

Rheological study of granular flows through a hopper: A comparative study

Satyabrata Patro^{1,*}, Vijendra Gupta^{2,**}, and Anurag Tripathi^{3,***}

¹R&D Tata Steel limited, Jamshedpur, Jharkhand, India

²Department of Chemical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

³Department of Chemical Engineering, Indian Institute of Technology Kanpur, Kanpur, Uttar Pradesh, India

Abstract. The study of particle flow in bins and hoppers is critical for optimizing industrial processes parameters and system design. Discrete element method (DEM) simulations have been extensively used by researchers to study and understand particle flow behavior. In solids handling industries, non-spherical particles are ubiquitous, as spherical particles are rarely encountered in practical applications. However, spherical particles are often used in simulations due to their simplicity and ease of modeling. Accurately simulating non-spherical particles presents significant challenges, making it a focal point for advancing simulation techniques and improving industrial processes.

This study investigates hopper flow of non-spherical particles, specifically dumbbells is compared with that of spherical particles of equivalent diameter. We compare key flow properties such as velocity profile near the orifice, mass flow rate, and packing fraction. Our findings reveal distinct differences in flow behavior between dumbbell-shaped and spherical particles. These differences highlight the crucial role of particle shape in hopper flow dynamics. This research provides valuable insights for the design and optimization of hoppers and bins used to handle complex-shaped particles.

1 Introduction

The flow of granular materials through hoppers and bins is a fundamental operation in numerous industries, including pharmaceuticals, agriculture, mining, and chemical engineering. The Discrete Element Method (DEM) has emerged as a powerful computational tool for simulating granular flows, enabling researchers to investigate particle-level interactions and macroscopic flow behavior. Historically, DEM simulations have predominantly employed spherical particles because of the simplicity of contact models and the reduced computational demand. This assumption, however, limits simulation realism, as most real-world particles exhibit non-spherical geometries. Non-spherical particles introduce additional complexity into flow simulations. Their orientation, interlocking potential, and asymmetric interactions influence packing structure, force transmission, and flowability. Although DEM contact-detection algorithms allow the calculation of forces arising from particle-particle interactions, the computational cost rises sharply with particle number [1, 2]. The challenge is even greater for non-spherical particles [3, 4], because accurately modeling irregular shapes is highly complex. Extensive research demonstrates that particle shape significantly affects granular rheology [5]. One strategy for reducing the computational cost is the rolling-friction technique, which adds a rolling-resistance torque to approximate shape effects [6, 7]. Alternative ap-

proaches for estimating rolling friction coefficients in non-spherical particles have also been proposed [1, 8]. Several studies have investigated non-spherical particles in shear flow, providing valuable insights into their rheological properties. For example, Jin et al. [9] experimentally examined the flow behavior of spheres, ellipsoids, hexahedrons, and binary mixtures in rectangular hoppers, reporting the highest discharge rates for hexahedrons, followed by spheres, binary mixtures, and ellipsoids. Reddy et al. [10] used DEM simulations to study dumbbells—two overlapping disks—in a shear cell and found that the friction coefficient depended weakly on aspect ratio at fixed solids fraction. Guo et al. [11, 12] simulated elongated rods and showed that normalized normal and shear stresses, as well as the friction coefficient, decrease with increasing aspect ratio.

In this study, we focus on the hopper discharge of dumbbell-shaped particles—representative of elongated, bonded particle systems—with different aspect ratios. Using DEM simulations, we systematically analyze the effects of particle shape by comparing the flow of dumbbells to that of spherical particles of equivalent volume. These findings underscore the importance of incorporating realistic particle geometries in DEM models to ensure accurate predictions and guide the optimal design of solids handling equipment.

