

3D PTV measurements on vortex structures induced by a free-falling sphere and sphere-wall interaction underwater

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ABSTRACT

This work experimentally investigates the vortex structures induced by a single free-falling sphere and its wall interaction in initially quiescent water. Extensive time-resolved 3-dimensional particle tracking velocimetry measurements and digital object tracking analysis were carried out. The sphere begins to deviate from the vertical trajectory for running distances $L/D > 5$ as the wake becomes unstable. This is associated with the shedding of a coherent vortex structure clearly resolved by the present measurements. The experiments provide insight into the vortex dynamics of a heavy spherical object settling in a dense fluid and reveal geometry-dependent sphere-wall interaction for different wall configurations. The results are useful for the validation of numerical schemes for solid/vortex interaction and collision modeling.

1. Introduction

The motion of a sphere through a fluid and its subsequent interaction with a solid boundary generate complex wake and vortex structures that strongly influence particle trajectories, collision dynamics, and momentum exchange. These fluid-structure interaction (FSI) phenomena are relevant for sediment transport, particle re-suspension, and multiphase flow processes in environmental and hydraulic engineering applications. Understanding the vortex dynamics associated with sphere motion and sphere-wall interaction is therefore important for predicting rebound behavior, near-wall transport processes, and the motion of submerged particles in dense fluids. For example, Eames & Dalziel (2000) used laboratory experiments to investigate the re-suspension characteristics of a spherical particle approaching a wall at varying angles. Their results demonstrated that sphere-induced vortices can entrain surrounding particles and strongly influence near-wall transport processes. Combined PIV measurements and lattice-Boltzmann simulations were conducted by ten Cate et al. (2002) to investigate settling spheres near walls, highlighting the importance of transient fluid-particle interaction. Experimental investigations by Horowitz & Williamson

(2010) further revealed the importance of wake instability for freely moving spheres and associated lateral motion. Young et al. (2022) experimentally investigated vortex structures induced by a falling sphere and sphere-wall interaction using particle tracking velocimetry and refractive-index-matched materials. Their results demonstrated that asymmetric vortex shedding develops at higher Reynolds numbers and can induce lateral deviations of the sphere trajectory. Furthermore, Young et al. (2022) discussed the correlation between pressure dynamics and vortex shedding for spheres falling in a fluid with non-axisymmetric flow at $Re = 2000$. They suggest that unsteady vortex shedding generates a pressure difference in the horizontal direction, thrusting the sphere laterally (Young et al., 2022). Similar pressure-related effects were investigated by Gold et al. (2024), who examined the role of pressure dynamics for underwater spherical pendulums and highlighted the strong coupling between vortex shedding and body motion. Previous studies by Gondret et al. (2002) and Joseph & Hunt (2004) focused on the collision dynamics of submerged particles. Gondret et al. (2002) investigated the bouncing motion of spherical particles in fluids and showed how the restitution behavior depends on the Stokes number, while Joseph & Hunt (2004) examined oblique particle-wall collisions in a liquid and the associated rebound dynamics. Despite these previous advances, detailed volumetric investigations of the fluid flow and vortex structures during sphere-wall interaction remain limited, particularly for concave geometries, where confined flow strongly affects the rebound behavior. Therefore, the present study employs time-resolved three-dimensional particle tracking velocimetry (tr-3D-PTV) to investigate the wake evolution of a free-falling sphere impacting concave, convex, and flat wall geometries at Reynolds numbers of order 10^4 . The measurements provide new insight into how wall geometry affects the resulting collision behavior, while also providing benchmark data for validating numerical models of submerged particle interaction with convex and concave wall geometries.

2. Methods

2.1. Experimental setup and tr-3D-PTV

In this study, a soda-lime glass sphere with $m^* = \rho_s/\rho_f = 2.5$ falls on three different wall geometries from a height of $185 \text{ mm} = 14.5D$. The different wall geometries were a concave cavity, a convex dome, and a flat wall. The corresponding Reynolds number Re based on the diameter $D = 12.71 \text{ mm}$ of the sphere and its falling velocity U_p is $Re \approx O(10^4)$ and the Galileo number $Ga = \sqrt{(gD^3|m^* - 1|)}/\nu \approx 5550$. The experiments were carried out within a glass tank that was 600 mm in length, 300 mm in width, and 300 mm in height. The tank and measurement equipment are supported by an aluminum rail-profile rack, equipped with dampened leveling feet to minimize vibrations (Gold et al., 2023).

