EPAPS

Anomalous sinking of spheres due to local fluidization of apparently fixed powder beds

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The sphere sinking experiments were performed at the bed heights of 300 mm and 150 mm. The experimental details for the two bed heights will be given separately.

Experimental details at bed height = 300 mm

Materials

Hydrophobic glass beads of diameter 0.21−0.25 mm were used as the powder bed medium. The powder bed density, ρ_{bed} was 1.53 gm/cm^3. Spherical plastic shells of diameter, D_{sphere} = 30 mm with different densities, ρ_{sphere} were used to investigate the sphere sinking phenomenon in the powder bed. Each sphere was attached to one end of a thin string (0.5 mm), and a stainless steel ring (3.8 gm) was attached to the other end of the string as a counter-weight, see Fig. S1. The sphere density ρ_{sphere} and scaled sphere density ρ_{sphere}/ρ_{bed} are shown in Table S1. The sphere densities were adjusted by varying the amount of iron or lead powder inside spherical plastic shells. For example, for a required sphere weight of 21.2 gm needed to give a sphere density ρ_{sphere} = 1.50 gm/cm^3, iron powder was added to the sphere to include the contribution of the counter weight: 21.2 gm + 3.8 gm = 25.0 gm in order to balance to the weight of the stainless steel ring. Spheres of the same weight partially filled with metallic powders of different densities gave the same results.

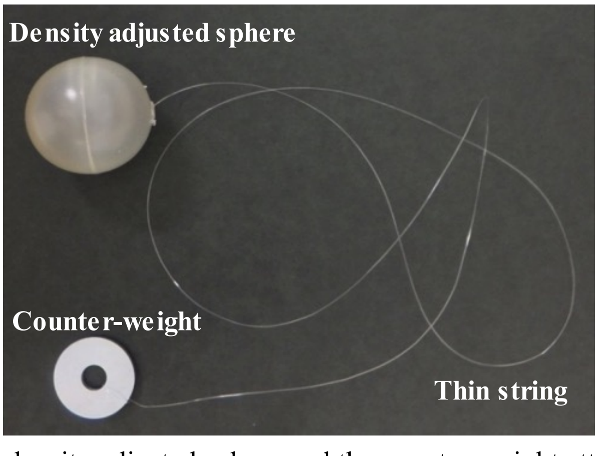

Fig. S1. A picture of the density adjusted sphere and the counter-weight attached to the thin string.

Table S1. Sphere density ρ_{sphere} and scaled sphere density ρ_{sphere}/ρ_{bed}, (ρ_{bed} = 1.53 gm/cm^3)

ρ_{sphere} [gm/cm^3]	1.10	1.30	1.40	1.50	1.66	1.83	2.00	2.50	3.00	3.50	4.00
ρ_{sphere}/ρ_{bed}	0.72	0.85	0.92	0.98	1.08	1.20	1.31	1.63	1.96	2.29	2.61

Experimental apparatus

The experimental setup comprised a cylindrical acrylic container with inner diameter of 150 mm and height of 405 mm set on top of an air distributor and an air chamber. The air distributor was fabricated by holding a piece of cloth between two perforated metal plates (thickness 1 mm) that have an equilateral triangular mesh of holes of diameter 2 mm and pitch 3 mm. Compressed air was fed in the air chamber, and the air was injected into the bottom of the container through the air distributor. The air injection superficial velocity

u_0 = (volume of air injected per second) / (cross-sectional area of the container) [cm/s]

was controlled by a mass flow controller.

Powder bed preparation and determination of minimum fluidization velocity

Establishing a stable initial state of the glass beads in the container was important to obtain reproducible data of the sphere sinking experiments. In particular, a minimum fluidization velocity, u_{mf} (see below for definition) had to be kept constant at each sphere sinking experiment. The u_{mf} was measured as follows.

