Superhydrophobic surfaces have the potential to reduce the viscous drag of liquids by significantly decreasing friction at a solid-liquid interface due to the formation of air layers between solid walls and interacting liquids. However, the trapped air usually becomes unstable due to the finite nature of the domain over which it forms. We demonstrate for the first time that a large surface energy barrier can be formed to strongly pin the three-phase contact line of air/water/solid by covering the inner rotor of a Taylor-Couette flow apparatus with alternating superhydrophobic and hydrophilic circumferential strips. This prevents the disruption of the air layer, which forms stable and continuous air rings. The drag reduction measured at the inner rotor could be as much as 77.2%. Moreover, the air layers not only significantly reduce the strength of Taylor vortexes but also influence the number and position of the Taylor vortex pairs. This has strong implications in terms of energy efficiency maximization for marine applications and reduction of drag losses in, for example, fluid transport in pipelines and carriers.

INTRODUCTION

In the past decades, to maximize the energy efficiency and enhance the traveling speed and distance of underwater and naval vehicles, as well as to minimize the drag losses in fluid transport in pipelines, researchers have made tremendous efforts to develop methods (1–3) to reduce wall frictional drag, which accounts for a large proportion of the total dissipation of well-designed underwater vehicles. Inspired by the fact that an object moving in air experiences much smaller drag force than in water, due to the large dynamic viscosity contrast between water and air, scientists and engineers have invented different ways to create an air layer covering the vehicles moving in water, thus reducing frictional drag (1, 2). Through the application of air cushioning, the solid-liquid interface is replaced by a solid-gas interface, which reduces the wall frictional drag significantly.

One of those attempted methods involves injecting air in the boundary layer, leading to drag reduction (DR) between 25 and 80% of the nominal drag (4–8). In the presence of limited air flux, air bubbles decrease the average density and viscosity of the fluid in the boundary layer, thereby modifying the transport of momentum and reducing drag. When the air flux is sufficiently high, the air bubbles coalesce into a continuous air layer (air cushioning), which fully separates the water flow and the solid surface, resulting in much larger DR. The utilization of superhydrophobic surfaces to form the injected air to remain attached to the wall has also been investigated (9). Another way to form thick air layers in the proximity of the wall is through the generation of cavities (1, 10, 11), which result from the vaporization of the surrounding water (called vaporeous cavities) (12) and normally require a large free-stream speed. By continuously injecting air, the required free-stream speed to sustain the cavity (called a ventilated cavity in this case) (11, 13) decreases moderately. The use of superhydrophobic surfaces to form a microscopic air layer that prevents direct fluid/solid contact has also been extensively studied (2, 14–20). It is widely accepted that the geometry and surface energy distribution of the micro- and nanoscale structures, characterizing a generic superhydrophobic surface, may prevent water from penetrating into the space between them (leading to a Cassie-Baxter wetting regime). Therefore, numerous air/water menisci form between the surface roughness and the local fluid dynamics occurring near the macroscopically nonwetting interface. Very similar effects have been found in terms of friction reduction and hydrodynamic load support in textured bearings (30–33).

DI may be induced by a transition from Cassie-Baxter wetting regime to Wenzel regime that significantly increases the contact area. This is also the reason why the maximum DR is obtained by air injection systems. Therefore, the reliability of DR obtained using superhydrophobic surfaces needs to be improved. To this end, the ideal design is one that produces stable and continuous air cushioning layers and exploits the nonwetting properties of superhydrophobic coatings. A recent contribution has shown how the “Leidenfrost” effect, achieved by active heating, can be used to sustain a stable air layer on the superhydrophobic surface, and a 90% DR was achieved (34). Here, we propose a new methodology of using alternating superhydrophobic/hydrophilic strips to passively create and maintain a stable air layer with a thickness of hundreds of micrometers in Taylor-Couette (TC) water flow. The air layer has no pinning structures along the flow direction but is strongly pinned normal to the flow direction, and an unprecedented DR is achieved without any air supply during flow. The DR is very similar to the best result that can be achieved by air feeding systems (~80%). In comparison, the unpatterned superhydrophobic surface only shows a much smaller DR (less than 15%) under the same flow conditions.
The experimental setup (see Methods) used to prove the effect of the trapped air layers on DR, determined by the alternation of superhydrophobic and hydrophilic surface strips, is depicted schematically in Fig. 1A. Similar methods based on the use of a TC apparatus for DR investigations have been reported in the recent literature (20, 34, 35).

