness of the implemented CFD–DPM framework.

Computational domain and meshing

A standard elbow with a diameter of 3 inches (76.2 mm) and an elbow radius of curvature to diameter ratio (r/D) of 1.5 was designed via COMSOL version 6.3. The geometry is illustrated in Fig. 4. To ensure fully developed flow, the upstream section preceding the elbow was extended to a length of 33 times the diameter (33D).

The computational domain was discretized via unstructured tetrahedral elements, which improved the numerical stability and supported smooth convergence throughout the simulation process. To accurately capture the complex flow behavior near solid boundaries, the mesh was locally refined in regions adjacent to the pipe walls, whereas a coarser mesh was applied in the central core of the flow domain. This meshing strategy allowed for precise resolution of near-wall interactions critical for erosion prediction while also maintaining reasonable computational demands for tracking particle motion within the bulk flow.

A mesh sensitivity analysis was performed to examine the influence of grid density on the predicted maximum erosion rate within the elbow section. As shown in Fig. 5, increasing the number of elements beyond approximately 1,229,629 did not result in significant changes in the calculated maximum erosion rate, indicating that further mesh refinement provided diminishing improvements in solution accuracy. Therefore, this mesh configuration was selected as the optimal balance between computational efficiency and numerical precision for all subsequent simulations.

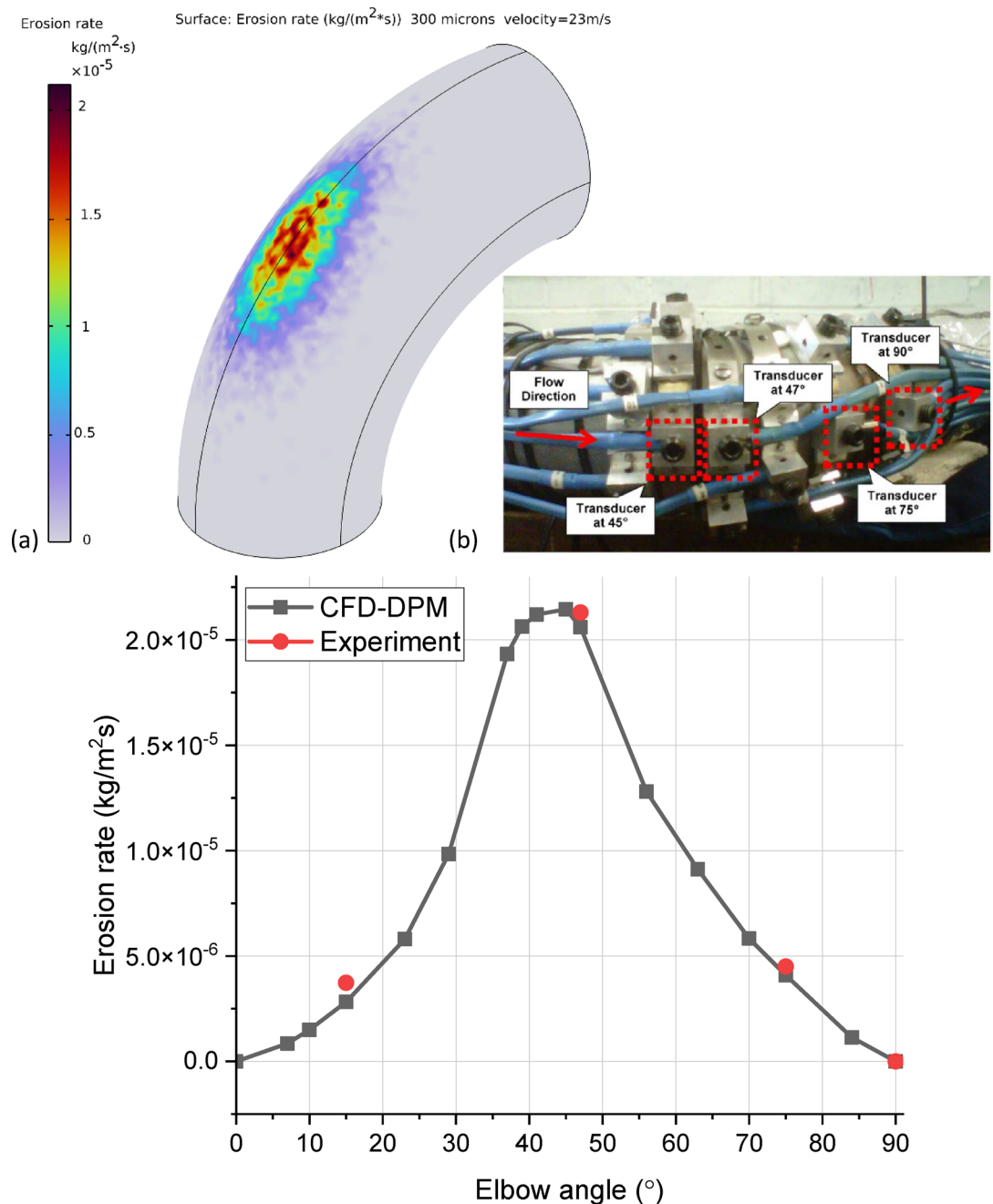


Fig. 3. Erosion rate for 300-micron particle sizes by CFD-DPM (a). A standard 76.2 mm elbow of the experimental setup (b); experimentally measured erosion rates at various angular positions along the elbow with the predicted CFD-DPM simulation results (c). Data shown for 300 μm angular quartz particles at 23 m/s gas velocity in a 76.2 mm ID stainless steel elbow ($r/D=1.5$). Experimental data extracted from UT transducers positioned at 15°, 47°, 75°, and 90°.

