Supplementary Materials for Suspension flow past a cylinder: particle interactions with recirculating wakes

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1. Dynamics of a single particle released in the free stream

Figure 1 shows a single particle released in the free stream, which is displaced laterally as it passes by the cylindrical post and remains separated from the wake region. The same basic behavior is observed starting from various initial locations in the y direction, with the displacement reduced for larger $|y|$. Basic features of the trajectory of a particle in the free stream are independent of the particle size. No entry to the wake was observed at any position of release for the particle-to-cylinder size ratios studied. The single particle motion in the free stream is also shown in *Movie1*.

2. Stable motion of a particle pair on limit cycle

The formal limit cycle behavior is not limited to a single particle. A pair of particles of the same size simultaneously released into one lobe of the recirculating wake are also observed by simulation to reach a stable periodic motion, with each following the same trajectory on the limit cycle. Owing to the different velocity at different points on the limit cycle trajectory, the separation between the two particles along the trajectory varies as the pair executes the cyclic motion. However, particle pairs attain an equilibrium separation in their periodic motion inside the wake, as illustrated in figure 2. Figure 2 (a) shows the trajectories of particle pairs for two sample initial configurations. For clarity, trajectories are demonstrated on separate lobes of the wake, but only two particles are released in either case. Figure 2 (b) shows that the magnitude of the separation between pairs reaches a steady periodic state which is equal for all pairs, regardless of the initial separation between particles. The pair motion is demonstrated in *movie4*.

3. Average distribution of particles in the flow domain

We present the solid fraction distribution in figure 3 for $\delta = 0.09$ and 0.16 at $Re = 24$ and $\phi = 0.06$. The average particle distribution is indicative of the likelihood of finding particles at any point in the flow domain after attaining steady state flow. Note that there is an average decrease in the number of wake particles with time; therefore, there might be slight variation in the probability distribution of wake region particles. We

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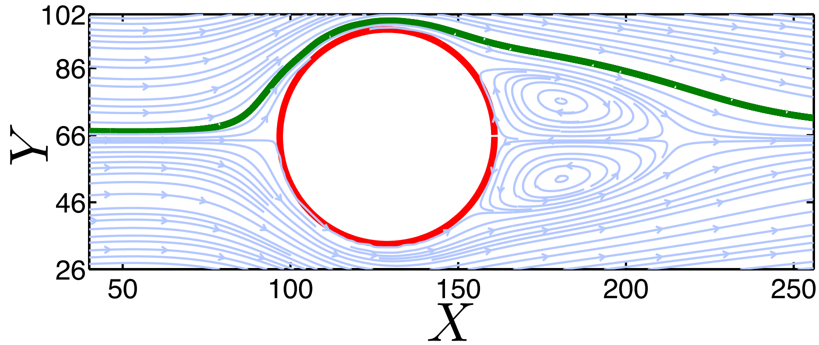
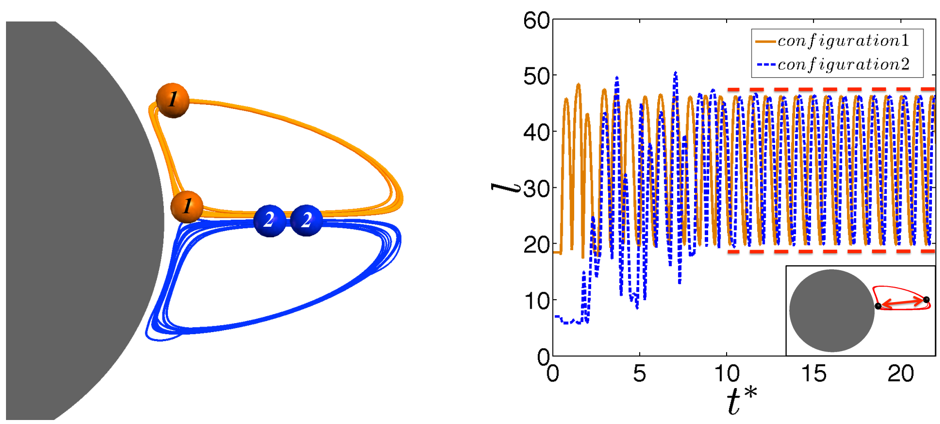


