

Supplementary Information

Turbulent Drag Reduction Measured on a Flat Plate Covered with Silicon Tiles of Longitudinal Superhydrophobic Microtrenches in a High-Speed Water Tunnel

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Appendix A: Baseline smooth plate turbulent boundary layer characterization

Figure A1 shows the PIV setup used to confirm fully turbulent flow conditions. Since the transition of the boundary layer developing along the sidewall is not set by a trip, transitional effects upstream of the drag balance at slow tunnel speeds are possible. The smooth reference drag plate was installed, and the water tunnel was operated at freestream velocities (U_∞) ranging from 1.5 to 16.8 m/s (5 to 55 ft/s in 5 ft/s increments). At each speed, velocity profiles were obtained using PIV at two streamwise locations: 27 mm upstream (US) of the drag pan leading edge and 27 mm downstream (DS) of the trailing edge. The PIV field of view was 24 mm in the streamwise (x) direction and 20 mm in the wall-normal (y) direction, centered at the spanwise (z-axis) midplane of the test section. The PIV measurements had a final vector spacing of 0.135 mm.

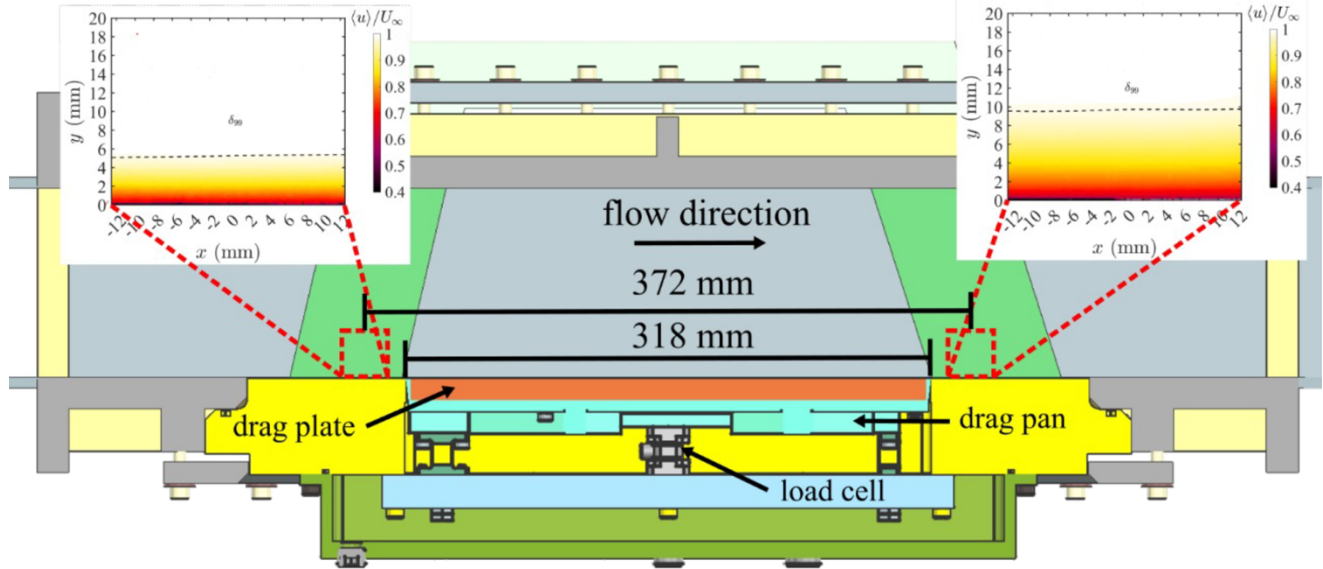


Fig. A1 Boundary layer characterization 2D-PIV setup

The mean velocity profiles, normalized by U_∞ , are plotted against height normalized by the 99% boundary-layer thickness (δ_{99}), as shown in Fig. A2. The results indicate that for the two lowest freestream speeds, 1.5 and 3.1 m/s (5 and 10 ft/s), the US boundary layer profile appears to have laminar and transitional features when compared to the DS profile of the drag balance. In contrast, the measurements at freestream velocities 4.7 m/s (15 ft/s) and greater show that the US and DS profiles have a similar turbulent shape, indicating that the entire drag balance top surface was exposed to turbulent flow for the measurement points at freestream velocities 4.7 m/s (15 ft/s) and greater.