2 Simulation methodology

The DEM simulations were performed using the linear spring and dashpot contact model. The rectangular bin

*e-mail: satyabrata.patro1@tatasteel.com

**e-mail: vk Gupta20@iitk.ac.in

***e-mail: anuragt@iitk.ac.in

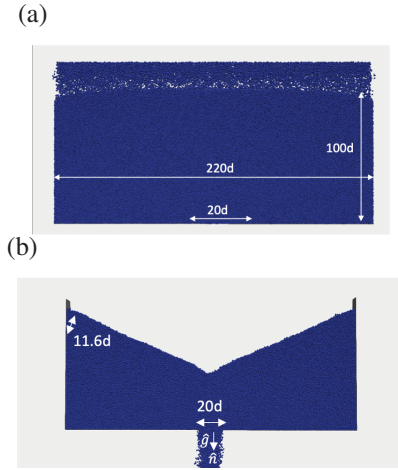


Figure 1. DEM simulation snapshot for (a) generation (b) flow through rectangular orifice for $\theta = 0^\circ$

has dimensions of $220d$ in the x -direction, $100d$ in the y -direction, and $11.6d$ in the z -direction, with periodic boundary conditions applied to maintain continuity. The orifice of the bin has a width of $20d$ (see Figure 1). **LIGGGHTS**, an open-source DEM software, is used to facilitate the creation of dumbbells, followed by a settling phase to achieve particle stabilization. Mono-dispersed particles with diameter of $d = 1\text{mm}$ and density $\rho = 2500\text{kg/m}^3$ are used in the simulations.

In the Linear spring dashpot model (LSD), the total contact force $|\vec{F}|$ on a particle due to contact with other particles is given by:

$$|\vec{F}| = (k_n \delta_n \hat{n} - \gamma_n \vec{v}_n) \cdot \hat{n} + k_t \delta_t \hat{t} - \gamma_t \vec{v}_t \cdot \hat{t} \quad (1)$$

We use a time step Δt equal to $t_{col}/50$, where the time for binary collision between particles is related to the spring constant (k_n) and damping coefficient (γ), and is given by:

$$t_{col} = \frac{\pi}{\sqrt{2k_n/m_{eff} - \gamma^2/4}} \quad (2)$$

3 Results and discussion

We present DEM simulation results for the flow of spheres through a rectangular bin, starting from a settled layer height of $L_y = 100d$, with a restitution coefficient $e_n = 0.88$. All quantities are expressed in SI units, with the exception of the stiffness constant, which is dimensionless with $k_n = 2 \times 10^5$ and $k_t = (2/7)k_n$.

Figure 2 shows a comparative analysis of the mass discharge behavior observed during the hopper flow of various particle configurations, with a particular emphasis on the influence of particle shape and aspect ratio. In this figure, DEM simulation data is presented for dumbbell-shaped particles with two distinct aspect ratios: $\lambda = 1.4$ and $\lambda = 1.7$, plotted using red triangles. These elongated particles represent bonded systems with increased shape anisotropy. The corresponding spherical particles are included for reference using three different diameter equivalencies: d_{eq} (volume-equivalent diameter of dumbbells,

used for equivalent spheres), shown as black circles, d_{avg} (mean of the two spheres in the dumbbell), shown as blue squares, and λd (a scaled equivalent based on λ), denoted by green inverted triangles. These are all used as reference spherical cases to compare against dumbbells. The average diameter d_{avg} is defined as the mean of the two spherical components forming the dumbbell. In the current setup, the spheres are of equal size, so $d_{avg} = d$. The results clearly indicate that the mass flow rate of dumbbell particles is consistently higher than that of the spheres across all comparative cases. This observation is somewhat counterintuitive, as one might initially expect that non-spherical, interlocking particles would hinder flow due to increased friction, alignment constraints, or mechanical entanglement. However, the simulations demonstrate that, under the specific conditions examined, dumbbell particles actually facilitate a more efficient discharge process than the corresponding spheres. Dumbbell particles, due to their elongated structure, may exhibit preferential alignment along the flow direction as they approach the orifice. In the regions near the orifice, we observed a consistent trend in which dumbbell shaped particles orient themselves preferentially along the direction of gravity (vertical direction). These are based on post-simulation visual analysis and no quantitative measurements were done or reported in this study. This alignment reduces cross-wise interlocking and promotes smoother discharge, allowing a higher number of particles to pass through the orifice per unit time. The fitted lines in figure 2 are intended to represent the overall discharge trend rather than strict physical laws. In reality, hopper discharge does not become begin precisely at $t=0$ due to the initial particle rearrangement and settling dynamics during the early simulation steps. This results in a slight delay in measurable discharge, especially for non-spherical particles. As a result, the discharge-time plots naturally exhibit a non-zero intercept which we have retained in the linear fits to better capture this behaviour.