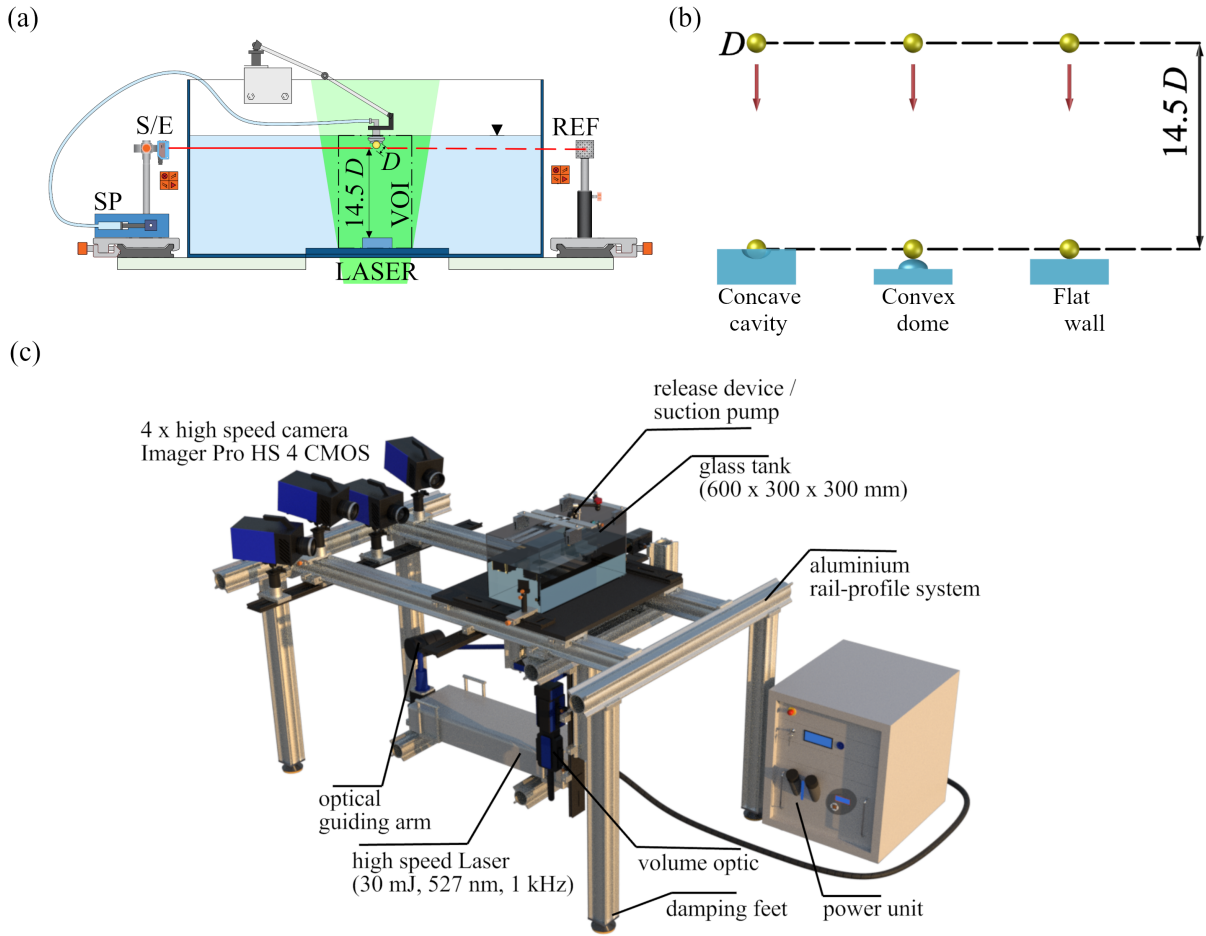


Figure 1. Experimental setup. (a) Glass tank with suction pump (SP), photoelectric sensor (S/E), reflector (REF) and the volume of interest (VOI) (b) Wall geometries left = concave cavity with width of $1.5D$ and depth of $0.5D$, middle = convex dome with width of $1.5D$ and depth of $0.5D$, right = flat wall. (c) PTV system (Gold et al., 2023)