The smooth plate velocity profiles obtained from PIV were used to estimate the friction velocity, $u_{\tau 0}$, and the local skin friction coefficient, C_f . The smooth plate boundary layer parameters are summarized for the US and DS location in Tables A1 and A2. The average of C_{f0} was obtained from the US and DS PIV and matches well with the direct drag balance results and with experiments performed in the same water tunnel facility using a different drag balance (Deutsch et al. 2004, Petrie et al. 2003).

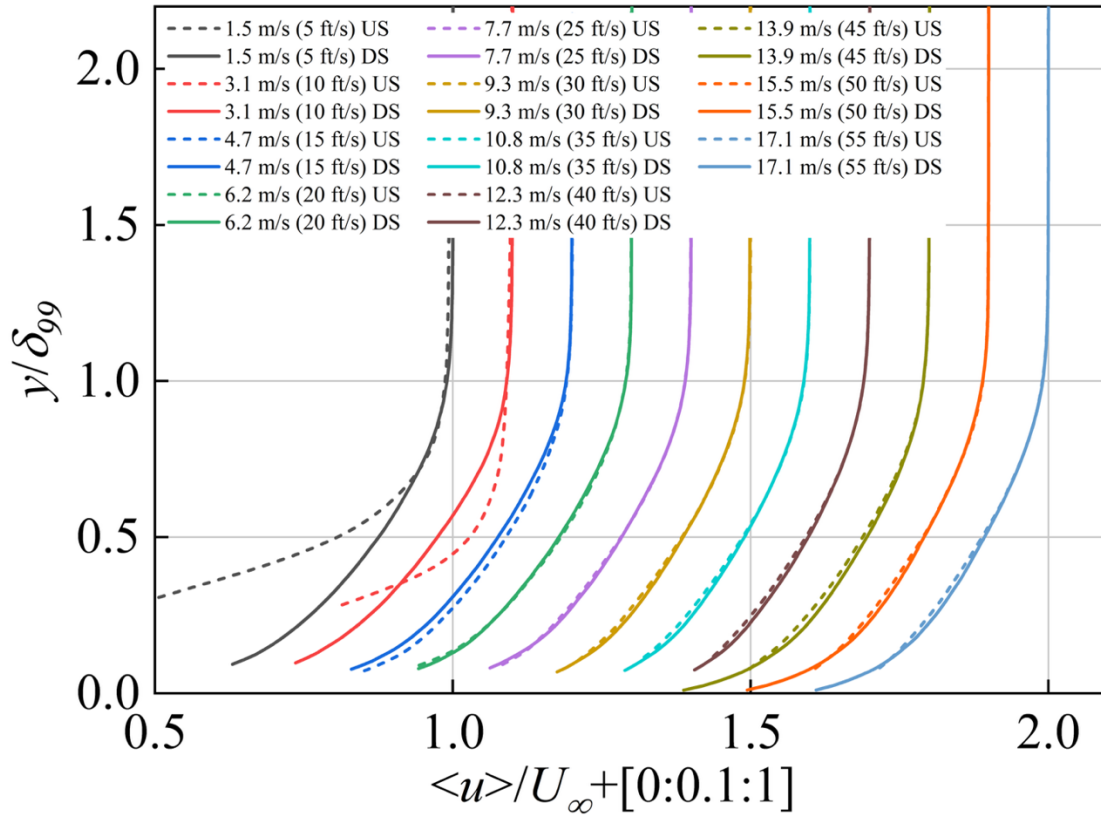


Fig. A2 Mean streamwise velocity $\langle u \rangle$ profiles normalized by U_∞ extracted from the US and DS PIV fields of view. Wall normal coordinate, y , is normalized to the 99% boundary-layer thickness (δ_{99}). Plots are shifted on horizontal axis by $[0:0.1:1]$ for visualization purposes.