Figure 3 presents a colormap visualization of the velocity magnitude for both spherical and dumbbell-shaped particles during hopper discharge. This is crucial in understanding how particle shape influences the velocity distribution within the granular flow, both in the entire domain and within the active flowing region. Figure 3(a-b) shows a qualitative comparison between the flow fields of the spherical and dumbbell particle assemblies. One of the key observations from this figure is the identification of a distinct non-flowing region within the bulk material. This stagnant zone is characterized by very low velocity magnitudes, defined here as less than or equal to 0.1 units. This threshold serves as a basis for demarcating the flowing region, which comprises particles moving with a velocity magnitude greater than 0.1. Within the velocity field, it is observed that the x -direction velocity component remains negligible throughout most of the hopper domain, except in the immediate vicinity of the orifice. The flow is primarily vertical due to gravity, as suggested by the symmetry and structure of the velocity magnitude contours, which exhibit minimal lateral spreading except near the orifice.

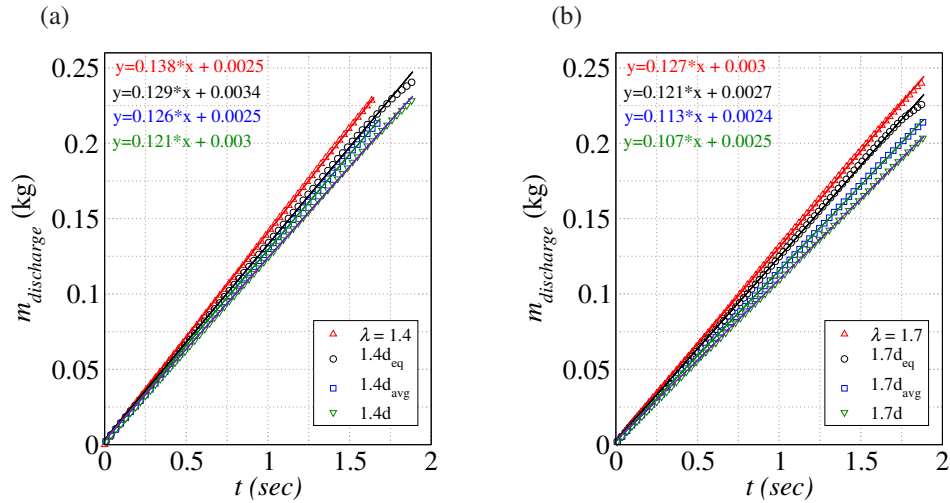


Figure 2. Comparison of mass discharge for non-spherical of aspect ratio (a) $\lambda = 1.4$ and (b) $\lambda = 1.7$, and reference spheres with equivalent diameters: volume-equivalent diameter of dumbbells (d_{eq} , black symbols), average diameter (d_{avg} , blue symbols), and scaled diameter (λd , green symbols). These are used as reference spherical cases to compare against dumbbells. Dumbbell results are shown using red symbols. Linear fits are shown to highlight discharge trends. Note: The fits do not pass through the origin due to the initial rearrangement dynamics before steady flow is established.