Results and discussions

The effect of particle intensity on erosion

Figure 6 presents the effect of particle intensity on the predicted erosion rate, with values ranging from 1000 to 300,000 tracked particles. The gas velocity was 23 m/s, and the particles were round, with a density of 2650 kg/m^3 and a size of 300 μm . Each point corresponds to the mean erosion rate, and the error bars represent the 95% confidence interval (CI) computed from the standard deviation of multiple simulation runs. At lower particle numbers (e.g., 1000–10,000), the erosion prediction exhibits a high degree of variability due to insufficient sampling of the flow domain and impact angle distribution. Because CFD-DPM methods rely on stochastic Lagrangian particle tracking, a small number of particles can result in irregular or biased coverage of the critical

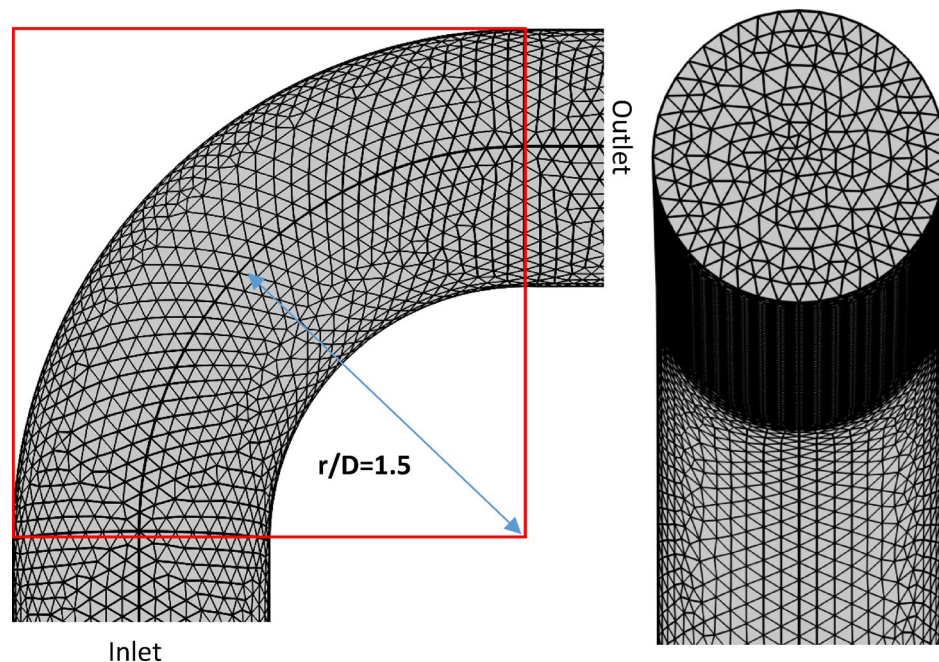


Fig. 4. Computational mesh of the pipeline and elbow used in the CFD-DPM simulations.

impact zones, leading to greater uncertainty. This is particularly evident when the CI range becomes comparable to or larger than the mean erosion value, as seen at 1000 particles.

As the number of particles increases, the statistical variability reduces significantly. Beyond approximately 100,000 particles, both the mean erosion rate and confidence interval converge, indicating that a representative ensemble of particle–wall interactions has been achieved. Therefore, a particle counts of 100,000 was adopted for all subsequent simulations to ensure reliable and repeatable results without incurring unnecessary computational cost.

In addition to the statistical convergence behavior, the erosion response also reflects a physical saturation mechanism. The dynamics of the particle impact and material response can be explained as follows: Initially, as particle intensity increases, both the frequency and kinetic energy of surface impacts rise, which leads to a proportional increase in material removal. However, beyond a certain threshold, the surface enters a saturation regime where the erosion rate plateaus despite the continued increase in particle flux. This non-linear response arises due to several physical mechanisms:

- **Surface Saturation:** Once the surface has been extensively eroded, additional particles tend to strike already damaged areas, reducing the availability of fresh material for removal.
- **Particle Shielding:** At higher intensities, particles can obscure one another's path, resulting in fewer direct high-energy impacts on the surface.
- **Energy Dissipation:** Increased particle–particle interactions at higher fluxes may absorb impact energy that would otherwise contribute to erosion, further diminishing the erosion rate increment.

These combined statistical and physical considerations explain both the initially large error margins at low particle counts and the eventual plateauing behavior observed at higher intensities. This dual interpretation reinforces the importance of selecting an appropriate particle count that ensures both convergence in prediction and fidelity to physical erosion mechanisms.

The effect of particle size on erosion

The erosion patterns observed under gas–solid flow conditions strongly depend on the particle size and flow velocity. Experimental tests using 75 μm and 300 μm quartz sand, Fig. 7, revealed that erosion was concentrated along the outer elbow radius of curvature, with maximum wear occurring approximately 45° from the inlet. Larger particles (300 μm) produced a wider and more elongated erosion zone extending beyond 60°, whereas the smaller 75 μm particles resulted in a narrower zone confined between 15° and 60°.

The observed increase in erosion with increasing particle size can be attributed to the greater inertia and impact energy of the larger particles. These particles are less influenced by turbulence and tend to follow more direct trajectories, resulting in stronger, more concentrated impacts on the elbow wall. In contrast, smaller particles are more easily deflected by turbulent eddies, reducing their impact effectiveness. Similar behavior has been reported in previous studies; for example, and Zhang et al.⁴⁷ and Khan et al.⁴⁸ reported that erosion rates increase with both particle size and gas velocity due to the increased momentum of the particles.

The angular distribution of erosion is consistent with findings from other elbow erosion studies. In particular, Zhu et al.⁴⁹ and Hong et al.⁵⁰ reported peak erosion near 45° in 90° elbows with small elbow radii of curvature