Table A1 Boundary layer parameters calculated from upstream (US) PIV for smooth wall reference cases. Entries marked N/A correspond to laminar conditions where turbulent-flow parameters are not defined

U_∞ (m/s)	U_∞ (ft/s)	δ_{99} (mm)	$u_{\tau 0}$ (m/s)	$\nu/u_{\tau 0}$ (μm)	$Re_{\tau 0}$	$C_{f0} \times 1000$ (from PIV)
1.78	5.82	2.62	N/A	N/A	N/A	N/A
3.16	10.37	2.84	N/A	N/A	N/A	N/A
4.67	15.34	5.60	0.193	4.71	1189	3.42
6.20	20.35	5.63	0.248	3.68	1531	3.20
7.76	25.5	5.44	0.302	3.01	1806	3.03
9.30	30.5	5.27	0.349	2.61	2020	2.82
10.8	35.5	5.23	0.401	2.27	2306	2.75
12.3	40.3	5.11	0.456	1.99	2562	2.75
13.9	45.6	5.15	0.514	1.77	2914	2.73
15.5	50.9	4.97	0.571	1.59	3128	2.71
17.1	56.1	4.89	0.606	1.49	3278	2.51

Table A2 Boundary layer parameters calculated from downstream (DS) PIV for smooth wall reference cases

U_∞ (m/s)	U_∞ (ft/s)	δ_{99} (mm)	$u_{\tau 0}$ (m/s)	$\nu/u_{\tau 0}$ (μm)	$Re_{\tau 0}$	$C_{f0} \times 1000$ (from PIV)
1.80	5.9	8.67	0.077	11.84	732	3.66
3.2	10.5	8.29	0.129	6.98	1187	3.23
4.7	15.5	10.4	0.179	5.08	2053	2.85
6.3	20.6	10.2	0.233	3.90	2604	2.75
7.8	25.8	9.92	0.287	3.18	3121	2.67
9.4	30.8	9.61	0.334	2.73	3523	2.51
10.9	35.9	9.64	0.385	2.37	4074	2.47
12.4	40.8	9.39	0.436	2.08	4505	2.46
14.0	46.1	9.46	0.484	1.87	5046	2.37
15.7	51.5	9.07	0.539	1.68	5391	2.36
17.3	56.8	8.95	0.591	1.53	5854	2.33

Drag balance measurements were used to quantify the baseline drag force, F_0 , and the corresponding skin friction coefficient, C_{f0} . The drag force, skin friction coefficients, and associated uncertainties measured via drag balance for the smooth plate are summarized in Table A3. B , u_c , and U_{95} corresponds to bias uncertainty, bias and precision combined uncertainty, and 95% confidence interval, respectively. The baseline Reynolds number, Re_{x10} , was determined using the distance from the virtual origin to the leading edge of the drag pan. The minimum resolvable force of the Kistler load cell and amplifier system was approximately 10 mN, which is well below 1% of the drag forces measured in the present study (1.55–16.4 N), thus was not separately considered. The bias uncertainty was obtained from the calibration residuals, and the precision was obtained from comparing the repeatability of measuring forces from multiple runs in the water tunnel. The bias and precision errors from calibration and repeated testing were calculated to be in the range of 3–7% (of the local mean force) for lower velocities and 1.5–3% for flow speeds greater than 9 m/s.

Table A3 Drag force, skin friction coefficients, and associated uncertainties measured via drag balance for smooth wall reference cases

U_∞ (m/s)	U_∞ (ft/s)	F_0 (N)	$B(F_0)$ (N)	$u_c(F_0)$ (N)	$U_{95}(F_0)$ (N)	$C_{f0} \times 1000$	$u_c(C_{f0}) \times 1000$	$U_{95}(C_{f0}) \times 1000$	Re_{x10}
1.57	5.15	0.46	0.0127	0.0127	0.0403	7.787	0	0	795959
3.04	9.98	0.84	0.0127	0.0136	0.0432	3.761	0.0362	0.0459	1615704
4.57	14.99	1.55	0.0128	0.057	0.1812	3.095	0.138	0.1665	3443363
6.11	20.06	2.55	0.0129	0.0773	0.2461	2.828	0.1492	0.2059	4751243
7.66	25.12	3.8	0.0130	0.0487	0.1551	2.696	0.1441	0.1797	5912434
9.21	30.23	5.29	0.0130	0.0525	0.1672	2.589	0.296	0.4741	7074667
10.72	35.17	7.03	0.0131	0.1225	0.3898	2.543	0.2591	0.3035	8172493
12.19	39.98	8.86	0.0131	0.097	0.3088	2.477	0.139	0.2237	9190056
13.79	45.25	11.14	0.0131	0.0973	0.3097	2.43	0.1394	0.2244	10424883