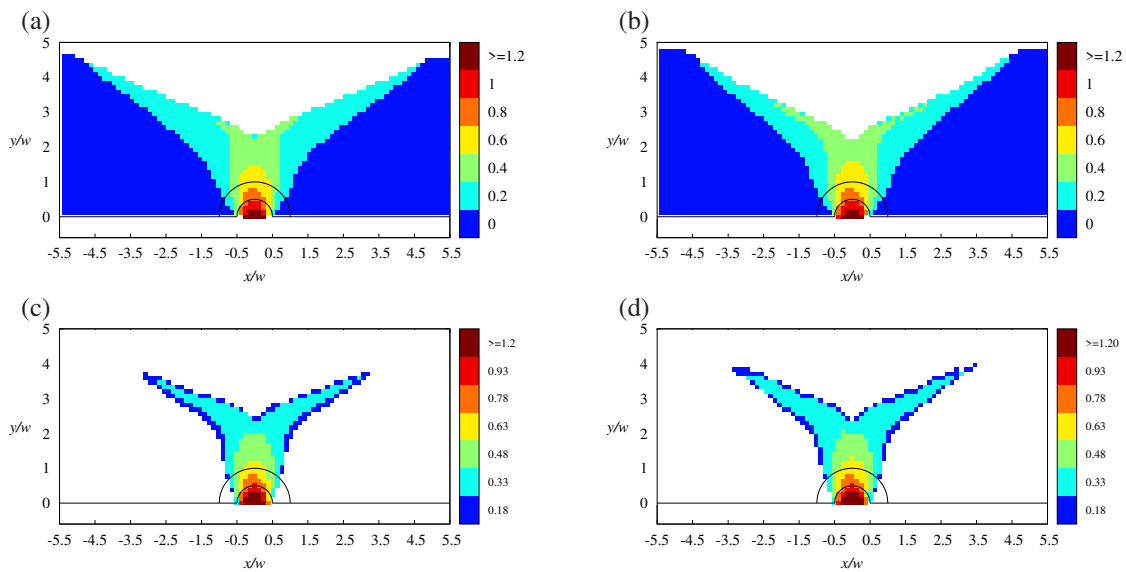


Figure 3. Variation of velocity magnitude of (a) spheres and (b) dumbbells with aspect ratio $\lambda = 1.4$ in the entire region (c) spheres and (d) dumbbells with aspect ratio $\lambda = 1.4$ in the flowing region near the orifice.

While the velocity plots in Figure 3 show magnitude, the overall structure of the field is consistent with dominant direction (y -direction) motion. This indicates that the bulk of the particle motion is aligned vertically, in the y -direction, as expected in gravitational flow scenarios. Near the orifice, localized horizontal movement emerges due to shear effects and particle rearrangements, especially as particles accelerate and reorganize to exit the system. As we move upward along the y -axis (vertical direction), the velocity magnitude gradually decreases. This reduction is accompanied by a broadening of the regions with non-zero velocity, indicating a gradual transition from fast-moving particles near the outlet to slower-moving or stagnant particles

cles higher in the hopper. Interestingly, both spheres and dumbbells display this general trend; however, the spatial extent and intensity of the flowing region vary between the two configurations, reflecting differences in how particle shape influences the development of shear zones and plug flow regions.

Our findings are consistent with the results reported in earlier studies such as those by Jin et.al.[9], who showed that discharge rates vary significantly with particle shape, with non-spherical particles like hexahedron and ellipsoids exhibiting lower flowability than spheres. However, in contrast to their observation, our simulations indicate that dumbbell shaped particles with moderate aspect ratios (for

e.g. $\lambda = 1.4$) can achieve higher mass flow rates than equivalent spheres. This discrepancy could be attributed to the different geometrical constraints and orientations allowed by the bonded dumbbell structure used here. Our results further extend these observations to hopper discharge, showing higher packing fractions and distinct alignment behaviour for elongated shapes. These comparisons highlight the complex interplay between shape anisotropy, packing, and flow dynamics in confined geometries.

4 Conclusions

This study presents a detailed investigation into the discharge behavior of non-spherical particles—specifically dumbbell-shaped particles with varying aspect ratios—during hopper flow using the Discrete Element Method (DEM). By comparing the flow characteristics of these elongated, bonded particle systems with those of spherical particles of equivalent volume, we have gained valuable insights into the complex role of particle shape in bulk material handling operations. Our simulation results clearly demonstrate that dumbbell-shaped particles exhibit markedly different flow behavior compared to their spherical counterparts. Key flow parameters such as velocity profiles near the hopper orifice, mass flow rate and packing fraction were significantly affected by the shape-induced constraints and orientation-dependent interactions inherent to non-spherical particles. The presence of interlocking, increased contact area, and shape anisotropy leads to altered force transmission pathways and changes in the local and global flow fields. The findings underscore the limitations of traditional DEM models that rely on simplified spherical approximations. While spherical particles offer computational efficiency, they fail to capture the flow behavior observed in realistic particle systems. Incorporating complex particle geometries, such as dumbbells, is therefore not merely a refinement—it is essential for ensuring accurate and predictive simulations. This is especially relevant in industries such as pharmaceuticals, agriculture, mining, and chemical processing, where the particles involved are rarely spherical and often exhibit irregular or elongated forms.

Moreover, this study highlights the importance of aspect ratio as a critical shape parameter that can significantly alter granular flow behavior. As the aspect ratio increases, particles demonstrate greater resistance to flow due to enhanced interparticle interactions and mechanical interlocking.

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