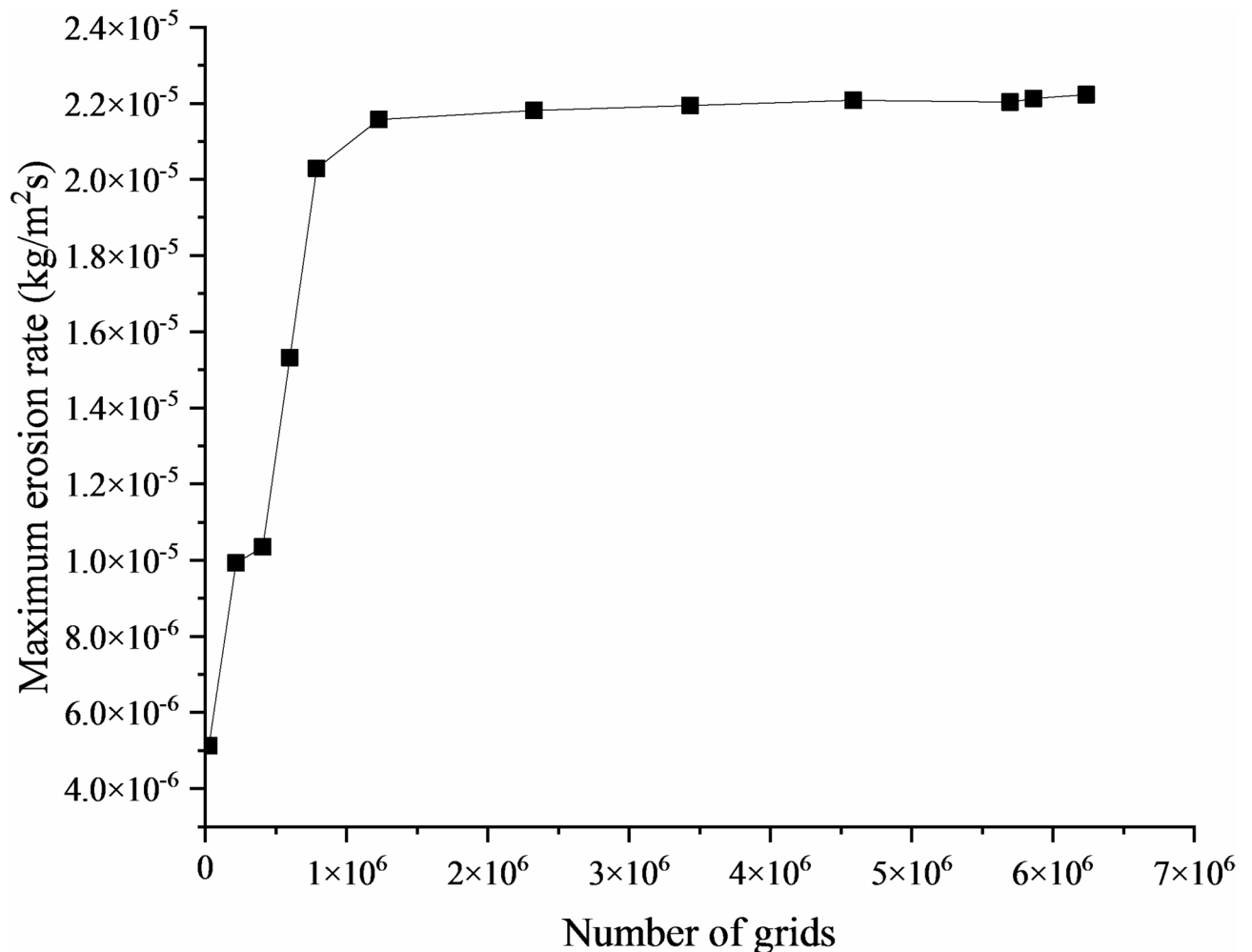


Fig. 5. Grid independence study showing the relationship between the number of mesh elements and the simulated maximum erosion rate at the elbow.

ratios ($r/D = 1.5$). Long-radius elbows ($r/D = 3.0$) were shown to distribute the impact zone more broadly and reduce peak erosion intensity. These results align with the erosion behavior documented in the current study and support the conclusion that geometry plays a key role in erosion localization and severity.

Compared with flume experiments conducted by Zheng et al.^{51,52}, notable differences in erosion mechanisms have been reported. The flume studies involved debris flows over sediment beds and revealed that erosion was more intense in coarse-grained beds because of increased basal pore pressure, which reduced friction and promoted material removal. Although the mechanisms differ—pore pressure-induced scour in flumes versus particle impact-driven erosion in elbows—both studies emphasize the influence of particle size and flow energy on erosion intensity. However, erosion in elbows is more localized and controlled by the particle trajectory and impact angle, whereas in flume channels, erosion tends to occur more uniformly or as mass failure, depending on the bed composition and flow moisture.

The effect of the elbow radius of curvature on erosion

Figures 8 and 9 present the erosion rate profiles for 25- and 300-micron particle sizes at various elbow curvature radii, demonstrating clear trends in the influence of both particle size and elbow geometry. For both particle sizes, the maximum erosion rate decreases as the elbow radius of curvature increases from 1.5D to 5D. This trend can be attributed to the longer bending path associated with larger curvature radii, which disperses particle impacts and reduces the intensity of erosion at localized points. At smaller curvature radii (1.5D and 2.5D), erosion is more concentrated because of frequent and intense particle impacts, increasing the risk of localized damage.

Comparing the two particle sizes, the 300-micron particles exhibit substantially higher erosion rates than their 25-micron counterparts at every curvature, which is consistent with greater particle mass and inertia leading to greater impact energy upon collision with the pipe wall. Furthermore, the erosion peak for 25-micron particles is observed at a higher elbow angle (approximately 70°), whereas the peak for 300-micron particles shifts to lower angles (approximately 40–50°), reflecting the effect of increased inertia and more direct trajectories of larger particles. These results highlight the combined importance of elbow curvature and particle size in determining