The three different wall geometries, each with a base dimension of 50×50 mm, were manufactured from cast epoxy resin. Fig. 1 shows details of the experimental setup and initial conditions. The high-speed-PTV system from LaVision contains four cameras (Imager Pro HS 4M CMOS 2016×2016 pixels) and a Laser (ND:YLF-PIV) Laser, $E = 30\text{mJ}$, $\lambda = 527$ nm) of the Litron LDY series. The release device is a suction pump (NIRYO Robotics) over a guiding arm. A microcontroller (OpenCM9.04, Type C) operates the slow movements of the suction-piston during the expansion-phase to avoid disturbing the flow field. The tracer-seedings have an average diameter of around $50 \mu\text{m}$ and a density of 1.016 gcm^{-3} , thereby ensuring a sufficiently small Stokes number such that the tracer particles accurately follow the fluid streamlines (Gold et al., 2023). During the experiments, seeding densities of 0.05 ppp were used. The imaging setup has a length scale of approximately 9 pixels/mm. Further, 3D camera calibration was performed for the designated volume of interest (VOI). This calibration involved adjusting the cameras until the calibration error for each camera's imaging plane was minimized to less than 0.25 pixel. Additionally, the

volume self-calibration (VSC) method by Wieneke (2008) was applied to further reduce errors in the particle-triangulation process. The VSC procedure was repeated until the error converged to a mean calibration error of 0.03 pixel, while the maximum error was 0.09 pixel. Following a 1-minute waiting interval to reduce disturbances in the fluid, the buffer-recording mode is started at a frequency of 1000 Hz. The trigger mechanism employs a Sick WL8 photoelectric barrier linked to the trigger input of the PTU. This includes a reflector (REF) and a photoelectric sensor (S/E) to transmit and receive light signals. Initially, the sphere interrupts the signal of the photoelectric barrier. When the suction pump releases the sphere, it passes the photoelectric barrier, and the S/E receives a signal and triggers the recording. The raw images are then preprocessed using an anisotropic diffusion filter (ADF). The ADF ensured that the images exclusively displayed visible tracer particles (Adatrao & Sciacchitano, 2019). Sparse Lagrangian tracks were established by applying the validated shake-the-box (STB) algorithm by Schanz et al. (2016). Non-physical tracks ("ghost-particles") were removed based on allowed velocity range relative to an estimate of the sphere's maximum velocity. To enhance flow field visualization and identify vortical structures, the sparse PTV data were interpolated onto a regular Cartesian mesh by employing the vortex-in-cell method introduced as VIC+ by Schneiders & Scarano (2016) and advanced as VIC# by Jeon et al. (2022). The resolution of the mesh is 9 voxel or 1 mm.

2.2. Digital object tracking of the sphere

The x - y trajectory of the sphere was obtained using a digital object tracking (DOT) procedure based on intensity segmentation (Gold et al., 2023) and circular edge matching. A static background image was constructed from the temporal median of the initial image sequence and used for background suppression and masking of stationary structures. For each frame, the image intensity field was processed in grayscale using contrast enhancement and adaptive threshold segmentation in order to isolate the sphere region from the surrounding background intensity field. Candidate sphere regions were detected from the segmented images and filtered according to their size and shape. The sphere position was estimated from the detected contour and subsequently refined by fitting a circular boundary with fixed radius around the sphere edge. To suppress spurious detections and improve computational efficiency, the tracking was restricted to a local search region around the previously detected sphere position. Fig. 2 exemplarily shows the tracking result at four representative instants. The tracked image coordinates were converted into physical coordinates using the image calibration scale. Prior to velocity estimation, the measured trajectories were smoothed using a moving-average window (MAW) of three frames in order to reduce frame-to-frame positional noise. Velocity components were subsequently reconstructed from the smoothed trajectories using finite-difference differentiation over a frame interval of $\Delta N = 5$. The rebound behaviour was evaluated from the pre- and post-impact vertical motion, where the corresponding rebound coefficients were determined from linear fits to the local displacement trajectories before

and after impact.