1) The cylindrical container of diameter 150 mm was filled to a bed height of 300 mm with the glass beads. The glass beads were fluidized at u_0 = 10 cm/s for 1 min.
2) A weight of 5.0 kg was put on the bed surface for 30 sec to obtain a compressed bed.
3) Air at various initialization velocities, u_{init} = 4.6, 6.3, 8.4, 10.0, 10.5 or 12.6 cm/s was injected into the compressed bed for 1 min to fluidize the glass beads to give a fixed (non-compressed and loose) bed as the initial state after the fluidization. Both the fluidized bed height, $h_{fluidized}$ during air injection, and the fixed bed height, h_{fixed} after the air injection was turned off, were measured at each u_{init}. These heights as functions of u_{init} are shown Fig. S2. Note that $h_{fluidized}$ increases with u_{init}, because the bed expands more as u_{init} is increased. On the other hand, h_{fixed} is constant at 300 mm regardless of u_{init}. These results show that identical and reproducible initial state of the glass beads bed can be prepared for sphere sinking measurements.
4) Air was then injected into the fixed bed prepared in this manner by gradually increasing the air velocity u_0 from 0 to 7.1 cm/s. The pressure drop, ΔP across the glass beads was measured using a manometer as u_0 is varied.
5) For low u_0, the pressure drop, ΔP increased linearly with u_0 (Fig. S3) that is characteristic of the Darcy Law of fluid flow through a rigid porous medium – we call this the *apparently fixed* bed regime of the glass powder column. However, for u_0 > 4.4 cm/s, the pressure drop ΔP remained constant at around 4.2 kPa, that is characteristics of the constant pressure drop exhibited by low Reynolds number flow of a viscous fluid along a pipe – we call this the *fluidized* bed regime.

6) The minimum fluidization velocity, u_{mf} is determined as the "transition point" between the linearly increasing *apparently fixed* bed and the horizontal *fluidized* bed regimes of the ΔP vs u_0 data (see Fig. S3).
7) The steps 1) to 6) were repeated three times for each u_{init} (Fig. S3) to determine the mean value of u_{mf}. As shown in Fig. S4, u_{mf} increased slightly with u_{init} for u_{init} between 4 cm/s to 8 cm/s and reached an almost constant value of 4.48 cm/s for u_{init} > 8.0 cm/s. The results also show that the use of a 5 kg weight to compress the bed (Step 2) did not affect this limiting value of u_{mf}.

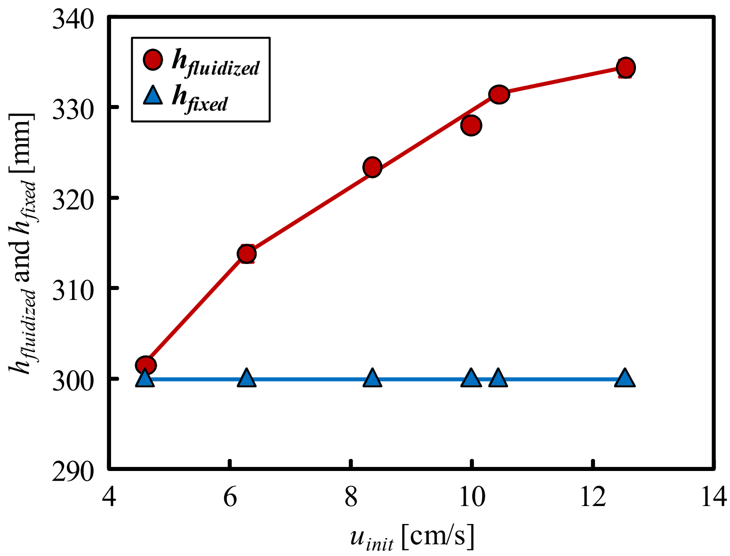

Fig. S2. The fluidized bed height $h_{fluidized}$ and the fixed bed height h_{fixed} as a function of u_{init}.

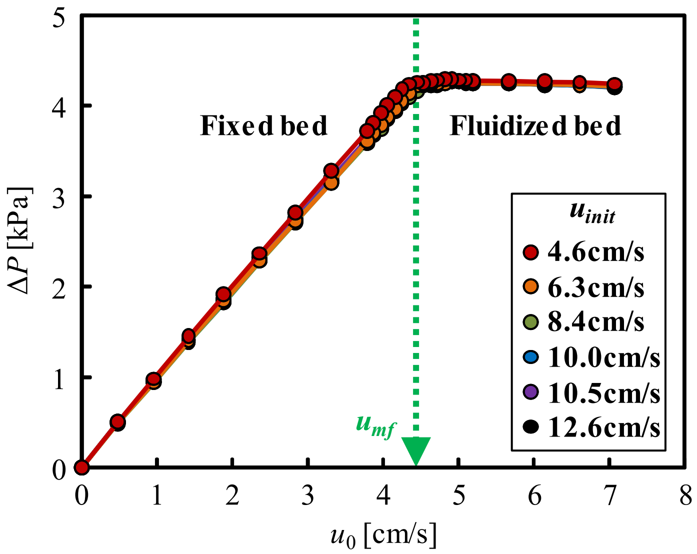

Fig. S3. The pressure drop ΔP as a function of u_0.