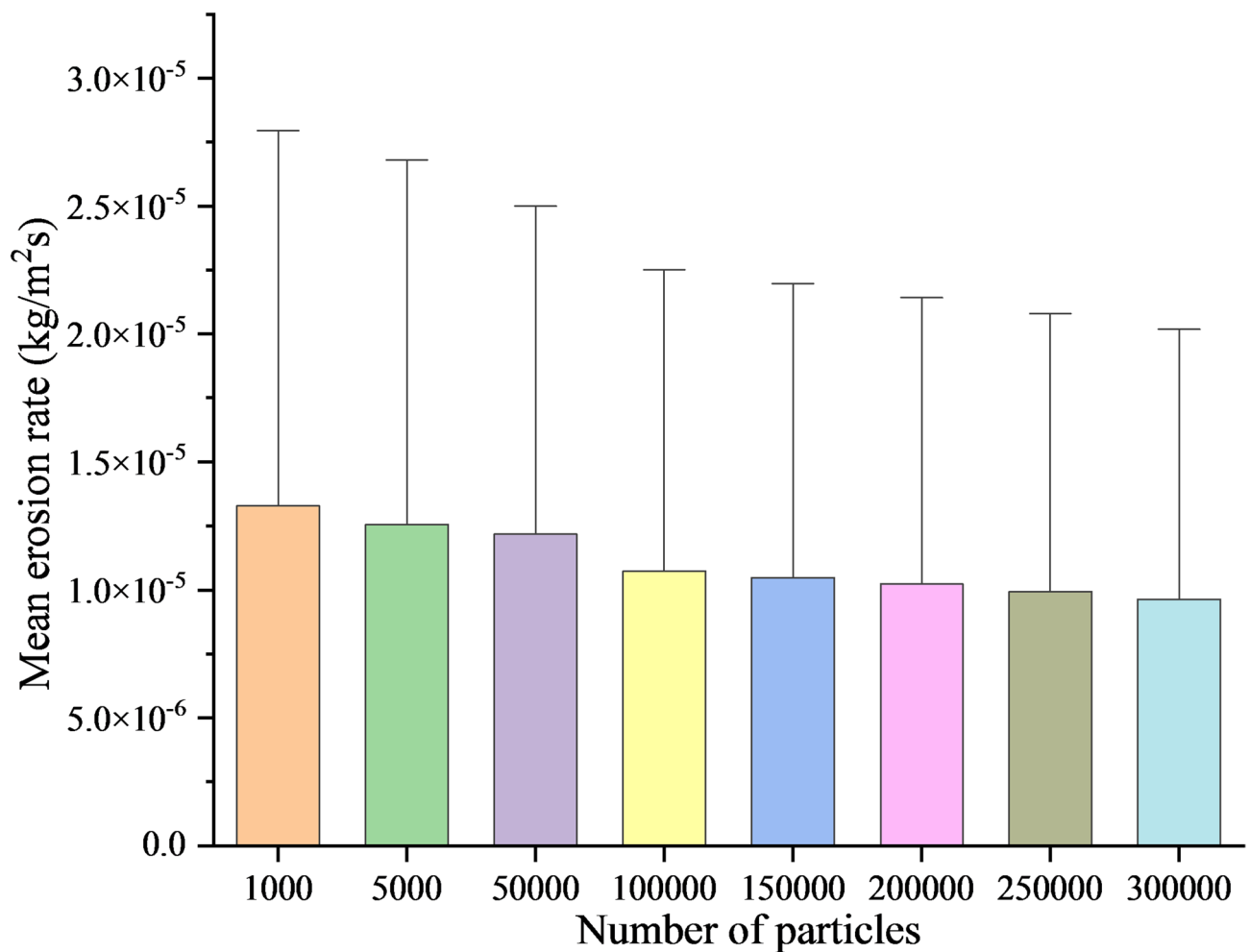


Fig. 6. Effect of the particle intensity on the erosion rate (mean and 95% confidence interval) at a 23 m/s gas velocity.

erosion severity; elbows with smaller radii of curvature and flows containing larger particles should be avoided when possible to minimize erosion and enhance system reliability.

The effect of solid particle shape on erosion

The impact of solid particles on a surface can lead to dents and cracks. Finnie⁵³ described the mechanisms by which ductile and brittle materials lose material upon impact, formulating the impact-deformation theory for these phenomena. When particles strike the oxide layers of a pipe, they induce surface cracks. Additionally, particles scraping along the pipe wall create furrows. Material removal occurs when particles hit the surface at a shallow angle, functioning similarly to the cutting edges of milling tools or the abrasive grains of grinding wheels⁵⁴. Consequently, furrow patterns can be observed on the surfaces of damaged pipe samples (Fig. 10).

To determine the effect of particle shape, 100,000 particles in gas with diameters of 25 and 300 microns were injected into an elbow at a speed of 23 m/s. The numerical erosion rates for sharp, semirounded, and rounded particles are shown in Figs. 11 and 12. The results showed that the amount of erosion has a direct relationship with the sharpness of the particles. Therefore, the greater the roundness is, the lower the amount of erosion. Additionally, the amount of erosion for particles with a size of 25 microns was less than that for those with a size of 300 microns. This can be explained by the following factors:

- **Particle shape and impact:** Rounded particles have a smoother surface and a more uniform shape, which reduces the intensity of their impact on the surface. This leads to less material removal than angular particles, which have sharper edges that can cause more significant damage upon impact.
- **Energy distribution:** When rounded particles collide with a surface, the impact energy is distributed more evenly across the contact area, resulting in less localized stress and, consequently, less erosion.
- **Fluid dynamics:** Smaller particles, such as 25-micron particles, are more influenced by fluid turbulence and tend to follow more erratic paths. This reduces their effective impact on the surface, leading to lower erosion rates than those of larger particles, which maintain more linear trajectories and impact the surface with greater force.

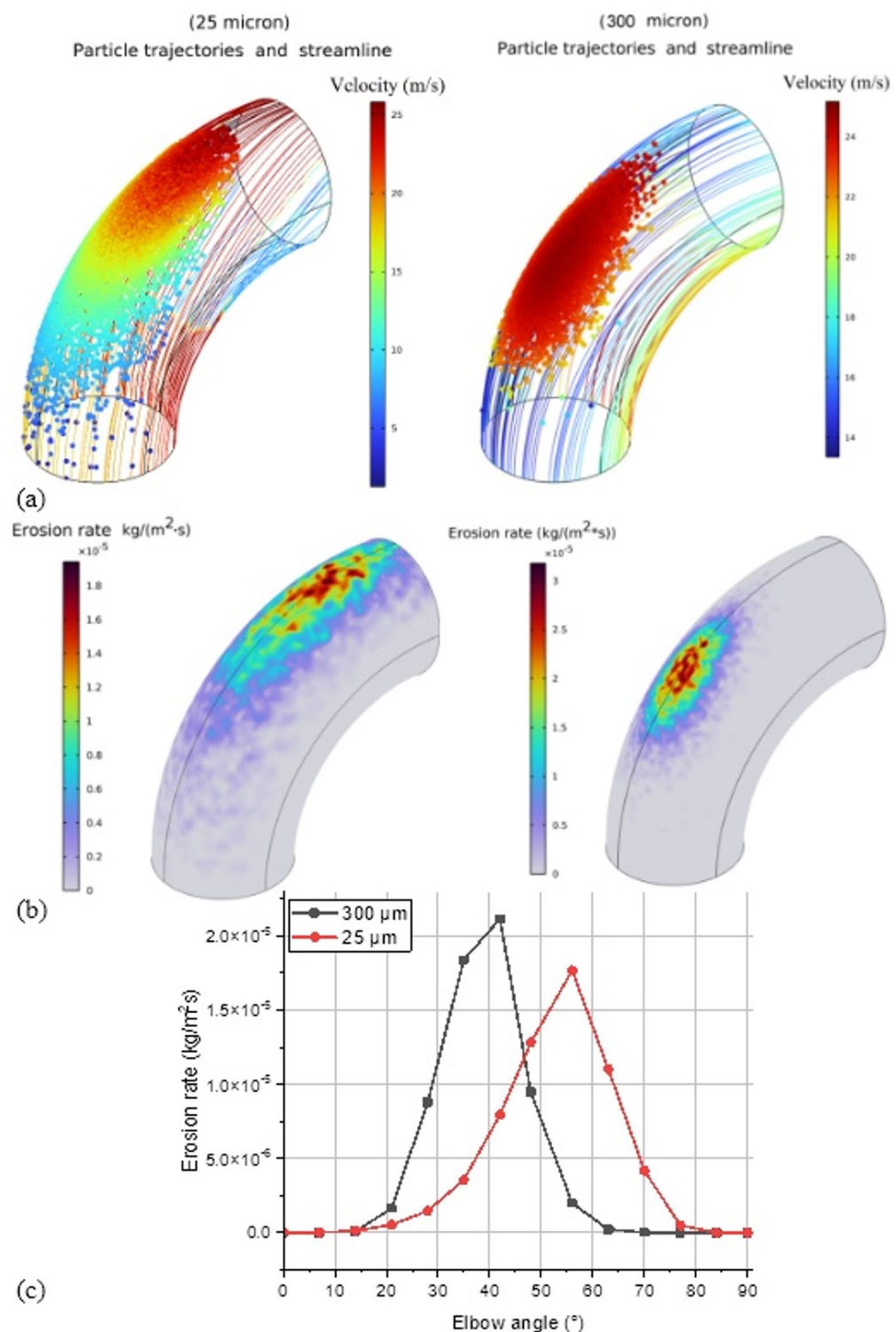


Fig. 7. Streamlines of fluids and particles (a) and erosion rate profile (b) for numerical simulations of 25- and 300-micron particle sizes via CFD-DPM.

