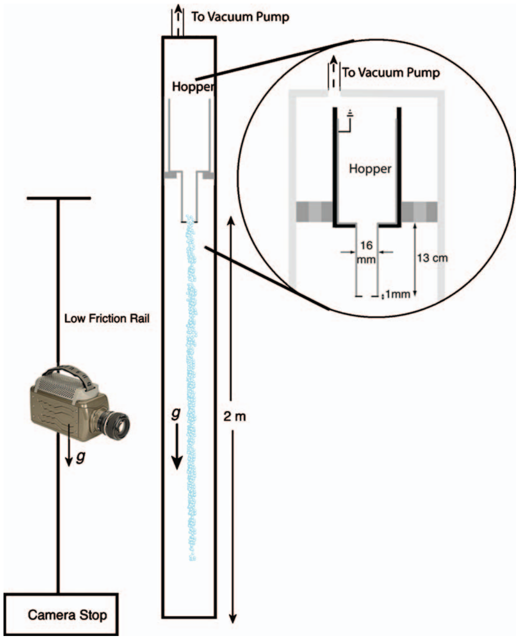

FIG. 1. (Color) Schematic of falling camera setup.

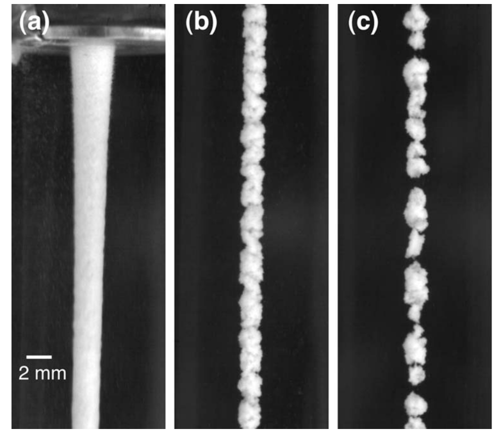

FIG. 2. Breakup of a stream of 54 μm grains captured with a free falling camera. [(a)–(c)] Images of a stream of $d=54$ μm glass grains falling out of a 4 mm diameter nozzle. (a) Just below the nozzle, (b) 20 cm, and (c) 55 cm from the top of the frame to the nozzle. The chamber is evacuated an ambient pressure of 0.05 kPa (enhanced online).[URL: http://dx.doi.org/10.1063/1.3211191.1]

Rupture and clustering in granular streams

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It is a common, well-known occurrence for a thin liquid stream to break up into droplets due to the surface tension of the liquid.[1] Surprisingly, this effect can also occur in granular materials, where an initially uniform stream of grains breaks up into discrete clusters, or droplets, of grains, even though granular materials are generally considered to lack surface tension. Using a high-speed camera in free fall, we image the breakup in the comoving frame with the freely falling granular stream. This allows us to track the onset of clustering and the subsequent cluster evolution in detail. By eliminating gravity and performing experiments in vacuum to reduce air drag, we can minimize the external forcing so only the interactions between the grains remain. Using these free falling streams, it is possible to investigate weak forces normally masked in other granular experiments and observe the vestiges of any residual surface tension.

A rough schematic diagram is shown in Fig. 1. A 9 cm diameter reservoir of grains feeds a nozzle that consists of a porous, 13 cm long, 16 mm diameter cylinder with a flat disk at the base containing a circular aperture. A remote controlled shutter beneath the nozzle is used to initiate and stop the flow, allowing the grains to be stored in the hopper under vacuum for long periods of time.

The nozzle and reservoir of grains are housed in a 2.5 m high acrylic tube, which is sealed and evacuated to as low as 0.03 kPa to reduce air drag. We observe the evolution of the falling stream using a high-speed camera (Phantom v7.1) falling along a low friction rail outside of the chamber. This allows us to image a 3 cm section of the stream as it falls 2 m from the nozzle to the bottom of the chamber with a resolution of 0.04 mm/pixel at a frame rate of 1000 frames per second.

Figure 2 illustrates the breakup process for a stream of $d=54$ μm diameter glass spheres emerging from a 4.0 mm diameter nozzle under vacuum [Fig. 2(a)]. The stream maintains its sharp boundaries as it falls, with very little loss of grains to the sides. As the stream accelerates under gravity, an axial velocity gradient develops and elongates the stream as it falls. While the stream stretches, initial undulations emerge and deepen [Fig. 2(b)], creating clusters connected by thin bridges a few grains wide [Fig. 2(c)]. These bridges eventually rupture as the clusters continue to separate. After the clusters have separated, the gaps between the clusters continue to grow while the clusters maintain a nearly constant size and shape.

Directly measurements of grain-grain interactions using atomic force microscopy reveal that the cluster formation is driven by minute, nanoNewton cohesive forces due to a combination of van der Waals interactions and capillary bridges between nanoscale surface asperities.[2] The shapes of these weakly cohesive, nonthermal clusters of macroscopic particles closely resemble droplets resulting from thermally induced rupture of liquid nanojets and ultralow surface tension fluids. Removing gravity and all other external forces makes these free falling streams both an exquisite probe of the weak interactions between grains and a unique system to explore the ultralow surface tension fluid regime in the absence of thermal fluctuations.

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