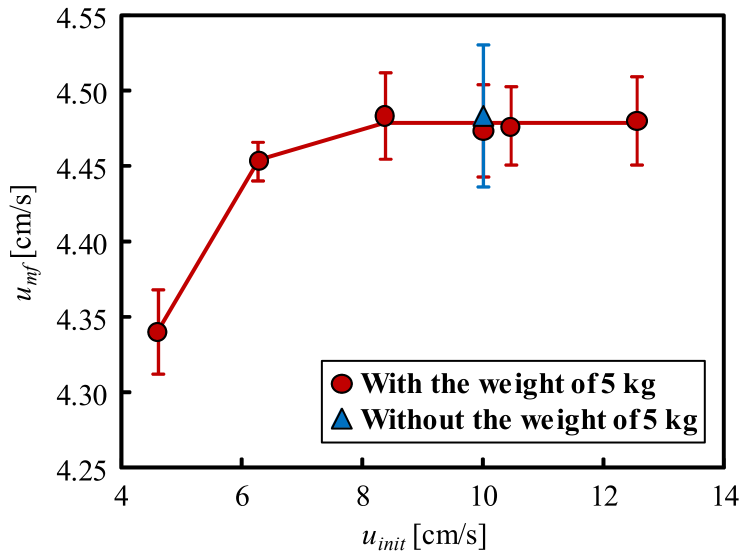

Fig. S4. The minimum fluidization velocity u_{mf} as a function of u_{init}.

These results indicate that u_{mf} can be kept constant if the glass beads are fluidized at u_{init} > 8.0 cm/s in Step 3) above in the bed preparation method. This means that the powder bed preparation procedure gave a reproducible state of the fluidized bed.

It is common practice to apply a static weight to the bed in Step 2) after the initial fluidization of the bed in Step 1). However, as seen in Fig. S4, the limiting value of u_{mf} (4.48 cm/s) is, within experimental uncertainty, independent of whether the weight in Step 2) was applied or not. Therefore in preparing the bed for our experiments we omit the application of a static weight in Step 2).

Sphere sinking experiment

The initial state of the glass beads was prepared according to the above protocol. The powder bed of glass beads, 300 mm in height was fluidized at u_0 = 10 cm/s for 1 min before the first sphere sinking experiment and repeated to prepare the initial state for subsequent experiments.

The sphere sinking experiments in the powder bed were performed with the aid of a pulley system shown schematically in Fig. S5. In order to work with an apparently fixed bed, the air injection superficial velocity was set at u_0/u_{mf} = 0.95 (< 1). At this superficial velocity, the powder bed had the same height (300 mm) as in the absence of air injection and air bubbles were not observed to percolate from the bed surface (see Fig. S2). The thin string was passed through the pulley system so the bottom of the sphere just rested on the bed surface and held at the counter-weight by hand.

Each sphere sinking experiment was started by releasing the counter-weight. When the sphere sank, the rise of counter-weight was measured using a scale mounted on the outside wall of the container. The ascent of the counter-weight was recorded at a rate of 210 frames per second for 10 min by the video camera1. Simultaneously, the motion of the sinking sphere at the bed surface was recorded at a rate of 30 frames per second by the video camera2. The sphere sinking experiment was repeated three times for each sphere of density, ρ_{sphere} (see Videos S1-S5).

