Advances in microfluidics have motivated a number of recent studies to optimally balance the friction and form drag and control resistance to laminar flows over objects with nanostructured surfaces. © 2010 American Institute of Physics.

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Nanostructured surfaces offer opportunities to modify flow induced drag on solid objects. Measurements of the terminal velocity reveal that the drag associated with laminar Stokes flows can be reduced for spheres with nanostructured superhydrophilic as well as superhydrophobic surfaces. Numerical simulations suggest that the formation of recirculating or nearly stagnant flow zones leads to significant reduction in the friction drag. Such reduction, however, is offset by an increase in the form drag that arises from nonuniform pressure distributions. Our work motivates further studies to optimally balance the friction and form drag and control resistance to laminar flows over objects with nanostructured surfaces.

Controlling flow induced drag on solid objects has long been a subject of scientific as well as technological interest. Advances in microfluidics have motivated a number of recent studies on surface treatment and texturing methods for drag reduction. In particular, several studies1–3 reported that one can achieve appreciable reduction in resistance to laminar liquid flows by using so-called superhydrophobic surfaces, which create a composite (solid and gas) interface with the liquid. This leads to apparent velocity slip and hence reduced surface friction since the viscosity of gases is orders of magnitude smaller than that of liquids.

For fully wettable surfaces, in contrast, one may expect surface roughness to impede liquid flows and thereby, increase the associated drag. This was indeed demonstrated both experimentally and theoretically for laminar liquid flows along microchannels with lithographically defined microscale roughness.4 From a simplistic consideration of increased liquid-solid contact areas, one would expect a similar trend for external liquid flows over objects with rough hydrophilic surfaces.

In this article, we report a rather counterintuitive experimental observation that the drag associated with laminar Stokes flows over macroscale spheres can be reduced by forming superhydrophilic as well as superhydrophobic nanostructured surfaces. Given that the surface area of spheres increased substantially after nanostructuring, we find drag reduction, albeit small in absolute magnitude, to be remarkable for the spheres with superhydrophilic surfaces. We perform numerical simulations of Stokes flows over spheres with much simplified surface topology to gain a further physical insight.

A convenient, yet precise way to characterize the flow resistance over a solid object is to drop the object in a quasi-infinite pool of liquid and measure its terminal velocity. The terminal velocity is determined by balance between the gravity force and the drag force exerted on the object by the surrounding fluid. This approach has the advantage that the terminal velocity can be measured much more precisely than flow rates or pressure.

We use two groups of commercially available copper spheres of different nominal diameters. The diameters are measured using a calibrated micrometer with a precision of 0.001 mm. The average values are 1.598 and 1.980 mm, matching the nominal values provided by the supplier to within 1%. The standard deviations in the measurements are 0.002 mm and 0.001 mm, respectively. The mass of each sphere (19.0 and 36.4 mg) is determined from the measured mass of randomly selected groups of 20 spheres. The standard deviations are less than 0.05 mg, which is the estimated precision of our mass measurements. The mass values also agree with the values calculated using the density of Cu and the measured diameters of the spheres to within 0.05 mg.

We perform terminal velocity measurements on spheres with three different types of surfaces such as: normally smooth surfaces of the as-received Cu spheres, nanostructured superhydrophilic surfaces, and nanostructured superhydrophobic surfaces. Lithography-based micro/nanofabrication techniques can produce features of ordered geometries that may potentially yield more enhanced drag reduction but they are difficult, if not impossible, to apply on three-dimensional (3D) objects. We instead use a quasiself-limiting chemical oxidation scheme reported earlier5,6 to form uniform and dense high-aspect-ratio CuO nanostructures of height approximately 1 μm over the entire sphere surfaces. The scanning electron microscopy (SEM) images of an as-received Cu sphere and the same sphere after nanostructuring are shown in Fig. 1. There are less than 0.1% changes in both the diameter and the mass of the spheres before and after oxidation. The contact angles of water and glycerin on flat Cu surfaces treated using nominally identical procedures as the spheres are measured using the sessile drop technique.7 The measured contact angles of water and glycerin are 70°–80° for the as-received Cu samples, below 10° for the nanostructured Cu surfaces, and 155°–165° after Teflon® coatings are applied on the nanostructured surfaces.
We estimate the roughness factor \( r \) to be approximately 10 and the solid fraction \( f_s \) to be approximately 0.03 using the models of Cassie and Wenzel.\(^5\)

![Image](a) (b)

FIG. 1. SEM images of the nominally smooth and nanostructured surfaces of Cu spheres used in the study.

A transparent acrylic tube of 76.2 mm in diameter and 0.6 m in height is filled with glycerin. We choose glycerin as our fluid to ensure that flows stay within the Stoke’s regime (Reynolds number < 0.1) for all cases and that the surface effect can be best elucidated. To prevent complications arising from trapped bubbles, the spheres are prewetted with glycerin degassed in a vacuum chamber before they are dropped into the tube.

Two time-synchronized charge coupled device video cameras located 0.1 and 0.6 m below the free surface are used to measure the transit time, from which we calculate the terminal velocity. The camera locations are determined by the settling distance\(^8\) to ensure that the sphere terminal velocity. The camera locations are determined by using to measure the transit time, from which we calculate the velocity camera operating at 1000 frames per second is used to confirm the linearity and reproducibility of the measured sphere trajectories at different time intervals and locations.