The effect of velocity on erosion

The effects of particle size and fluid velocity on erosion magnitude were studied simultaneously using two particle sizes, 25 and 300 µm, with flow rates of 15, 23, and 49 (m/s). A total of 100,000 particles were injected with gas into the elbow. As shown in Figs. 13 and 14, the amount of erosion for the 25- and 300-micron samples increased with increasing flow rate. Additionally, with increasing particle diameter, the erosion rate of the 300-micron particles was greater than that of the 25-micron particles. This can be explained by the following factors:

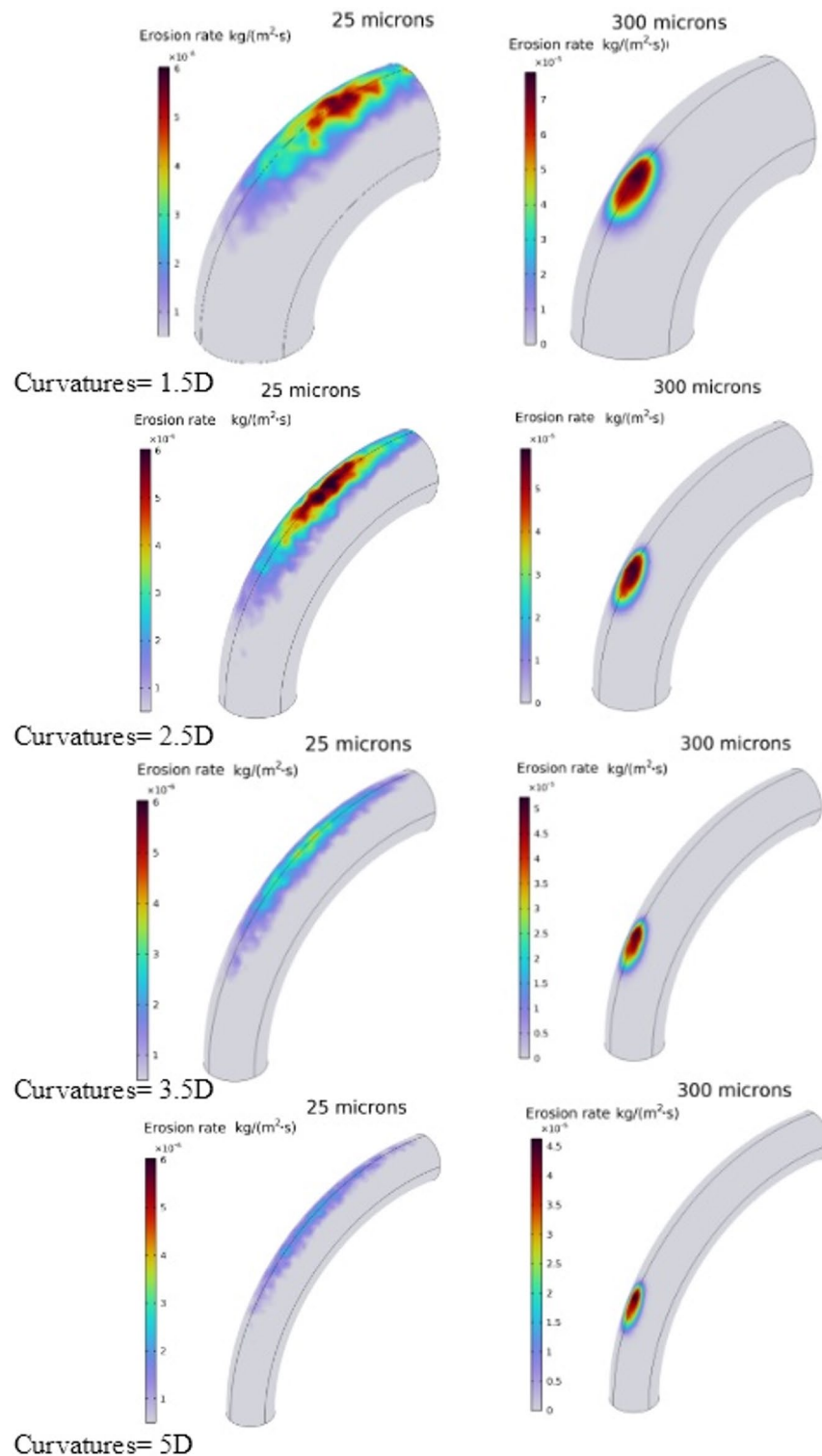


Fig. 8. Erosion rates for numerical simulations of 25- and 300-micron particle sizes in elbows with different elbow radii of curvature via CFD-DPM.

- **Impact Energy:** As the flow rate increases, the velocity of the particles also increases. This results in higher impact energy when particles strike the surface, leading to more significant erosion. Compared with smaller particles, larger particles (300 microns) have more mass and thus carry more kinetic energy, causing greater erosion upon impact.
- **Inertia and trajectory:** Larger particles have greater inertia, allowing them to maintain more linear trajectories even at higher flow rates. This means that they are more likely to impact the surface directly and with greater

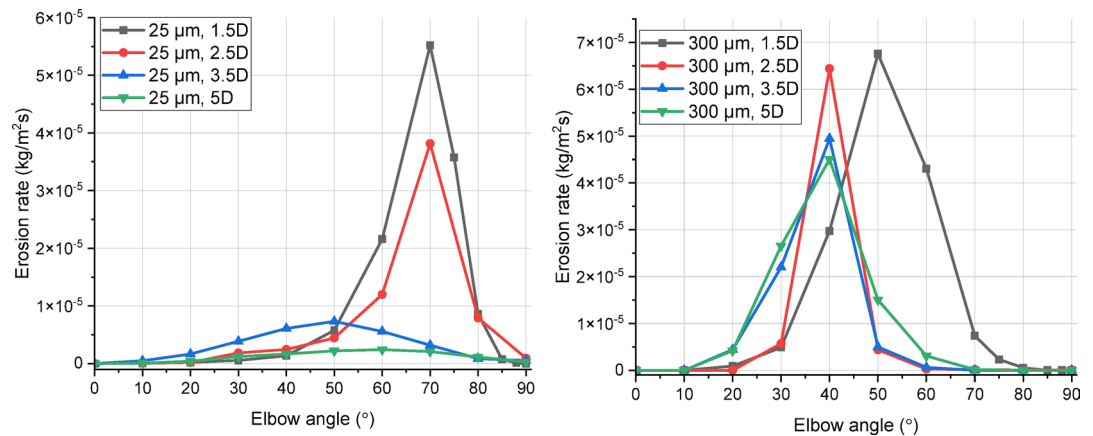


Fig. 9. Erosion rate profile of 25- and 300-micron particle sizes above the elbow with different elbow radii of curvature by CFD-DPM.