15.3	50.19	13.62	0.0131	0.1602	0.5098	2.417	0.2276	0.3694	11662741
16.91	55.49	16.35	0.0131	0.1144	0.3641	2.374	0.1633	0.2638	12906132

Appendix B: Downstream velocity profile of smooth vs. SHPo surface

The mean streamwise velocity profiles immediately downstream (DS) of the drag balance for the smooth plate and the P50GF90D100L10 plate are plotted in Fig. A3. At free-stream velocities up to 9.1 m/s, the velocity profiles show a clear flow acceleration near the surface over P50GF90D100L10 compared with the smooth, indicating drag reductions. However, at 10.7 m/s, the velocity profile shows a clear flow deceleration over P50GF90D100L10, indicating drag increase. The uncertainty in the mean velocity measurement ranged 0.1–0.4% of the local mean value, which is negligibly small compared to overall profile.

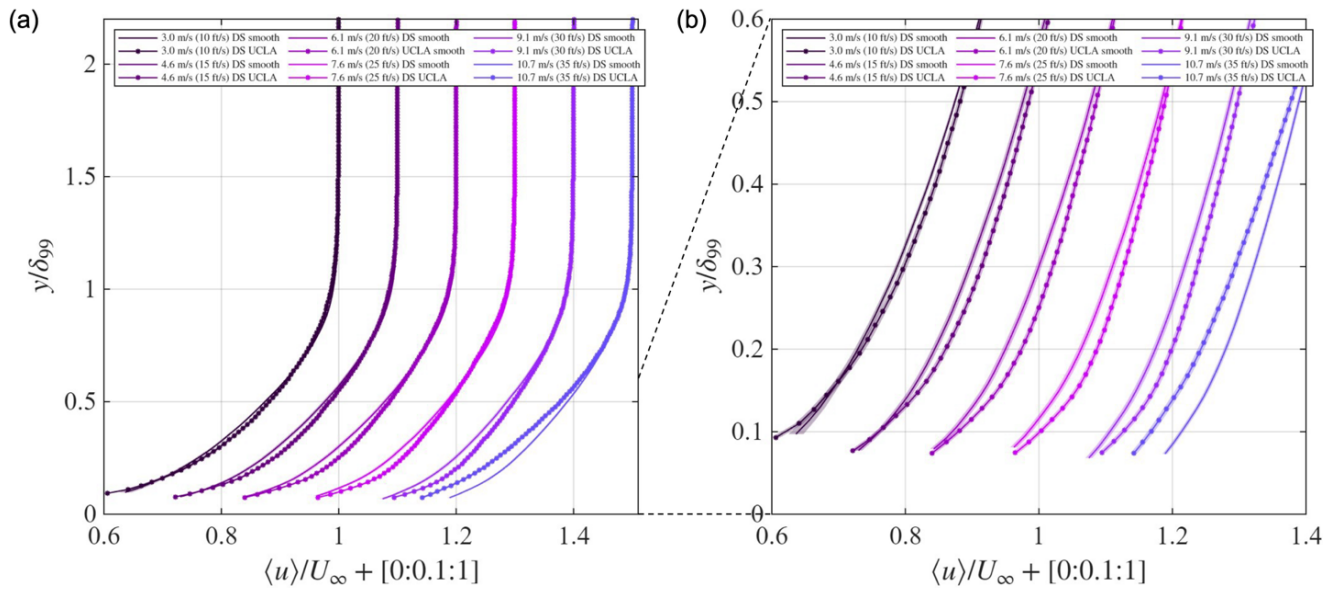


Fig. A3 Mean streamwise velocity profiles immediately downstream (DS) of the drag balance for the reference smooth plate and the P50GF90D100L10 plate. (a) Overall velocity profiles, where the mean velocity and wall normal distance are normalized to the free-stream velocity (U_∞) and boundary layer thickness (δ_{99}), respectively. The velocity profiles are shifted on the x-axis for visualization purposes. (b) A close-up view of (a) with shaded regions denoting 95% confidence intervals