The experimentally measured terminal velocity for the spheres is shown in Fig. 2. The velocity is normalized with respect to the value obtained from the smooth spheres. Each error bar represents the standard deviation of 6 independently measured values in one set of experiments. The reproducibility of the data is confirmed by repeating the experiments over multiple days and using different experimental setups. The theoretically predicted terminal velocity agrees with the data for the nominally smooth spheres to within 0.5%. A small wall effect resulting from the finite size of our tube is accounted for using a correlation reported earlier\(^9\)

\[
V = V_s \left( \frac{1 - d/D}{1 - 0.475d/D} \right)^4
\]

here, \( V_s \) is the terminal velocity predicted for an infinite liquid pool, \( d \) is the diameter of the sphere, and \( D \) is the diameter of the tube. The viscosity of glycerin is independently measured using Brownian microscopy.\(^10\)

As expected, the largest terminal velocity is observed for the spheres with superhydrophobic surfaces. The observed increase is approximately 2%, smaller than ~8% increase reported by McHale et al.,\(^3\) who used spheres with much higher roughness (350 \( \mu \)m compared with the current 1 \( \mu \)m). The remarkable observation from our experiment is that even rough superhydrophilic surfaces can lead to a finite increase in the terminal velocity. Given that the surface area of the spheres increased substantially (estimated \( r = 10 \)) after nanostructuring, we find the increase, albeit small in absolute magnitude, to be surprising. The measured changes in the cube and diameter of the spheres are less than 0.1% before and after the nanostructuring and such systematic error cannot explain the observed increase in the terminal velocity.

A parameter commonly used to characterize drag reduction resulting from a surface treatment is the effective slip length \( a \). We first derive an analytic solution to the Stokes equation with the slip condition specified for the circumferential velocity component at the surface: \( u_\theta = a (\partial u_\theta / \partial r) \). The total drag force is then calculated by integrating the shear and pressure force over the surface of the sphere

\[
F_D = \pi \mu U \left( \frac{2D^2 - 2aD}{D + 4a} + \frac{D^2(D + 2a)}{D^2 + 4aD} \right).
\]

This reduces to the familiar expression \( F_D = 3 \pi \mu UD \) for the no slip case (\( a = 0 \)). The slip length calculated using our experimental data is of the order of 10 \( \mu \)m, comparable to values reported in previous studies of superhydrophobic surfaces.

To gain a further physical insight, we solve the 3D incompressible Navier–Stokes equations for a laminar flow past a sphere. Since the computational cost of faithfully representing the geometry of our spheres and surface roughness is prohibitive, we only consider spheres of much smaller diameters (<100 \( \mu \)m) and focus on qualitative features of the flows rather than direct quantitative comparison with the experimental data. The roughness is modeled as an array of truncated cones of height 1 \( \mu \)m, base radius 0.1 \( \mu \)m, and interspacing 0.5 \( \mu \)m, as schematically illustrated in Fig. 3. These parameters are chosen to match the estimated solid fraction and roughness factor. The Reynolds number is set to be the same as that of the actual experiments.

The drag force exerted on a sphere consists of the friction drag, which is induced by viscous shear stress on its surface, and the form drag, which is induced by nonuniform pressure distributions around the sphere. Our simulations

![Image](chart)

FIG. 2. Experimentally measured terminal velocity for three different surface conditions.
show that the friction drag can be significantly reduced due to the formation of recirculating or nearly stagnant liquid zones between roughness features (Fig. 4). These zones separate the main external flow from the solid surface and serve as lubricating layers. Well-defined recirculating zones are observed to form when the ratio between the roughness height and spacing is below approximately 3. Figure 5 shows the predicted radial profiles of the circumferential velocity around a sphere with zero or finite surface roughness. The variable \( r^* \) denotes the radial coordinate normalized by the sphere radius and \( u^*_r \) is the velocity normalized by the free stream velocity. For the smooth sphere, there exists a finite velocity gradient and hence a finite shear stress at the surface. In contrast, for the rough sphere, the corresponding radial gradient is close to zero. The velocity profile asymptotically approaches that of the smooth sphere as \( r^* \) increases.

Unlike the friction drag, the form drag generally increases with increasing roughness. The magnitude of this increase depends on the detailed characteristics of a main flow as well as the geometries of roughness features. For internal flows along a smooth linear channel, for example, the form drag is in principle zero. Increase in the form drag due to surface roughness can easily outweigh any reduction in the friction drag. As a result, the total drag in laminar microchannel flows always increases for hydrophilic roughness. For external flows over blunt macroscale objects, in contrast, the form drag is already significant even for objects with smooth surfaces. Micro/nanoscale roughness features may result in a relatively small perturbation to the overall pressure distribution. The total drag can therefore be smaller for objects when their surfaces are nanostructured. Drag reduction is expected to be more difficult to achieve, however, in high-Reynolds number external flows where the form drag dominates over the friction drag.

In summary, we experimentally demonstrate that nanostructured superhydrophilic surfaces can reduce the resistance to Stokes flows over macroscale spheres. The estimated velocity slip length is comparable to the values reported for planar superhydrophobic surfaces. Numerical simulations are used to elucidate the mechanism of the observed reduction. The formation of recirculating or nearly stagnant flows zones at the surface leads to significant reduction in the friction drag but such reduction is offset by increase in the form drag. Our work motivates further work, especially advanced analytic and numerical models that can efficiently capture flow physics around nanostructured macroscale objects, to achieve a meaningful reduction in the total drag by optimally balancing the friction drag with the form drag.

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**FIG. 3.** Schematic illustration of the model of a sphere with 3D roughness features used in our numerical simulations.

**FIG. 4.** Streamlines around the surface roughness features of different height (\( h \)) to spacing (\( s \)) ratios illustrating the formation of recirculating or nearly stagnant flow zones.

**FIG. 5.** Predicted radial profiles of the circumferential velocity in a Stokes flow over a sphere (8 \( \mu m \) in diameter) with zero or finite surface roughness.