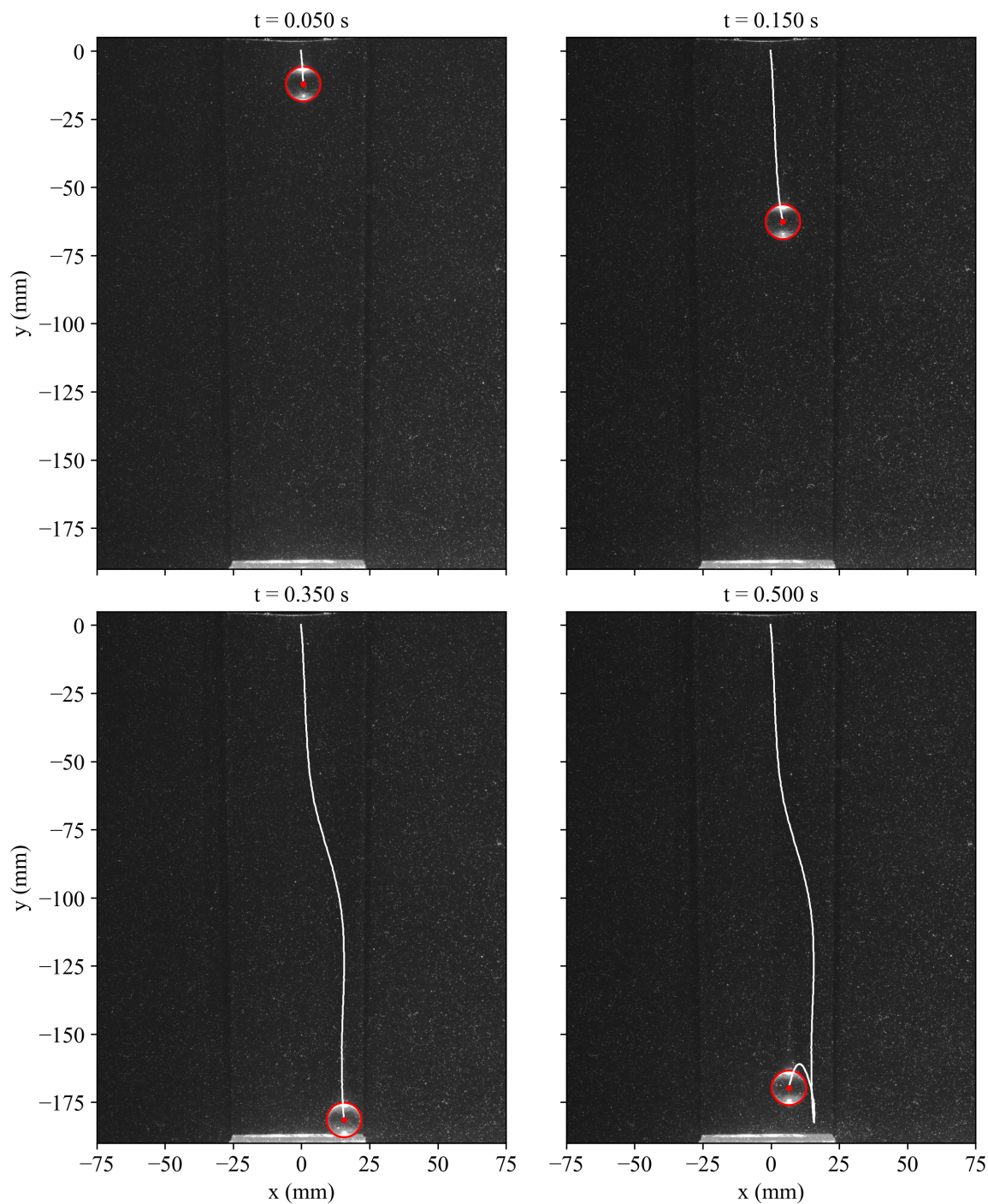


Figure 2. Digital object tracking (DOT) result for flat wall geometry and four time instants representative stages of the tracked sphere. The detected sphere position is indicated by the red circle, while the white line shows the accumulated trajectory. The sequence illustrates stable trajectory tracking during: descending motion (upper left and right); impact (lower left); and last frame (lower right).

