Recirculation cells for granular flow in cylindrical rotating tumblers (supplementary material)

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FIG. 1. Colored vertical slices of particles to show the drift. The tumbler is filled at 50% with 2 mm particles and rotates at 15 rpm. (a) Initial vertical bands of particles; (b) particle positions after exactly 2 passes of the particles through static zone and flowing layer.



FIG. 2. Displacement vector map measured on a plane perpendicular to the free surface and including the rotation axis. The displacement vectors have been artificially increased by a factor of 3 to visualize the central recirculation cell. The 0.14 m long tumbler is 30% full and rotating at 15 rpm. The upper blue curve is the free surface, and the lower black curve is the boundary where the flow velocity is zero (in the laboratory reference frame).



FIG. 3. Displacement vector map measured on a plane perpendicular to the free surface and including the rotation axis. The 0.28 m long tumbler is a 30% full and rotating at 15 rpm. If the vector map of the 0.14 m long tumbler is superimposed while matching the left endwall, the vectors almost perfectly coincide. The upper blue curve is the free surface, and the lower green curve is the boundary where the flow velocity is zero (in the laboratory reference frame). The vertical dashed lines indicate the boundary between the endwall and the central recirculation cells. To reduce overlap, the vector lengths are divided by a factor of 2.



FIG. 4. Full displacement vector map of the end wall recirculation cell for various fill levels: (a) 25%, (b) 40% and (c) 50%. The tumbler is 0.14 m long and rotates at 15 rpm. The dashed lines indicate the boundary between the endwall and the central recirculation cells. To reduce overlap, the vector lengths are divided by a factor of 2. $_{5}$



FIG. 5. Particle trajectory curvature measured along 0.28 m long cylindrical tumbler for various fill levels from 25% to 50%, and a rotation speed of 15 rpm.



FIG. 6. Particle trajectory drift measured along a 0.28 m cylindrical tumbler for various fill levels from 25% to 50%, and a rotation speed of 15 rpm.



FIG. 7. Displacement vector map of the end wall recirculation cell for various fill levels: (a) 25%, (b) 40% and (c) 50%. The tumbler is 0.28 m long and rotates at 15 rpm. If the vector map of the 0.14 m long tumbler is superimposed while matching the left endwall, the vectors almost perfectly coincide. The dashed lines indicate the boundary between the endwall and the central recirculation cells. To reduce overlapping, the vector length are divided by a factor of 2.



FIG. 8. Particle trajectory curvature measured along 0.28 m long cylinder for various rotation speed (2.5 to 30 rpm) and a fill level of 30%.



FIG. 9. Particle trajectory drift measured along a 0.14 m cylindrical tumbler filled at 30% for various fill levels friction coefficient of the endwall. The friction coefficient of the cylinder wall is kept at $\mu = 0.7$ to avoid any transition from rolling to slumping regime.