Appendix C: Compensation for the smooth rims around the drag pan and plate

For the low-profile shear comparator involving two floating elements developed by Xu et al. (2020) and successfully utilized (Xu et al. 2020, Xu et al. 2021, Yu et al. 2024), the shear force on a floating element was exclusively that on the sample surface. On the contrary, the shear force measured on the drag pan by the drag balance in the current experimental setting includes the shear forces acting on the smooth rims around the drag pan and those around the drag plate installed in the pan. As a result, the measured shear forces are affected by the smooth rims and do not represent the measured shear forces purely on the tile samples. To compensate for

such deviations and thereby obtain the drag data purely of the SHPo surfaces, a compensation procedure that removes the contribution by the smooth rims from the measured data is introduced. Note that the shear stress decreases in the streamwise direction as a result of the spatial development of the turbulent boundary layer. Considering this decreasing trend, it is necessary to account for streamwise variations when compensating for the smooth rims. Using the empirical relation for wall shear stress in turbulent boundary layer flow, $\tau_0(x) = 0.0288\rho^{4/5}U^{9/5}\mu^{1/5}x^{-1/5}$ (Schlichting and Gersten 2016), the shear forces on different sections on the drag pan can be estimated as follows:

$$F_{all} = b \int_{x_1}^{x_1+a} \tau_0(x) dx = 0.0984U^{9/5}$$

$$F_{front} = b \int_{x_1}^{x_1+r_a} \tau_0(x) dx = 0.002U^{9/5}$$

$$F_{sides} = 2r_b \int_{x_1+r_a}^{x_1+a-r_a} \tau_0(x) dx = 0.0076U^{9/5}$$

$$F_{rear} = b \int_{x_1+a-r_a}^{x_1+a} \tau_0(x) dx = 0.0018U^{9/5}$$

where F_{all} , F_{front} , F_{sides} , and F_{rear} correspond to smooth wall drag forces applied to the whole surface of the drag pan (including the drag plate installed in it), the leading rim, the two streamwise rims, and the trailing rim, respectively, and other parameters defined in Fig. A4. Combining the forces obtained from these relations with the geometric dimensions of the drag pan as listed in Table A4, we derive the following expression for the drag ratio purely on the drag-reducing tiles:

$$\left(\frac{F}{F_0}\right)_{tile} = \frac{\left(\frac{F}{F_0}\right)_{pan} F_{all} - (F_{front} + F_{sides} + F_{rear})}{F_{all} - (F_{front} + F_{sides} + F_{rear})} = 1.132 \left(\frac{F}{F_0}\right)_{pan} - 0.132$$

where $(F/F_0)_{pan}$ and $(F/F_0)_{tile}$ represent the drag ratio before and after applying the compensation, respectively.