3. Results

3.1. Settling of the sphere

The observed trajectories of the free-falling sphere are shown in Fig. 3. The sphere begins to deviate from the vertical trajectory once the running distance exceeds $L/D > 5$. Therefore, the convex and concave targets had to be placed with an offset to the initial sphere location, and the experiments were repeated until the sphere hit the target at its center point. A possible small initial lateral trend of the sphere trajectory may be associated with the suction-based release mechanism. During detachment, the release process could introduce a small asymmetric flow disturbance, which may subsequently influence the sphere's motion and wake development.

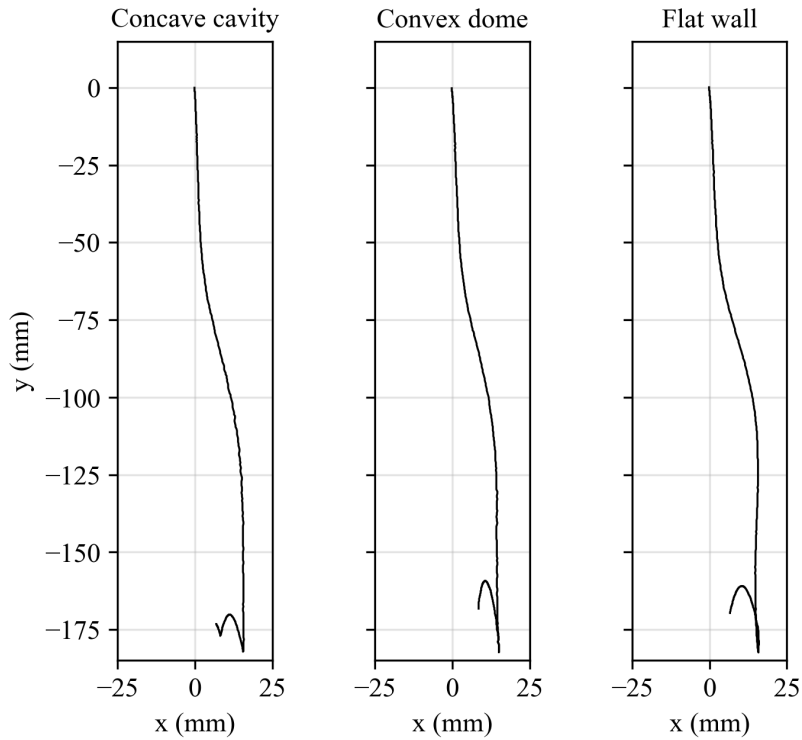


Figure 3. Sphere x - y plane trajectory for three wall geometries: concave cavity (left), convex dome (middle), flat wall (right). Trajectories are shown in physical coordinates obtained from the DOT analysis.

Young et al. (2022) report similar behavior for falling spheres in a viscous fluid and discuss the correlation between pressure dynamics and vortex shedding for spheres falling in a fluid with non-axisymmetric flow and $Re = 2000$. For running distances $L/D > 5$, unsteady vortex shedding induces an asymmetric pressure distribution around the sphere, leading to lateral deflection (Young et al., 2022). The role of vortex-pressure dynamics in the out-of-plane motion of spherical pendulums was also demonstrated by Gold et al. (2024). Based on the present tr-3D-PTV measure-

ments, such vortical structures associated with the sphere wake were identified (Fig. 4).

Analogous vortex-shedding topologies were observed for all configurations during the initial free-fall phase, since the early wake development is independent of the wall geometry. The wake structures are already visible at a falling distance of approximately $L \approx 2D$, as shown in Fig. 4 (a,e,i). The observed sideward motion starting at $L/D > 5$ coincides with the first shedding of a coherent vortex structure (Fig. 4 b,f,j). Additional vortices are shed shortly before impact with the wall (Fig. 4 c,g,k). Following impact, secondary near-wall vortex structures develop for the flat wall and convex dome configurations (Fig. 4 h,l), whereas no comparable secondary vortex formation is observed for the concave cavity (Fig. 4 d).