Here, an inner cylinder (radius \( r_i \)) is subjected to a steady rotation (with angular speed \( \Omega \)) with respect to an outer cylinder (radius \( r_o \)). The gap between the cylinders is filled with water, and the inner cylinder is textured with alternating superhydrophobic and hydrophilic strips, which continuously cover the rotor in the circumferential direction. We note first that topographical (but also chemical) heterogeneities uniformly distributed over a solid surface form a locus of pinning sites (local discontinuities) for a bubble; thus, whenever air is entrapped and a three-phase contact line is produced on such discontinuities, the air contact angle hysteresis (36, 37) will characterize the contact line movements. The air contact angle hysteresis is generally defined as \( \Delta \theta = \theta_A - \theta_R \), where \( \theta_A \) and \( \theta_R \) are the advancing and receding air contact angles, respectively; however, here, these two angles are identified using the notation \( \theta_u \) and \( \theta_l \), respectively, to identify the upper and lower air contact angle considering buoyancy-induced deviations (see Fig. 1B). It should be noted that the contact angle of the air bubble is used, which provides a better characterization of the geometry of the air bubble than the water contact angle; also, which provides a better characterization of the geometry of the air bubble than the water contact angle.

A large energy barrier to stop the movement of the bubble is formed here by interposing hydrophilic (phi) surfaces (that is, aerophobic) between superhydrophobic (pho) (that is, aerophilic) surfaces. It is shown in Fig. 1D, which is simply used for illustrative purposes, that the air contact angle hysteresis at the boundary between superhydrophobic and hydrophilic surfaces is very large only in the plane of symmetry of the bubble (>110°) and that the corresponding three-phase contact line is stably formed in a macroscopic configuration. Using this principle, a number of alternately arranged superhydrophobic/hydrophilic strips are prepared (see Methods) on the surface of the rotor to create a two-dimensional bubble line contact, which extends to the entire circumference of the rotor and is always orthogonal to its axis. By slowly injecting air onto the superhydrophobic strips using a microsyringe, annular air bubbles (called air rings) are formed and suspended along the surface of the rotor. A full view of the inner rotor of the experimental apparatus showing fully developed air rings is displayed in Fig. 1E. In contrast with the ordinary thin air layer that forms on superhydrophobic surfaces and is sustained by the microstructural features of the surface roughness (43–45), the air rings are...
sustained by the stability of the three-phase contact line and the air/water surface tension. The annular air rings present a continuous circumferential bubble pinning boundary along the flow direction when the rotor spins.

RESULTS

Air rings shape

The air rings deform and change shapes depending on the surface design and running conditions; therefore, the rotation rates are systematically varied to measure the torque contribution of the TC flow, $T_i$, on the inner rotor, with annular air rings having different widths and thicknesses. The width of the hydrophilic strip $w_{\text{phi}} = 1 \pm 0.05$ mm is constant, whereas the width of the superhydrophobic surface $w$ ranges from 2 to 6 mm. The average radial thickness of the air ring is defined as $TH = \sqrt{(V + \pi w_{\text{rho}} r_i^2) / \pi w_{\text{rho}} - r_i}$, where $V$ is the air injected volume (see the inset at the bottom right of Fig. 2).