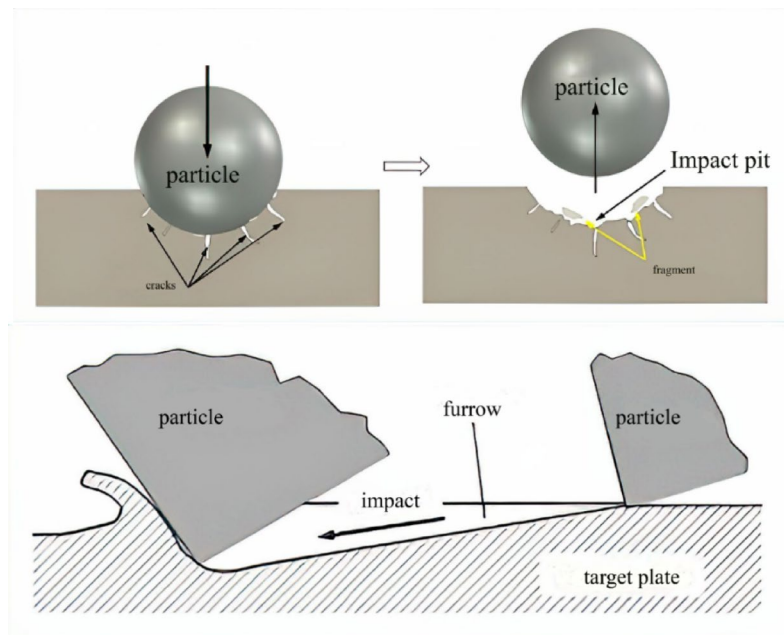


Fig. 10. The theory of impact deformation and the theory of microcutting.

force, leading to increased erosion. On the other hand, smaller particles are more influenced by turbulent flow and may follow more erratic paths, reducing their effective impact on the surface.

- **Shear Forces:** Higher flow rates increase the shear forces exerted by the fluid on the particles. For larger particles, these shear forces can enhance the erosion process by causing more substantial material removal from the surface.

Limitations, strengths, and practical implications

This study incorporates a validated CFD framework that simulates gas–solid erosion via discrete particle tracking and rebound modeling. A key strength is the alignment between simulated and experimentally observed erosion locations and magnitudes, particularly within elbow geometries. The framework captures realistic physical interactions—such as energy dissipation, impact angle effects, and secondary collisions—enabling accurate mapping of erosion-prone zones. The findings confirm known trends, including the influence of particle size, shape, and velocity on wear severity, and provide a computational platform for predicting erosion under conditions common in gas transmission pipelines.

A further strength lies in the integration of five key erosion-controlling parameters—particle geometry, size, intensity, flow velocity, and elbow curvature—within a single simulation framework. This multiparameter coupling provides a more comprehensive and realistic modeling approach compared to previous studies that typically isolate one or two variables. Additionally, this work introduces a mechanistic explanation for erosion