3.2. Fluid-structure and sphere-wall interactions

The terminal settling velocity of the sphere is estimated from a balance between the buoyancy-corrected weight and the hydrodynamic drag. For a sphere of diameter D and density ρ_s settling in a fluid of density ρ_f , the force balance at terminal conditions reads:

$$\frac{\pi D^3}{6}(\rho_s - \rho_f)g = \frac{1}{2}\rho_f C_D \frac{\pi D^2}{4} U_t^2 \quad (1)$$

where g denotes the gravitational acceleration and C_D is the drag coefficient. Solving for the terminal velocity yields

$$U_t = \sqrt{\frac{4D(\rho_s - \rho_f)g}{3\rho_f C_D}} \quad (2)$$

For the present experiments, with $D = 12.71$ mm and a density ratio $m^* = 2.5$ in water, and assuming a representative drag coefficient $C_D \approx 0.44$, the terminal settling velocity is estimated as

$$U_t \approx 0.75 \text{ m s}^{-1} \quad (3)$$

In the present experiments, the available fall height is limited so that the sphere approaches but does not necessarily reach the terminal velocity prior to interaction with the wall (Fig. 5). The collision was quantified using the definition of the normal coefficient of restitution following Joseph & Hunt (2004). Herein the wall-normal direction corresponds to the vertical motion of the sphere. The restitution coefficient was therefore determined from the ratio of the fitted post- and pre-impact vertical velocity components,

$$e_n = -\frac{U_{p,y,\text{out}}}{U_{p,y,\text{in}}}, \quad (4)$$

where the minus sign accounts for the reversal of the wall-normal velocity across impact.