Figure 2A provides a comparison between the predicted bubble shape in the meridian plane (red curves, see section S1) and the optical acquisition (dark region, see Methods) of the air rings for a superhydrophobic strip of 4 mm and for $r_i = 12.5$ mm. The agreement is well within the experimental accuracy in determining the injected air volume. It should be observed that for the lower volume (0.05 ml), the predicted bubble axial thickness is $w_{a} = 0.35$ mm, less than the size of the superhydrophobic strip. During the air injection process, the air bubble first nucleates and pins on the upper border of the strip (I). Upon further air injection, the bubble grows toward the lower end of the strip to finally pin at the lower hydrophobic strip border (II). Consequently, by further air injection, the bubble grows along the radial direction (III and IV) until the unstable equilibrium configuration is reached. Because of the buoyancy, the cross section of the air ring is generically curvilinear, as shown in Fig. 2A, and its exact shape depends on different parameters, as discussed in section S1. Each air ring has different upper, $\theta_u$, and lower, $\theta_l$, air contact angles, thus forming a capillary force $F$, which equilibrates the buoyancy $F_B$, with $F_B = \gamma_l A_l (\cos \theta_l - \cos \theta_u)$, where the length of the contact line is $l = 2\pi r_i$. When $\theta_u$ reaches its critical value, $\theta_{cr}$, the air ring reaches its maximum volume, leading to $V_{\text{max}} = \gamma_l A_l (\cos \theta_l - \cos \theta_{cr}) / \rho g$. The maximum volume of air in an air ring formed on a 4-mm-width superhydrophobic strip under static water measured in this study is 0.36 ml.

Figure 2B shows the simulated bubble shape and its evolution in terms of slip states as a function of the hydrophobic strip size (points A to E), $w_{\text{rho}}$, for constant bubble thickness, $TH$. At constant air ring thickness, the increase of the bubble axial size $w_{a}$ is not linearly proportional to the superhydrophobic strip size $w_{\text{rho}}$. Therefore, in correspondence to the largest values of $w_{\text{rho}}$, the bubble only partially extends over the hydrophobic domain (Fig. 2B: C to E), which is thus wet in a generic Cassie-Baxter regime. As we will see in the following, the existence of this partial wetting regime will strongly affect the drag and, therefore, the measured torque. The bottom of Fig. 2B shows the theoretical prediction of the bubble axial length $w_{a}$ as a function of the hydrophobic strip size, $w_{\text{rho}}$, for different air ring thicknesses, namely, $TH = 0.16$, 0.31, 0.47, and 0.62 mm, and for $r_i = 12.5$ mm. This has been obtained using the analytical model described in section S1.

The role of the Bond number $B_o = (w_{a} / l_c)^2$, where $l_c = \sqrt{\gamma_{lA} / (\rho g)}$, in the bubble formation and shape evolution predicted by simulations...
The measured torque indicates that the air rings are very stable. For the air-saturated water used in this investigation, the in-water diffusion of air on the time evolution of the air ring thickness is shown (see section S6). For large Bond numbers, a larger pinning strength can be provided because of the increasing value of \( \cos(\theta) \). Thus, our air ring textured cylinder, does not alter the bubble shape to any measurable extent. Thus, our air ring does not alter the bubble shape to any measurable extent. Thus, our air ring’s design is demonstrated to be insensitive to the parametric variation of the interface physical properties, thus stably providing the cushioning effect as a tool to achieve significant DR.

Considering that the thickness of the air ring is critical to its DR ability, we assessed the effect of the compressibility and water solubility (in-water diffusion) of air on the time evolution of the air ring thickness (see section S6). For the air-saturated water used in this investigation, it was observed that the volume of the air ring changes by less than 2% in 4 hours when the inner rotor rotates at 20.9 rad/s. This indicates that the air rings are very stable.

**Measured torque and DR**

The measured torque \( T_m \) is the sum of two contributions, \( T + T_b \). \( T \) is the contribution coming from the flow in the proximity of the cylindrical surfaces, whereas \( T_b \) is the torque given by both the top and bottom cylinder flat surfaces. Here, we measured \( T_b \) using the same linearization method as that used by Greidanus et al. (46). This is done by measuring the torque of the inner rotor with different lengths submerged in water. In this process, \( T_b \) (more precisely, half \( T_{b,i} \)) keeps constant, whereas the contribution of the side wall increases linearly with its submerged length. The results show that the measured ratio \( T_b/T_m \) ranges from 0.12 to 0.13 for different rotating speeds.

Thus, we determined the contribution of the cylindrical surfaces, \( T \), by subtracting the measured \( T_b \) from the measured \( T_m \). For each point, the torque \( T_m \) is measured for a period of 30 s. Four tests are performed for each of the states, and the torque is averaged across all runs. The DR is defined as \( DR = (T_b/T)_i \times 100\% \), where \( T_i \) and \( T \) are the cylinder torque contributions of the TC flow for smooth uncoated inner rotor and the results obtained in the presence of air rings, respectively.