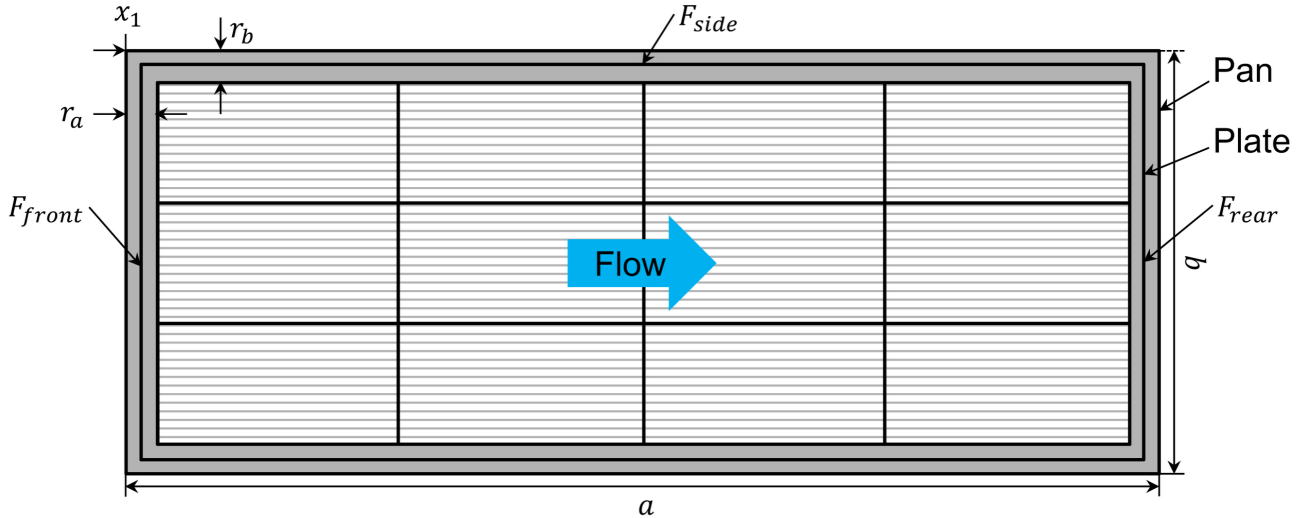


Fig. A4 Schematic illustration of the drag pan, which includes the drag plate filled with 12 tiles. The outer rims of drag plate and drag pan are shown in grey, and the 12 tiles are shown in white with horizontal stripes drawn along the trench direction. The overall dimension of the drag pan is a (streamwise) by b (spanwise). The total rim widths are r_a in streamwise direction and r_b in spanwise direction. The coordinate x_1 denotes the distance from the virtual origin to the leading edge of the drag pan

Table A4 Geometric dimensions of the drag pan, drag plate, and their outer rims

x_1 [mm]	a [mm]	b [mm]	r_a [mm]	r_b [mm]
381	317.32	152.39	6.07	6.16

This compensation isolates the shear stress exerted on the SHPo tiles and enables a fair comparison with a smooth surface to determine the drag reduction on the tiles more accurately. However, the differences turned out to be relatively small, only a few percent. For example, the compensated drag ratio data were smaller than the as-measured (i.e., uncompensated) values by 3.0–4.7% between 15–25 ft/s (4.6–7.6 m/s) on P50GF90D100L10 and by 5.4–5.6% between 15–21 ft/s (4.6–6.4 m/s) on P100GF92D200L20. This difference shrunk and disappeared when the plastron was deteriorated and completely lost at higher speeds understandably as the tile surfaces did not reduce drag anymore. Lastly, note there are additional regions of no slip, such as the rims around each of the 12 silicon SHPo tiles and the gaps between the tiles. However, we chose to be conservative and ignore their negative effects because they are difficult to quantify and likely small.

Appendix D: All data in the current flow experiment

As the flow speed increased to 35 ft/s over the P50GF90D100L10 plate, random dark patches appeared, indicating localized depinning of the plastron, as shown in Fig. A5(a). While the 35 ft/s (10.7 m/s) snapshot depicts the plastron immediately after reaching the speed, the dark regions continued to expand even when the speed was held constant. At 40 ft/s (12.2 m/s), the surface became fully wetted and appeared uniformly dark. This progressive plastron breakdown is directly attributed to the increasing wall shear stress with flow speed. The imposed shear stress on the air–water interface deforms and sweeps the plastron downstream; as the flow speed rises, its magnitude eventually exceeds the capillary pinning force, leading localized depinning (at ~30 ft/s or ~9.1 m/s) and subsequent full wetting transition of entire surface (35–40 ft/s or 10.7–12.2 m/s). Similarly, Fig. A5(b) presents two snapshots of the plastron on the P100GF92D200L20 plate at 20 ft/s (6.1 m/s) and 22 ft/s (6.7 m/s). The depinned regions clearly expand with increasing speed following the onset of depinning around 20 ft/s, following a similar progressive trend. Figure A5(c) shows the complete set of drag-ratio measurements for all tested cases as a function of water speed and the corresponding smooth wall shear stress. In contrast to Figs. 4 and 5, which present only successful cases with intact plastrons, Fig. A5(c) documents the results of all tested cases, including the high-speed flows where the plastron was completely lost. Consistent with the visual observations in Figs. A5(a) and (b), the drag ratio increased as the plastron began to fail. As the degradation progressed with water speeds, the drag ratio continued to increase and eventually crossed over to a drag increase at 35 ft/s (10.7 m/s) on P50GF90D100L10 and 25 ft/s (7.6 m/s) on P100GF92D200L20.