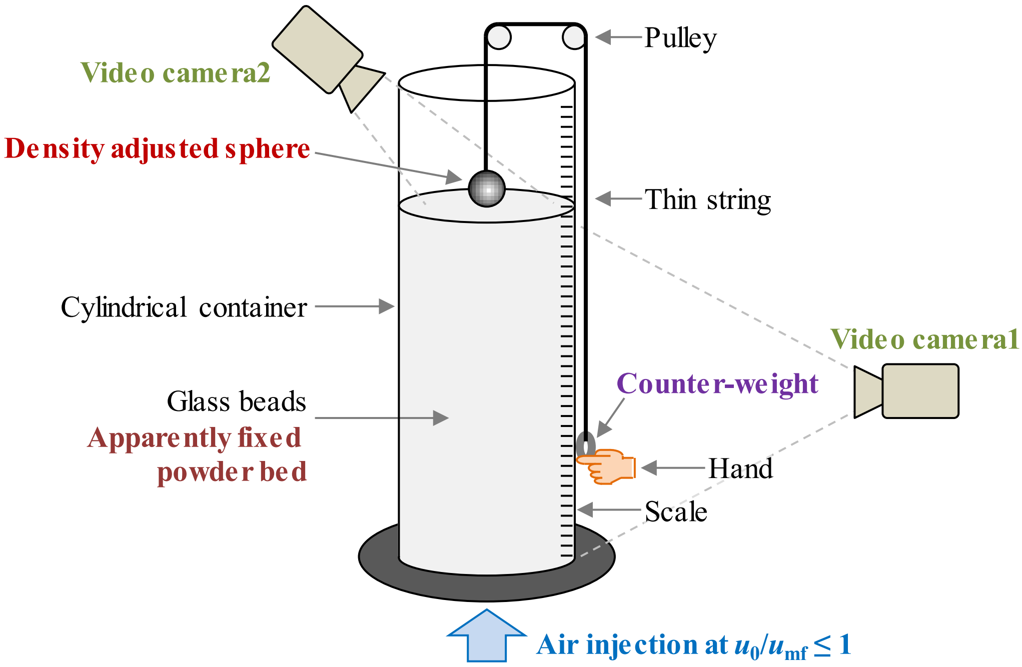

Fig. S5. A schematic drawing of the experimental setup used for the sphere sinking experiments at the bed height = 300 mm.

The recorded movie of the counter-weight ascent was used to obtain data of the sphere position inside the bed as a function of time. The position of the counter-weight and the thin string was measured using the scale, and was converted to the position of the bottom of sphere within the bed. The distance between the sphere bottom and the bed surface was regarded as the sinking depth h. The sinking depth was divided by the sphere diameter D_{sphere} = 30 mm to obtain the scaled depth h/D_{sphere}. The bottom of the container is at h/D_{sphere} = 10 as the bed height was 300 mm. The scaled "final" depth h_{final}/D_{sphere} was used to compare the sinking of spheres of different densities. For each sphere of density, ρ_{sphere}, movies of three repeat measurement of each sinking experiment were used to obtain mean value of h/D_{sphere} and h_{final}/D_{sphere}.

Experimental details at bed height = 150 mm

The glass beads as the powder bed medium and the apparatus consisted of the cylindrical container were same as those used at the bed height = 300 mm. The cylindrical container was filled to a bed height of 150 mm with the glass beads. The density adjusted spheres of diameter, D_{sphere} = 30 mm were also prepared by the same as above. Each sphere was attached to the string, but the counter-weight was not attached to the other end of the string to simplify the experiments.

The method of conducting the sphere sinking experiments at the bed height = 150 mm was slightly different from that with a 300 mm bed. Firstly, the glass beads were fluidized at u_0/u_{mf} = 1.1 and the sphere was then lowered into the fluidized bed by hand until the top of the sphere sinks just below the bed surface. Then the air injection was stopped so that the sphere remained just below the bed surface. Then air at various superficial velocities, $0.8 \leq u_0/u_{mf} \leq 1.1$ was injected into the bed to start the sphere sinking. By doing so, we eliminated the effect of the sphere having to pass through the bed surface on the sinking depth. The length of the string below the bed was measured after three minutes. The distance between the sphere bottom and the bed surface was calculated by adding the sphere diameter (30 mm) to the string length, and was regarded as the final sinking depth h_{final}. It should be noted that it was not possible to define the string length below the bed when the sphere floats (h_{final} < 30 mm, the sphere diameter). In this case, the value of h_{final} was regarded as 0. The final sinking depth was divided by the bed height h_{bed} = 150 mm to obtain the scaled depth h_{final}/h_{bed}.

Supplemental Video Legends:

Video clips from two camera perspectives of experiments of a 30 mm diameter sphere sinking in a 300 mm deep, apparently fixed powder bed of glass beads (diam 0.21-0.25 mm) at u_0/u_{mf} = 0.95 that correspond to the experiments in Fig. 2a of the main text.

	Sphere density ρ_{sphere} [gm/cm^3]	Scaled sphere density ρ_{sphere}/ρ_{bed}
Video S1	1.30	0.85
Video S2	1.50	0.98
Video S3	2.00	1.31
Video S4	3.00	1.96
Video S5	4.00	2.61

Video S6: Videos of the top view of the powder bed for spheres at densities ρ_{sphere}/ρ_{bed} = 0.85, 0.92, 0.98, 1.08, 1.20, 1.31, 1.96 and 2.16 at u_0/u_{mf} = 0.95.

Video S7: Animated comparison of the time dependence of the depth of the sinking spheres of the 5 densities in Fig. 2a of the main text. The animation is played back on a frame rate that is logarithmic in time.