As shown in Fig. 4, considerable DR is observed experimentally for all the inner rotors with air rings on them. The dimensionless torque \( T' \) of the inner rotor increases with Reynolds number \( Re_C \) following the power law of \( T' = Re_C^n \), whereas the scaling exponent \( n \) decreases from 1.44 ± 0.01 for smooth inner rotor to 1.32 ± 0.01 for inner rotor in the presence of fully formed air rings (Fig. 4, left). Here, \( T' = T/(\rho u^2 L) \), \( Re_C = r_i u_{\text{in}}/u \), where \( \rho \) and \( u \) are the density and kinematic viscosity of water, respectively. For all the inner rotors with air rings on them, up to 77.2% of DR is observed, and the DR varies within 2% in the range of Reynolds numbers tested (inset to Fig. 4, left). Furthermore, in Fig. 4 (right), the experiments conducted at constant Reynolds number show that the DR increases with the TH of the air ring. Instead, a maximum DR exists as a function of the hydrophobic strip axial length, \( w_{\text{pho}} \), at constant TH of the air ring and at constant \( w_{\text{pho}} \). Such a maximum can be justified as follows. For small \( w_{\text{pho}} \), increasing \( w_{\text{pho}} \) determines a proportional increase of the axial width of the air ring \( w_b \), leading to a larger fraction of the inner rotor surface being covered by the slippery air.
bubble, consequently, this leads to an improved DR and to a reduction of the effective azimuthal wall velocity $v_0$ with respect to the externally applied cylinder azimuthal velocity $v_0$. Note that the effective azimuthal wall velocity $v_0$ can be considered as the equivalent azimuthal velocity of the untextured cylinder ($v_0 < v_0$ takes into account the air bubble slippage in the equivalent untextured TC flow) (see section S4). By further decreasing the effective azimuthal wall velocity $v_0$ (thus increasing $w_{\text{pho}}$) a shift in the dynamics of the flow toward the laminar regime is observed, given that the effective Reynolds number ($\sim v_0$) of the TC flow decreases. Because the generic TC flow regime is characterized by a torque scaling prefactor [the so-called modified torque coefficients in the study of Bilgen and Boulou (47)], which strongly increases toward the laminar regime, the further increase of $w_{\text{pho}}$ results in a reduced DR. This, in addition to the formation of partial bubble contact occurring at increasing $w_{\text{pho}}$ and leading to a reduced air ring coverage over the superhydrophobic strip, definitely provides a decrease of the DR, as observed experimentally in Fig. 4 (right). Therefore, influenced by these two factors, the DR curves show the existence of a maximum in correspondence of hydrophobic strip size of about 4 mm for our system.

**DISCUSSION**

The results in terms of DR are analyzed with flow field simulations of the TC geometry at varying texture parameters, as presented in Fig. 5 (the calculation methods are presented in section S4). In particular, in Fig. 5, we show, on the top, the effect of bubble skewness (asymmetry due to large Bond numbers), bubble thickness (TH), bubble axial length ($w_b$), and hydrophobic textured area density ($\alpha$) on the predicted dimensionless torque ($\tilde{\alpha}$, defined in eq. S4.4; note that $\tilde{\alpha} = 1$ for the untextured case). Here, all the simulations are done assuming a full bubble contact over the hydrophobic strip ($w_{\text{pho}} = w_b$).

We note first that, for all the investigated cases, the smaller the effective azimuthal wall velocity $v_0$, the smaller the dimensionless drag torque (in section S4, we show that both dimensionless torque and mean azimuthal flow velocity curves are qualitatively similar). Furthermore, we note that the bubble skewness has a negligible influence on the drag torque; the azimuthal velocity field is skewed too, but the smallest bubble-wall speeds are similar in the two cases. Moreover, we note that the strongest effects on the torque reduction are given by the increase of the patterned area density. However, when introducing the effect of the (more realistic) bubble partial contact (bottom panel), the incomplete contact introduces a geometric effect on the DR, which leads to the maximum in the curves shown in Fig. 4 (right).