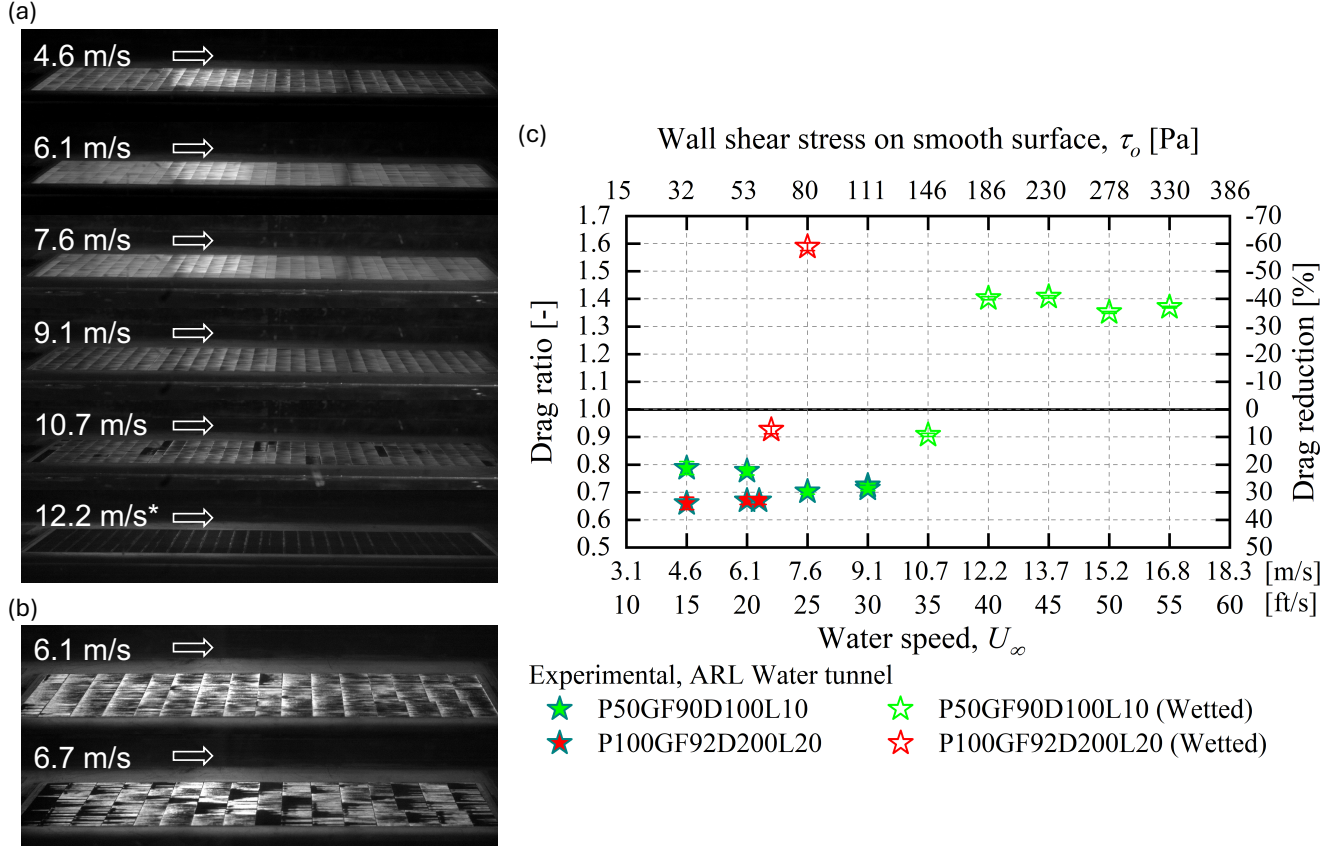


Fig. A5 Appearances of the plastron and measured drag ratios for all tested cases, including those with completely lost plastron. (a) Snapshots showing the plastron state on the P50GF90D100L10 plate at each speed during a speed ramp-up from 0 to 35 ft/s (10.7 m/s); the 40 ft/s (12.2 m/s) snapshot was obtained separately, i.e., not during the same ramp up. (b) Snapshots of the plastron state on the P100GF92D200L20 plate during a speed ramp-up. An unexpected interruption made only the snapshots for 20 ft/s (6.1 m/s) and 22 ft/s (6.7 m/s) available. (c) Drag-ratio data including both pinned and compromised plastron cases for P50GF90D100L10 (green stars) and P100GF92D200L20 (red stars) as a function of water speed. The data for P50GF90D100L10 were obtained from two sets of experiments, one up to 35 ft/s (10.7 m/s) and another from 30 to 55 ft/s (9.1 to 16.8 m/s), resulting in two data points at 30 and 35 ft/s. The hollow stars indicate the compromised (depinned and completely lost) plastron cases. The right vertical axis indicates the corresponding drag reduction, and the upper horizontal axis shows the smooth wall shear stress. Error bars denote the 95% confidence intervals

Appendix E: Relative importance of surfactant effects

The drag reduction observed in the present water tunnel experiments is greater than that for the boat measurements of Yu et al. (2024). Here we assess whether the boat performance may have been affected by Marangoni stresses due to naturally occurring surfactants, which are present in greater amounts in the ocean than in the tap water used in this study. We use the concept of “mobilization length”, introduced by Temprano-Coleto et al. (2023). They showed that, in order to be affected by surfactants, the trench length needs to be comparable to, or smaller than, a length scale given by

$$L_m = h \frac{\kappa_a}{\kappa_d} \Gamma_m \left(\frac{n_s R T c_0}{\mu D_{diff}} \right)^{1/2},$$

where κ_a/κ_d is the ratio of adsorption and desorption coefficients, Γ_m is the maximum theoretical surface concentration of surfactants, c_0 is the bulk surfactant concentration, R is the ideal gas constant, T is the absolute

