

Bubble Drag Reduction Requires Large Bubbles

Ruben A. Verschoof,¹ Roeland C. A. van der Veen,¹ Chao Sun,^{2,1,*} and Detlef Lohse^{1,3,†}

¹*Department of Applied Physics, MESA+ institute and J. M. Burgers Center for Fluid Dynamics, University of Twente, P.O. Box 217, 5 7500 AE Enschede, The Netherlands*

²*Center for Combustion Energy and Department of Thermal Engineering, Key Laboratory for Thermal Science and Power Engineering of the Ministry of Education, Tsinghua University, 100084 Beijing, China*

³*Max Planck Institute for Dynamics and Self-Organisation, 37077 Göttingen, Germany*

(Received 21 June 2016; published 1 September 2016)

In the maritime industry, the injection of air bubbles into the turbulent boundary layer under the ship hull is seen as one of the most promising techniques to reduce the overall fuel consumption. However, the exact mechanism behind bubble drag reduction is unknown. Here we show that bubble drag reduction in turbulent flow *dramatically* depends on the bubble size. By adding minute concentrations (6 ppm) of the surfactant Triton X-100 into otherwise completely unchanged strongly turbulent Taylor-Couette flow containing bubbles, we dramatically reduce the drag reduction from more than 40% to about 4%, corresponding to the trivial effect of the bubbles on the density and viscosity of the liquid. The reason for this striking behavior is that the addition of surfactants prevents bubble coalescence, leading to much smaller bubbles. Our result demonstrates that bubble deformability is crucial for bubble drag reduction in turbulent flow and opens the door for an optimization of the process.

DOI: [10.1103/PhysRevLett.117.104502](https://doi.org/10.1103/PhysRevLett.117.104502)

Theoretical, numerical and experimental studies on bubble drag reduction (DR) of a solid body moving in a turbulent flow have been performed for more than three decades [1–6]. In the last decade from the maritime industry there was a renewed interest into this subject and into air lubrication, because other contributions to the total drag such as pressure drag and wave drag have already been optimized thanks to sophisticated vessel design [7]. A few volume percent ($\leq 4\%$) of bubbles can reduce the overall drag up to 40% and beyond [8–15]. However, the exact physics behind this drag reduction mechanism is unknown, thus hindering further progress and optimization, and even the dependence of the effect on the bubble size is controversial [16–18], though it is believed to be independent of the bubble size [1].

In this Letter, we experimentally investigated the mechanism behind bubble drag reduction in a Taylor-Couette (TC) system, i.e. the flow between two independently rotating coaxial cylinders. The TC system can be seen as “drosophila” of physics of fluids, with many concepts in fluid dynamics being tested therewith, ranging from instabilities, to pattern formation, to turbulence; see the reviews [19,20]. Here we inject bubbles into the system, which due to the density difference to water experience a centripetal force towards the inner cylinder, mimicking the upwards gravitational force acting on bubbles under a ship hull.

The experiments are performed in the Twente Turbulent Taylor-Couette facility (T³C) [21], with the inner one strongly rotating, corresponding to very large Reynolds number of $Re \sim 10^5$ – 10^6 . The setup has an inner cylinder with a radius of $r_i = 200$ mm and an outer cylinder with a radius of $r_o = 279$ mm, resulting in a radius ratio of