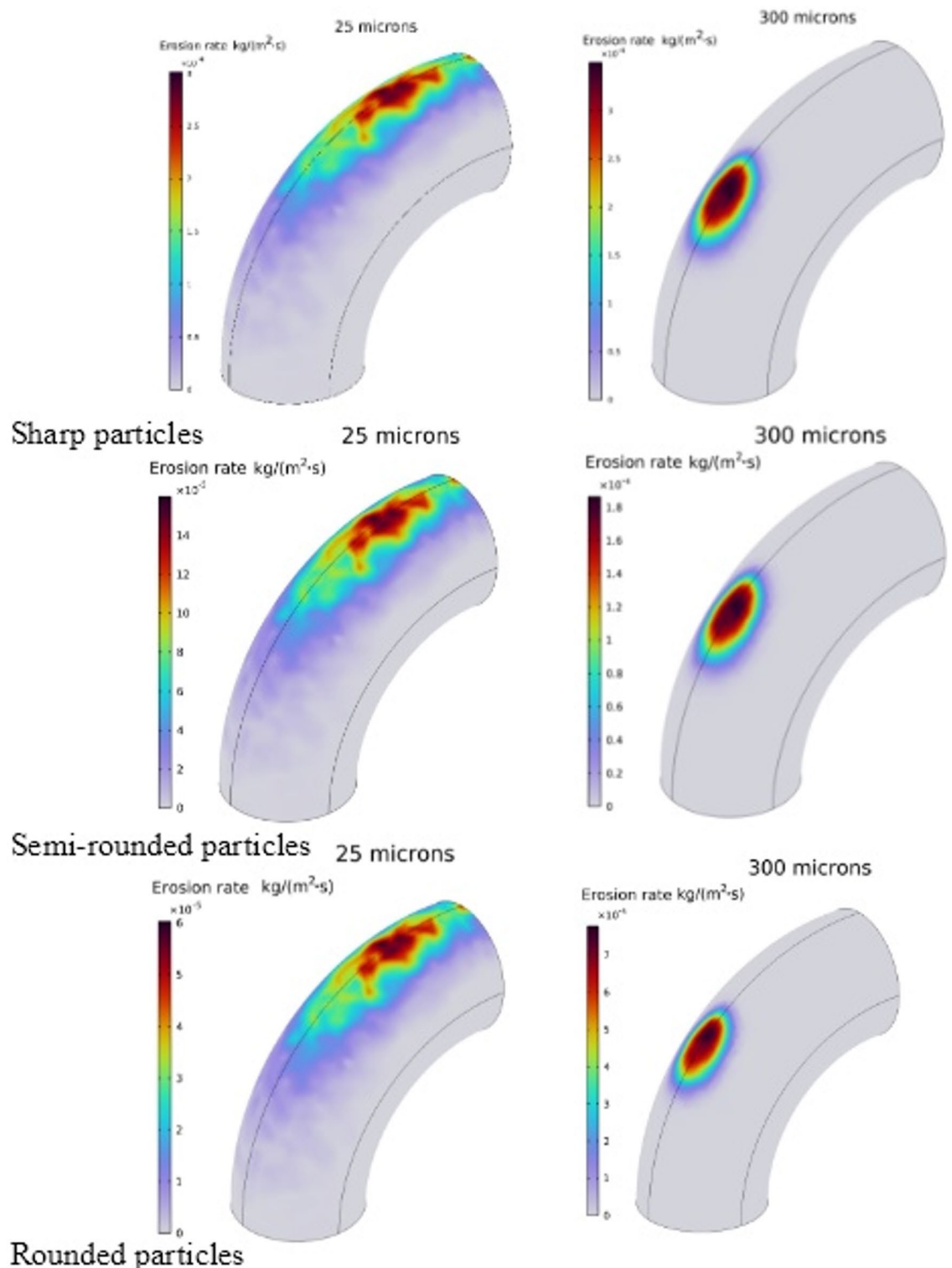


Fig. 11. Erosion rate visualization of 25- and 300-micron sharp, semirounded, and rounded particles above the elbow with different elbow radii of curvature via CFD-DPM.

saturation, identifying a threshold beyond which increased particle intensity does not lead to higher erosion. This behavior is attributed to surface saturation, particle shielding, and energy dissipation through interparticle interactions, providing a dual physical and statistical basis for understanding erosion-limiting behavior under high-load conditions.

However, several limitations and assumptions must be acknowledged. The study assumes a dilute particle regime (volume fraction < 10%), which is consistent with standard industrial gas–solid flows but not

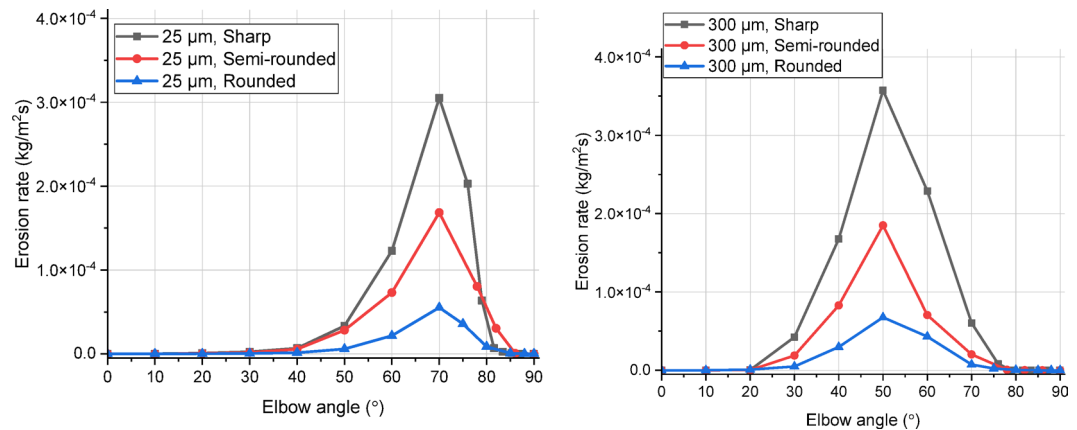


Fig. 12. Erosion rate profile of 25- and 300-micron sharp, semi-rounded, and rounded particles above the elbow with different elbow radii of curvature by CFD-DPM.

representative of dense-phase systems such as multiphase oil pipelines with high sand content. Under such conditions, particle–particle interactions, turbulent energy modulation, and flow clustering become significant. These effects are not fully accounted for in the traditional DPM (Discrete Phase Model), potentially resulting in underprediction of localized wear. To address this, future work could incorporate the dense discrete phase model (DDPM), which allows for two-way and four-way coupling and explicitly models interparticle collisions and turbulence modulation—which is critical for accurately simulating dense particle suspensions.

From a mechanistic standpoint, the erosion patterns observed in this study are strongly linked to particle inertia and its interaction with local turbulence structures. Particles with higher inertia (as quantified by the Stokes number, St) are less responsive to turbulent eddies and tend to impact walls more directly, especially at elbow radii where centrifugal forces drive particles toward the outer bend. Larger or denser particles, which correspond to higher St values, exhibit ballistic trajectories that result in focused erosion zones. In contrast, finer particles (with lower St) are more influenced by fluid turbulence, leading to broader dispersion and less concentrated wear. This behavior is critical for engineers seeking to optimize flow conditions, as it suggests that manipulating velocity, particle size, or turbulence intensity can help redistribute erosive forces and reduce hotspot damage.

While the current simulations consider idealized pipe geometries and steady, fully developed flow, field systems often involve transient flow rates and swirl and multibend configurations. The assumed homogeneity of particle and pipe materials also neglects site-specific variables such as corrosion, thermal gradients, or anisotropic wear. Additionally, the model does not capture dynamic processes such as particle fragmentation, shape evolution, or erosion–corrosion synergy, which are important in long-term operation.

Despite these constraints, this study has practical value. The selected parameters—including the particle characteristics, elbow radius of curvature, and velocity range—are based on real operating conditions in gas processing infrastructure. The erosion rate evaluation can serve as predictive tools for maintenance planning and component design. For example, areas with concentrated wear—typically approximately 45° in short-radius elbows—can be reinforced through targeted wall thickening or the application of erosion-resistant liners such as tungsten carbide, ceramic, or polymer-based coatings. These mitigation strategies are widely used and can be refined through simulation-informed risk maps. Future improvements may include transient modeling, coupling with corrosion mechanisms, and validation of material and geometric countermeasures under relatively high particle loadings.

Conclusions

The effects of the size, shape, velocity, and concentration of particles in gas flow on elbow erosion were studied through CFD-DPM. The numerical results were experimentally validated, and the following conclusions were drawn:

- The increase in particle intensity caused an increase in erosion up to a certain point, beyond which there was no further effect on the amount of erosion with increasing particle intensity. This can occur for several reasons, including surface saturation, particle shielding, and energy dissipation.
- The metal loss in the elbow was greater for 300-micron particles than for 25-micron particles. Smaller particles were more affected by turbulence with random paths, whereas larger particles showed more resistance with more linear paths and caused more erosion. This can occur for several reasons, including the effects of turbulence and pathways, inertia and linear pathways, and impact energy.
- There was less erosion for both particle sizes when more rounded particles were present. Erosion was lower for the 25-micron particles. Factors such as particle shape and impact, energy distribution, and fluid dynamics collectively contribute to the observed reduction in erosion, with more rounded particles and lower erosion rates for smaller particles.