Let us now focus on another aspect of the mechanisms responsible for the DR. First, it can be shown (see section S2) that, even for the thinnest air ring, the contribution to losses due to air-solid friction can be neglected, and therefore, solid-liquid friction accounts for most of the drag measured on the inner rotor. Because the air rings cover 80% of the vertical surface of the inner rotor, the DR based on $T$ would be expected to range from 74 to 78% for air rings with different TH. However, the measured DR only ranges from 56.6 to 77.2%. To shed light on the reasons for this discrepancy, the velocity distribution along the radial and radial-axial vorticity fields of the gap flow are measured.

Because the air-solid friction in the air ring is very small, the water between the air rings and the outer cylinder gets little azimuthal momentum from the air-water interface. Thus, there exists an azimuthal velocity gradient in the axial direction between the fluid flowing near the hydrophilic strips and the fluid in the proximity of the air rings. However, the intense viscous shear stress and Taylor vortices developing in the flow lead to strong azimuthal momentum transport.

Because the azimuthal momentum generated in correspondence to the hydrophilic strips is transported to the fluid flowing near the air rings, the azimuthal velocity above the hydrophilic strips at the same radial position of the air-water interface is much lower than that generated for the equivalent case but with a smooth inner rotor (see the experimental results reported in Fig. 6A); this means that there is a larger velocity gradient ($\frac{\partial v}{\partial r}$) at the inner rotor wall. Therefore, the shear stress

---

**Fig. 4.** Experimental investigation of the effect of the Couette Reynolds number $Re_C$, air ring radial (TH), and axial ($w_{\text{pho}}$) width on measured torque and DR obtained experimentally. (Left) Variation of the dimensionless torque $T = \frac{T}{(\rho u^2 L)}$ against $Re_C$ (red dots) for the uncoated inner rotor and for different bubble radial thickness (including the case of no air injection). The solid red lines represent the fit to the scaling $T \sim Re_C^n$ and $n$ is the scaling exponent. The solid and dashed black lines represent the empirical power law describing the dimensionless torque for the transition and low-turbulent regime, respectively (the calculation methods are presented in section S3). Inset: Variation of the DR against $Re_C$. Results are measured for a constant value of $w_{\text{pho}} = 4$ mm. (Right) DR as a function of the hydrophobic strip size for different equivalent radial widths (TH) of the air ring but at constant $Re_C = 1320$. 

---

**Fig. 5.** We show, on the top, the effect of bubble skewness (asymmetry due to large Bond numbers), bubble thickness (TH), bubble axial length ($w_b$), and hydrophobic textured area density ($\alpha$) on the predicted dimensionless torque ($\tilde{\alpha}$, defined in eq. S4.4; note that $\tilde{\alpha} = 1$ for the untextured case). Here, all the simulations are done assuming a full bubble contact over the hydrophobic strip ($w_{\text{pho}} = w_b$).
on the hydrophilic strips ($\tau = \rho \frac{dx}{dt} - \frac{w}{2}$) is larger than that on the surface of the equivalent smooth inner rotor (note that at the rotor surface, the term $\frac{w}{2}$ for comparing two cases is equal to $\Omega$). This is why the total DR is less than expected. Moreover, it can be inferred that there is a large azimuthal velocity gradient near the inner wall of the hydrophilic strips (48, 49). When the air-water interface penetrates deeper into the gap flow, the azimuthal velocity gradient along the axial direction between the fluid flowing near the air rings and the water in the proximity of the hydrophilic strips, as well as the intensity of the Taylor vortexes, gets smaller (Fig. 6B). Accordingly, the momentum transport between the water above the hydrophilic strips and the air rings gets smaller, leading to an increase in DR with TH. Visualization of the flow scenarios of planar and patterned rotors at $Re_C = 1320$ is provided in movie S1. The Taylor vortex axial position slightly varies along the azimuthal direction with time for both the smooth and patterned inner rotors. However, the intensity of the Taylor vortexes for the smooth inner rotor is stronger than that for the patterned inner rotor, which makes the ink strongly constrained by the Taylor vortexes on the smooth inner rotor.