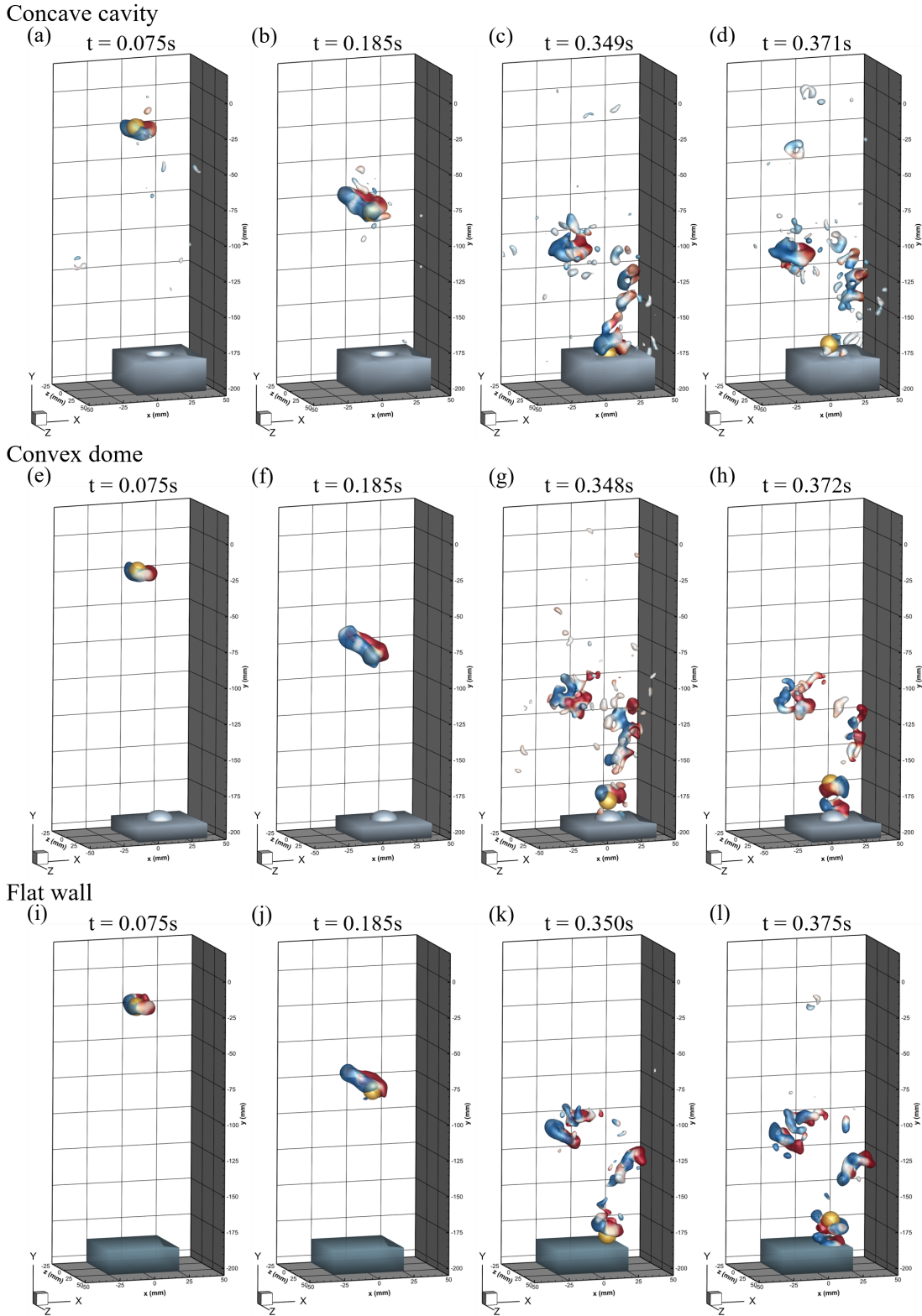


Figure 4. Vortex shedding topology during settling, impact, and rebound of the sphere for the three investigated wall geometries: concave cavity (top row), convex dome (middle row), and flat wall (bottom row), shown at four different time instants. Coherent vortical structures are identified using the Q -criterion and coloured according to the magnitude of the out-of-plane vorticity component ω_z . Analogous wake topologies are observed during the initial free-fall phase, whereas geometry-dependent differences emerge during near-wall interaction and rebound.

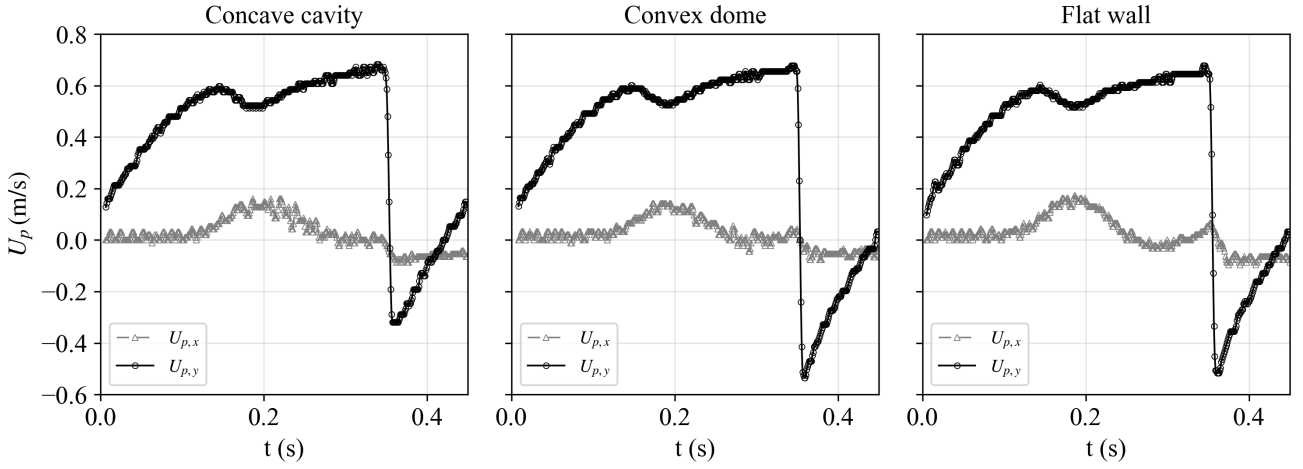


Figure 5. Sphere velocity components ($U_{p,x}$, $U_{p,y}$) as a function of time for the three investigated geometrical configurations: left = concave cavity, middle = convex dome, right = flat wall. Solid black lines represent the vertical velocity component $U_{p,y}$, while dashed grey lines denote the horizontal velocity component $U_{p,x}$. The results illustrate the settling, impact, and rebound dynamics for the different geometrical configurations.