$\eta = r_i/r_o = 0.716$. The inner cylinder rotates with a frequency up to $f_i = 20$ Hz, resulting in Reynolds numbers up to $Re = 2\pi f_i r_i (r_o - r_i)/\nu_\alpha = 2 \times 10^6$, in which ν_α is the kinematic viscosity of water-bubble mixture. At these rotation rates, the influence of gravity is negligible compared to the centripetal acceleration [21]. The outer cylinder is at rest. The cylinders have a height of $L = 927$ mm, resulting in an aspect ratio of $\Gamma = L/(r_o - r_i) = 11.7$. The flow is cooled through both end plates to prevent viscous heating through the viscous dissipation. The torque τ is measured with a coaxial torque transducer (Honeywell Hollow Reaction Torque Sensor 2404-1K, maximum capacity of 115 N m), mounted inside the middle section of the inner cylinder, to avoid measurement uncertainties due to seals and bearing friction and end plate effects. Details are described in Ref. [21]. The gap between the cylinders is either fully filled with water ($T = 20^\circ\text{C}$) or, when measuring with bubbles, partly filled with water. The effective viscosity and density of a bubbly liquid can be approximated using $\rho_\alpha = \rho(1 - \alpha)$ and the Einstein relation [14,22], $\nu_\alpha = \nu(1 + \frac{5}{2}\alpha)$, in which ρ and ν are the density and the viscosity of the single phase liquid, and α is the *global* volume fraction of air. Air bubbles form over the entire cylinder height because of the large turbulent fluctuations and the high centripetal forces.

The main result is seen in Figs. 1(a) and 1(b), where we show the drag coefficient $c_f(t)$ at $Re = 2 \times 10^6$ as a function of time for four different bubble concentrations. It is calculated as $c_f = \tau/(L\rho_\alpha\nu_\alpha^2Re^2)$ [see Fig. 1(a)] from the measured required torque $\tau(t)$ to keep the inner cylinder rotating at the fixed angular velocity ω_i . While with bubble