For the TC flow generated using a smooth inner rotor, pairs of counter rotating vortexes, known as Taylor vortexes, form after a critical Reynolds number due to centrifugal instabilities (50). The axial length of each pair of vortexes (spatial period) is approximately $2d$ (51). When the air rings are introduced at the inner rotor surface, the intensity of the centripetal acceleration tends to have a periodical distribution because the azimuthal velocity in the flow has periodic gradients along the axial direction. The periodic centripetal acceleration causes new periodic vortex pairs, and the spatial period of these new vortex pairs is almost twice the period of the air rings. Moreover, because of the low air-solid friction, the total azimuthal momentum in the flow gets smaller. Thus, both the vorticity of the new vortex pairs and the azimuthal momentum transport in the radial direction decrease. This corresponds to the result that the exponent $\eta$ in the measured torque scaling decreases from 1.44 to 1.32 (this can be referred to as "laminar shift").

Despite the fact that the air rings with different thickness are extremely stable in all the experiment conditions with Reynolds numbers up to 1320, corresponding to a rotating speed of 200 rpm (see section S6 and movie S2), we have also conducted an introductory study at one

---

**Fig. 5.** Theoretical investigation of the effect of flow strips, air ring behavior, and geometrical configuration on torque obtained numerically.  
**Top** Dimensionless torque $\tilde{\tau}$ (see section S4) as a function of the bubble thickness $TH$ for different texture area density $\alpha$ and Bond numbers. In the calculations, we have considered the case $w_{pho} = w_b$ (bubble covering the whole hydrophobic strip), whereas the superhydrophobic/hydrophilic reference texture is characterized by $TH = 0.35$ mm and $w_b = 4$ mm. Increasing the Bond number (green path) has no effect on the drag torque. Instead, increasing the texture area density $\alpha$ (red path) determines a net reduction of the water velocity on the bubble surface, resulting in a stronger reduction in the generated drag torque. The bubble thickness $TH$ (blue path) has an influence similar to $\alpha$ but weaker in terms of reduction of the water speed on the bubble wall.  
**Bottom** Dimensionless drag torque reduction (and effective azimuthal wall velocity $\tilde{v}_0$) as a function of the hydrophobic axial size $w_{pho}$ (here, $w_{pho} \geq w_b$) for $TH = 0.16$ mm (corresponding to the red curve in Fig. 2B). The wetting condition in the portion of the hydrophobic strip, which is uncovered by the air ring (width $w_{pho} - w_b$), is governed by the slip parameter $\beta$ ($0 \leq \beta \leq 1$). We have analyzed two conditions, namely, no slip ($\beta = 0$) and partial slip ($\beta = 0.043$, see section S4). The DR does not increase linearly with $w_{pho}$ due to the occurrence of the partial bubble contact on the hydrophobic strip. Instead, a maximum in the DR exists, supporting the experimental results of Fig. 4 (right).
As a result, not only the intensity of the Taylor vortex decreases but also its position and periodicity varies. The present work demonstrates the order of magnitude larger Reynolds numbers, therefore investigating the high turbulent regime, adopting a newly developed TC apparatus. The rig, not featuring a torque gauge in this initial realization, has an inner and an outer rotor with diameters of 50 and 70 mm, respectively, and the maximum rotating speed is 1500 rpm. It has been used to provide a preliminary investigation of the air ring stability in the high turbulent regime. In particular, we found that the TC flow in the presence of air rings experiences three markedly different regimes as the rotating speed is increased: (i) a stable-ring regime, (ii) a deformed-ring regime, and (iii) a ring-breakup regime (see movie S3). Further details will be provided in our follow-up contribution.