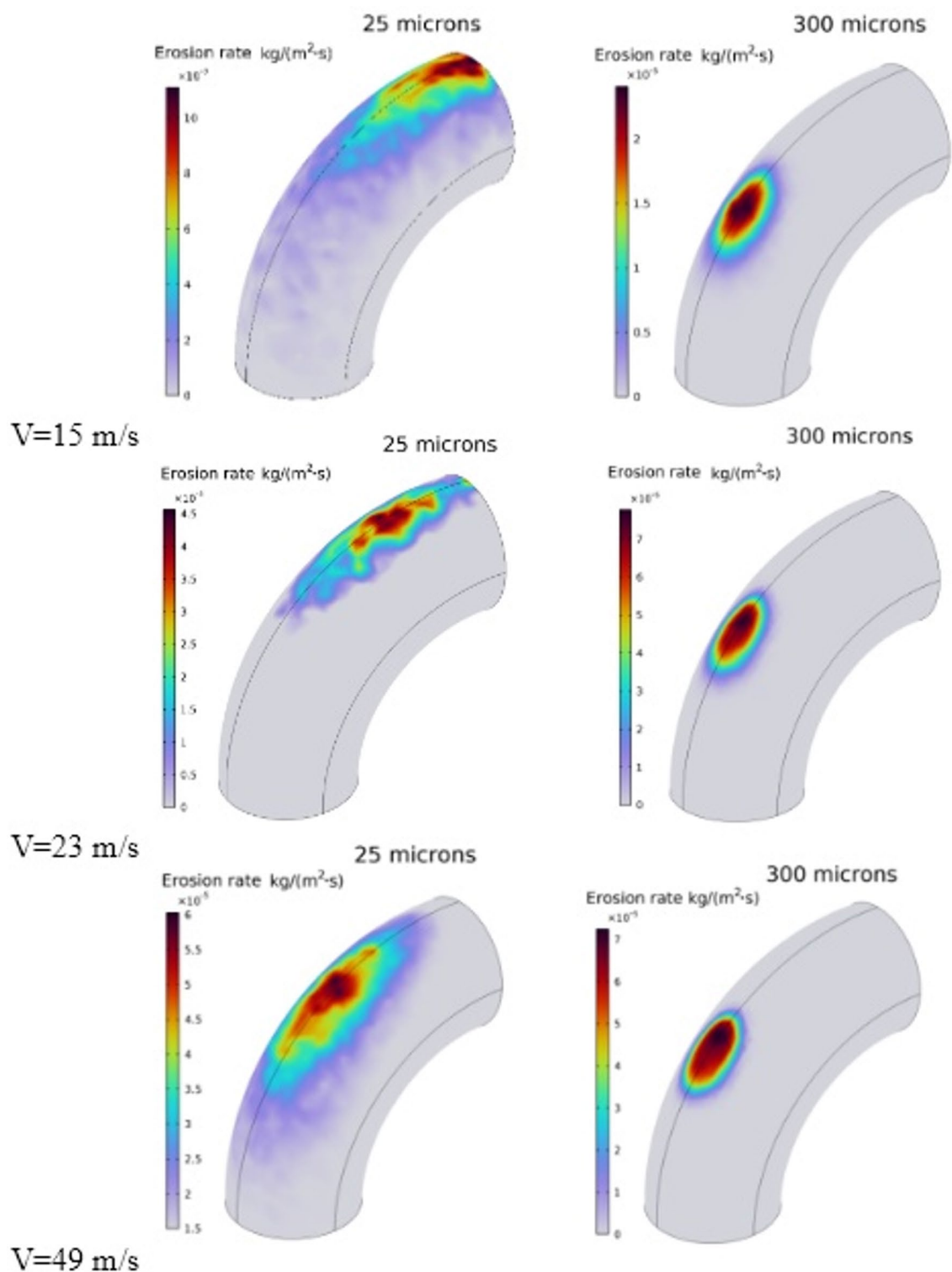


Fig. 13. Visualization of erosion rates at velocities of 25 and 300 microns at different fluid velocities ($V = 15$ m/s, $V = 23$ m/s, $V = 49$ m/s) above the elbow with different elbow radii of curvature via CFD-DPM.

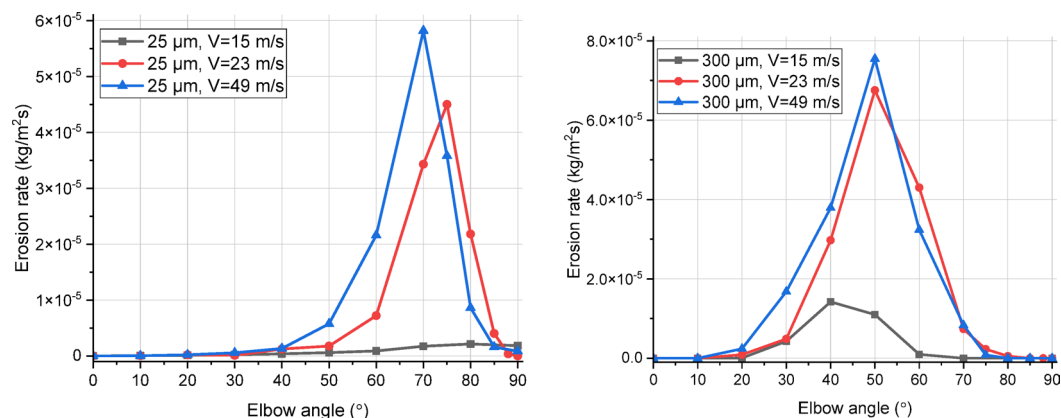


Fig. 14. Erosion rate profiles of 25 and 300-micron particles at different fluid velocities ($V = 15$ m/s, $V = 23$ m/s, $V = 49$ m/s) above the elbow with different elbow radii of curvature according to the CFD-DPM.

- The amount of erosion increased with increasing flow rate for both particle sizes. Erosion was greater for 300-micron particles. The impact energy, inertia, trajectory, and shear forces can collectively explain why erosion increases with flow rate and why larger particles cause more erosion.

Data availability

The data supporting this study's findings are available upon request (Corresponding Author: Yousef Shiri; Email: yousefshiri@shahroodut.ac.ir).

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Author contributions

Y.S. did Conceptualization, methodology, software, resources, data curation, writing—original draft, supervision, and project administration. O.M. did Validation, Formal analysis, Investigation, Writing—Review & Editing, and Visualization.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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