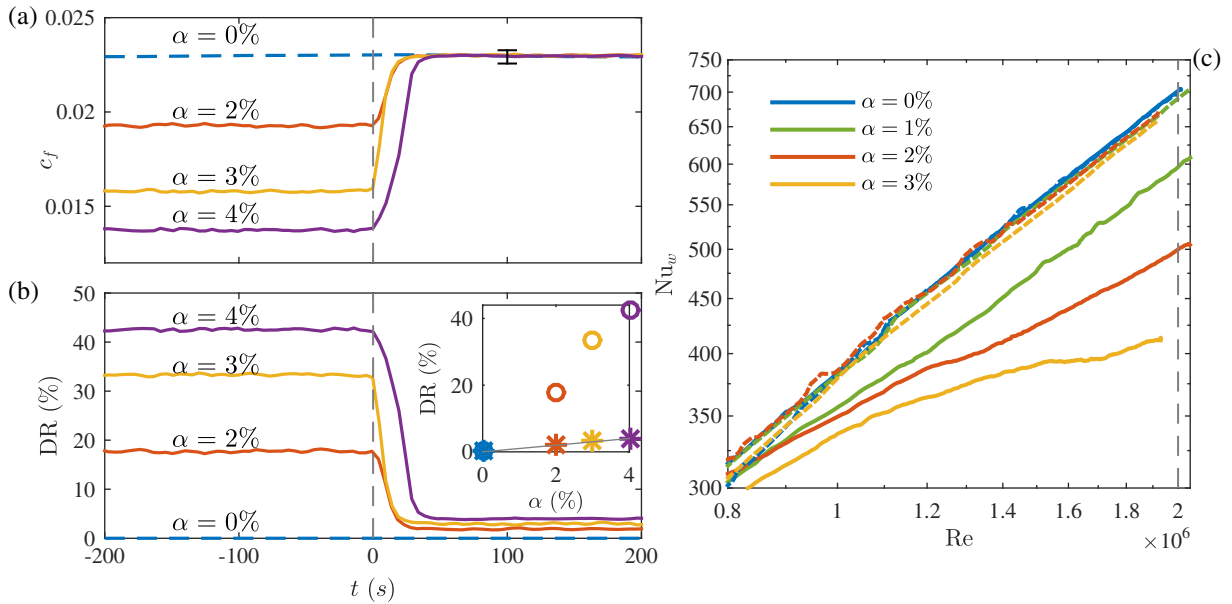


FIG. 1. (a) Drag coefficient c_f as a function of time (for $f_i = 20$ Hz, corresponding to $Re = 2.0 \times 10^6$ at $\alpha = 0\%$) for different gas volume fractions α . At $t = 0$ s the surfactant is injected, as indicated by the dashed vertical line. We then observe a large jump in the measured friction coefficient and within ~ 20 s all curves overlap. (b) Drag reduction (DR) as function of time. Nearly all DR is lost after injection of the surfactant at $t = 0$ s. Inset: averaged DR before (circles) and after (asterisks) addition of the surfactant, as a function of the gas volume fraction α . The thin line equals $DR = \alpha$, showing that after addition of the surfactant the small residual DR is accounted for by the reduced density of the fluid mixture. (c) The dimensionless torque $Nu_\omega = \tau/\tau_{\text{lam}}$, which is the torque τ divided by the torque in the laminar and purely azimuthal case [20], as a function of the Reynolds number Re for various $\alpha = 0\%$, 1% , 2% , 3% , both with (dashed lines) and without (solid lines) the surfactant Triton X-100. (a),(b) correspond to $Re = 2.0 \times 10^6$ (at $\alpha = 0\%$), shown by the thin vertical line in the plot.

volume concentration between 2% and 4% the drag is remarkably reduced between 18% and 43% as compared to the single phase flow case without bubbles [14], adding the surfactant Triton X-100 at $t = 0$ s at a concentration of only 6 ppm reduces the drag reduction within 20 s (the time needed for Triton X to mix over the whole system) to the value corresponding to the volumetric gas concentration of 2%–4%. Here the percentage of drag reduction is expressed as $DR = (\tau^{\text{with}} - \tau^{\text{without}})/\tau^{\text{without}}$, with the superscripts *with* and *without* referring to the cases with, and without surfactant, respectively. The same holds for weaker turbulence—here we tested down to $Re \approx 8 \times 10^5$ [see Fig. 1(c)]—though for weaker turbulence the original drag reduction effect through the bubbles is less pronounced. Here, we show the dimensionless torque in terms of the Nusselt number $Nu_\omega = \tau/\tau_{\text{lam}}$, in which $\tau_{\text{lam}} = 4\pi L \rho_\alpha \nu_\alpha r_i^2 r_o^2 \omega_i / (r_o^2 - r_i^2)$ is the torque needed in the purely azimuthal and laminar flow case. The Nusselt number can also be directly related to the drag coefficient c_f by $Nu_\omega = c_f \omega_i (r_o - r_i)^2 (r_o^2 - r_i^2) / (4\pi \nu_\alpha r_o^2)$.

Figure 2 shows snapshots of the bubbly turbulence at three different length scales (reflecting the multiscale character of bubbly turbulence) without (upper row) and with (lower row) the addition of Triton X-100. It is seen that the addition of the surfactant dramatically changes the structure of the turbulent dispersed bubbly flow, resulting

in much smaller bubbles (with the same total volume concentration) in the case with Triton X-100. The reason is that the surfactant suppresses bubble coalescence [23,24]. Earlier studies noticed the role of the bubble Weber number in bubble drag reduction [5,11,14]. The Weber numbers $We = \rho_\alpha u'^2 D_{\text{bubble}}/\sigma$ before and after addition of Triton X-100 are estimated as follows: From Fig. 2, we estimate that the equivalent bubble diameters are of order $D_{\text{bubble,without}} = O(1 \text{ mm})$ for clean water, and $D_{\text{bubble,with}} = O(0.1 \text{ mm})$ for water with Triton X-100, respectively. The surface tension between water and air is known for clean water, i.e. $\sigma_{\text{without}} = 73 \text{ mN/m}$ at room temperatures. After the addition of 6 ppm Triton X-100 (equivalent to $5 \times 10^{-5} \text{ mol/L}$), the surface tension lowers to $\sigma_{\text{with}} = 40 \text{ mN/m}$ [25]. The velocity fluctuations, as well as bubble sizes and the spatial distribution, are impossible to measure in the bulk of the flow after the addition of surfactant, as the bubble flow is too dense to be optically accessible. We know that *without bubbles*, $u' \approx 0.03 \omega_i r_i$ [14] in the bulk of the flow, and that this ratio is constant over a large range of Reynolds numbers, as long as the flow is fully turbulent [26]. Furthermore, it has been shown that this ratio does not change much after adding a few percent of mm-sized bubbles [14]. For a rotation rate of 20 Hz, we calculate that $u' = 0.76 \text{ m/s}$. We assume that this is a reasonable measure for the fluctuations in our