In conclusion, the newly designed alternated superhydrophobic and hydrophilic strips produce a large surface energy barrier at their junction zone and are responsible for the generation of annular air rings, which form a persistent continuous circumferential boundary along the flow direction in a TC flow configuration; this is responsible for the large DR measured in our apparatus. Because of the low dynamic viscosity of air, the air-solid friction in the air ring is small enough to be neglected. In the flow between the two cylindrical surfaces, there is a strong azimuthal momentum transport due to the viscous shear stress and Taylor vortexes, which leads to larger solid-water friction on the hydrophilic strips of the inner rotor with air rings than on the equivalent smooth inner rotor. Moreover, the momentum transport in the flow is strongly influenced by the location of the air-water interface in the gap between the cylinders; as a result, the total DR increases with the thickness of the air ring and approaches, but cannot reach, its maximum theoretical value. As the azimuthal velocity in the flow between the cylinders varies periodically with the strips in the axial direction, the centripetal acceleration, which controls the formation of the Taylor vortex, exhibits the same periodicity. As a result, not only the intensity of the Taylor vortex decreases but also its position and periodicity varies. The present work demonstrates the feasibility of a newly proposed design strategy that is capable of producing unprecedented DR efficiency by the optimized use of patterned superhydrophobicity/hydrophilicity. The proposed solution has significant application potential in designing novel DR devices, particularly in the marine sector and fluid transport and processing industries.

METHODS

The total torque $T_m$ on the inner rotor was measured by a viscometer with a maximum rotating speed of 200 rpm (Brookfield Programmable LVDV-II+, Brookfield AMETEK, reproducibility error of ±0.2%). TC flow was created with a rotating inner rotor with radius $r_i = 12.5 \pm 0.02$ mm and a stationary outer cylinder with radius $r_o = 17 \pm 0.02$ mm. A schematic depiction of the apparatus is given in Fig. 1. The radius ratio $\eta = r_i/r_o$ was 0.74, and the gap between the cylinders $d = r_o - r_i$ was 4.5 mm. The height of the inner rotor was $L_o = 91 \pm 0.1$ mm, and the corresponding aspect ratio $\xi = L_o/(r_o - r_i)$ was 20.2. The gap between the cylinders was filled with air-saturated water at 25 ± 0.5°C. The height of the outer cylinder was $L_i = 111 \pm 0.1$ mm, whereas the gap between the bottoms of the inner and the outer cylinders was 10 ± 0.1 mm. The rotation rate of the inner rotor $\Omega$ was in the range of 10.47 to 20.93 rad/s, which lead to an attainable range of $Re_C$ between 660 and 1320. In this range of Reynolds numbers, by neglecting in first approximation the influence of the axial array of slippage areas on the TC regime boundaries, the TC flow regime was expected to be located in between wavy flow and modulated-wavy vortex flow (low-turbulent flow) (47, 52, 53).

To measure the shape of the air ring, a water bath tank of rectangular cross section was used in our experiments. The camera was set 30 cm away and normal to the cross section of the air rings. A scale plate was put 1 cm beside the air ring in its meridian plane. A panel light was used as background light to enhance the contrast between the air rings and...
REFERENCES AND NOTES


Acknowledgments
Funding: This research was financially supported by the National Natural Science Foundation of China (51679203, 51335010, 21434009, and 11372305) and the Natural Science Basic Research Plan in Shaanxi Province of China (2016JM1002). D.D. would also like to acknowledge the support received from the Engineering and Physical Sciences Research Council under Established Career Fellowship grant EP/N025954/1. Author contributions: H.H., D.D., and F.Z. proposed the idea. H.H., J.W., and L.B. performed the experiment and drafted the paper. L.B., L.J., D.S., B.S., G.P., and Q.X. discussed the experiment results. M.S. and D.D. performed simulation. H.H., J.W., M.S., D.D., and F.Z. discussed the results and revised the paper. Competing interests: The authors declare that they have no competing interests. Data and materials availability: All data needed to evaluate the conclusions in the paper are present in the paper and/or the Supplementary Materials. Additional data related to this paper may be requested from the corresponding authors: huhaibao@nwpu.edu.cn, d.dini@imperial.ac.uk, and zhouf@licp.cas.cn.


Submitted 27 December 2016
Accepted 4 August 2017
Published 1 September 2017
10.1126/sciadv.1603288
Significant and stable drag reduction with air rings confined by alternated superhydrophobic and hydrophilic strips

Haibao Hu, Jun Wen, Luyao Bao, Laibing Jia, Dong Song, Baowei Song, Guang Pan, Michele Scaraggi, Daniele Dini, Qunj Xue and Feng Zhou

Sci Adv 3 (9), e1603288.
DOI: 10.1126/sciadv.1603288