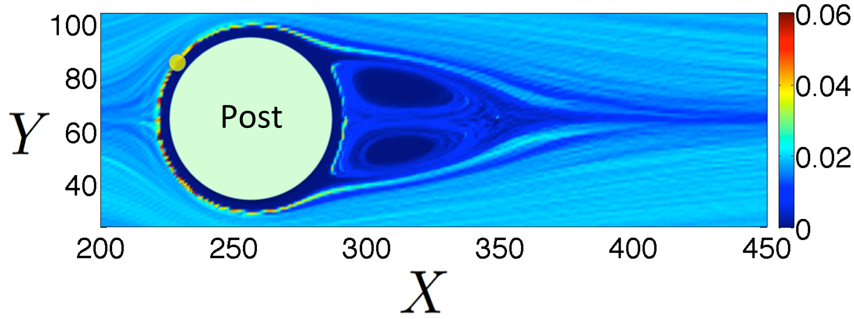
FIGURE 1. Trajectory of a single spherical particle released in the flow at $Re = 18$: A single particle released in the free stream passes the cylindrical obstacle without entering the wake region



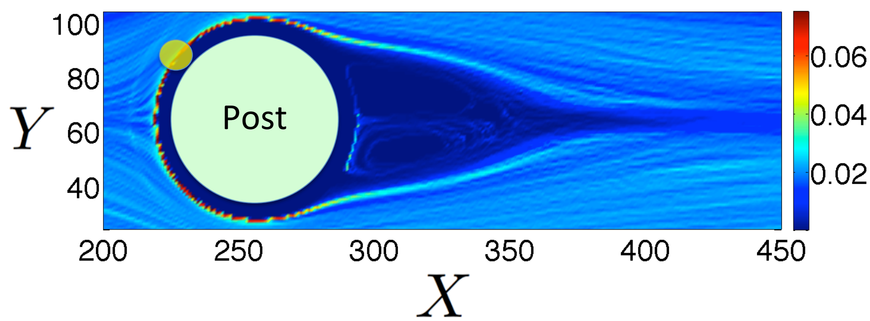
(a) (b)

FIGURE 2. The limit cycle for a pair of equal-sized ($\delta = 0.09$) particles. (*a*) Trajectories of the particles in a pair for two sample initial configurations. For more clarity, trajectories are demonstrated on separate lobes of the wake (*b*) The separation measured along the limit cycle, l, between a pair of particles moving on the limit cycle trajectory plotted as a function of dimensionless time, $t^* = \frac{tD}{U}$. The figure inset demonstrates the definition of l. The periodic separation, indicated by dashed lines, is the same for all initial pair configurations of particles in a pair.

see in figure 3 a region of large probability at the leading edge of the cylindrical post in contact zones. This large probability zone extends to the back of the obstacle and appears as two large probability bands that form around the wake. A depleted probability zone forms in the neighboring regions of these bands in the free stream. Because the particle densities are calculated using the particle centers, the depleted zone corresponds to the excluded volume effect between particles in the band and neighboring particles. In both figures, particles in the wake accumulate near the boundaries and the core of the wake is largely depleted of particles, consistence with the experimental observation of the largely particle-free wake zone behind the obstacle.



(a)



(b)

FIGURE 3. Probability distribution of the particles in the flow domain at $\phi = 0.06$ for $(a)\delta = 0.09$ and $(b)\delta = 0.16$. The core regions of the wake is depleted. A high probability zone forms in the front side of the post and extends to the back and engulfs the wake region.

4. Movies

We have provided movies of our simulations which include:
Movie1: Motion of a single particle released in the free stream for $\delta = 0.09$ and $Re = 18$.
Movie2: Motion of a single particle released inside the wake region toward the limit cycle for $\delta = 0.09$ and $Re = 18$.
Movie3: The stable motion of a pair of particles released on the limit cycle for $\delta = 0.09$ and $Re = 18$. Four initial separations are demonstrated in the movie.
Movie4: The dynamics of multiple particles released inside the wake region for $\delta = 0.09$ and $Re = 18$.