temperature, D_{diff} is the surfactant diffusivity, and n_s relates to whether the surfactant is ionic. The variable h is the length scale for the viscous and diffusive layer above the plastron, which is equal to the viscous sublayer thickness for a turbulent boundary layer.

Although surfactant properties are challenging to measure in hydrodynamic experiments, we can use published data for ocean surfactants to obtain an order-of-magnitude estimate for the mobilization length, and thereby assess whether surfactants may have played a role in the measurements of Yu et al. (2024). Frossard et al. (2019) documented ocean surfactants, obtaining measurements of concentration as well as adsorption isotherms. Since no algal blooms or similar events were documented for the boat experiments of Yu et al. (2024), we select the datasets for oligotrophic locations. We estimate, to the nearest order of magnitude, $\kappa_a/\kappa_d \sim 10^3/\text{mol}$ and $c_0 \sim 10^{-4} \text{ mol/m}^3$. The surfactants were non-ionic, implying $n_s = 1$. Based on surfactant literature (Chang and Franses 1995), the maximum surface concentration of surfactants is of the order $\Gamma_m \sim 10^{-5} \text{ mol/m}^2$, and diffusivities are of the order of $D_{diff} \sim 10^{-9} \text{ m}^2/\text{s}$. This implies, using $h \sim 10 \delta_{\tau 0}$ and $\delta_{\tau 0} \sim 5 \mu\text{m}$ from Yu et al. (2024),

$$L_m \sim 370 h \sim 3,700 \delta_{\tau 0} \sim 20 \text{ mm}.$$

Since the trenches in the boat experiments of Yu et al. (2024) were between 10 and 20 mm long, it is likely that ocean surfactants were strong enough to impair drag reduction. In tap water, surfactants are at most present in trace amounts, such that their effects are expected to be several orders of magnitude smaller, implying that trenches with a length of the order of 10 mm are likely to be unaffected in water tunnel experiments, consistently with our present findings.

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