The post-collision velocity shown in Fig. 5 and therefore the restitution coefficient varies with wall geometry. The convex dome and flat wall configurations yield comparable values, with $e_{n,\text{convex}}$ and $e_{n,\text{flat}} \approx 0.80$. In contrast, the concave cavity geometry exhibits a significantly reduced restitution coefficient of $e_{n,\text{concave}} \approx 0.55$. The reduced restitution observed for the concave cavity configuration is attributed to enhanced energy dissipation associated with geometric confinement, increased FSI, and the generation of more complex flow structures, which promote additional momentum dissipation during impact and rebound.

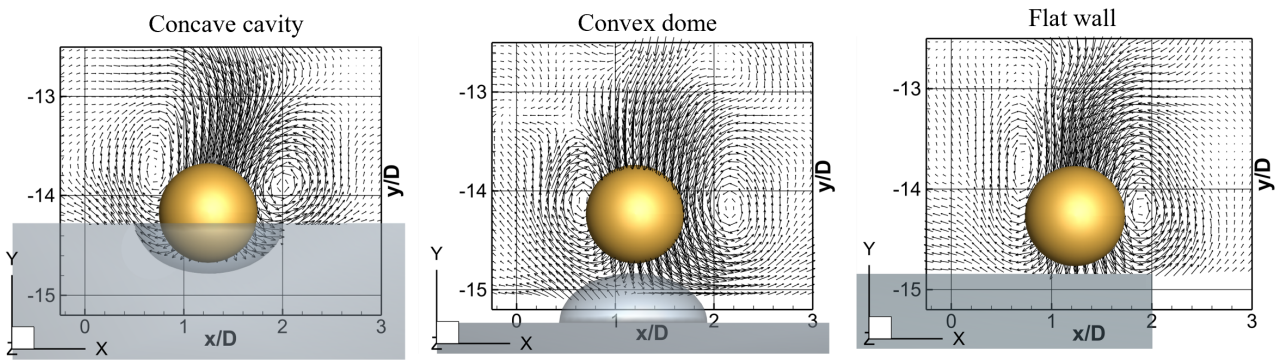


Figure 6. Instantaneous velocity field in the vicinity of the sphere shortly prior (2 ms) to impact with the wall for three different geometries: concave cavity (left), convex dome (middle), and flat wall (right).

During the sphere-wall interaction, different flow structures develop, with the concave cavity exhibiting distinctly different near-wall flow patterns as shown in Fig. 6. For both the convex dome and the flat wall, the fluid primarily deflects sideward. In contrast, for the concave cavity the

sphere must displace a portion of the surrounding fluid, generating flow opposing its initial falling direction. This opposing flow increases damping and contributes to the reduced rebound observed for the concave cavity geometry.

4. Conclusions

The present study experimentally investigated the settling, rebound, and wake dynamics of a free-falling sphere interacting with concave cavity, convex dome, and flat wall geometries using time-resolved tr-3D-PTV measurements. The present DOT analysis was limited to the reconstruction of the sphere trajectory within the x - y image plane, and hence the rebound analysis was based on the projected wall-normal motion. The results showed that the sphere trajectory departs from a purely vertical motion once the travel distance exceeds approximately $L/D > 5$, coinciding with the onset of asymmetric vortex shedding and the formation of coherent vortex structures in the wake. The volumetric flow field measurements further revealed the evolution of near-wall vortical structures during impact and rebound, highlighting the strong coupling between wake dynamics and sphere motion. The rebound behavior was found to depend on the wall geometry. The flat wall and convex dome configurations exhibited comparable rebound characteristics, whereas the concave cavity geometry resulted in a substantially reduced restitution coefficient due to enhanced confinement effects and increased fluid-induced damping. The near-wall flow fields demonstrated that the concave cavity geometry promotes opposing flow motion and enhanced momentum dissipation during impact and rebound. The combined DOT and volumetric tr-3D-PTV measurements provide time-resolved benchmark data for sphere-wall interaction and rebound behavior in different geometrical configurations. The present dataset is therefore suitable for the validation of numerical models addressing convex–convex and convex–concave particle collisions.

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