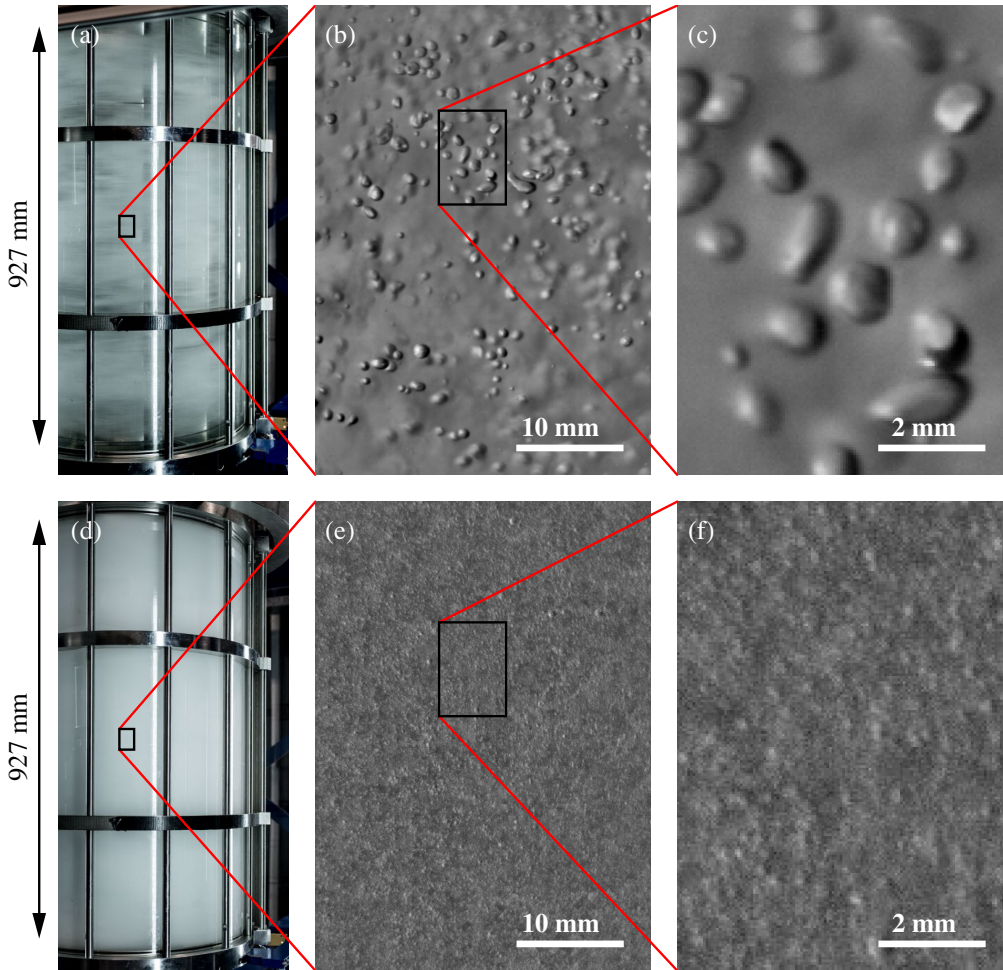


FIG. 2. Snapshots of the bubbly turbulence ($\alpha = 1\%$, $Re = 2 \times 10^6$) with increasing magnification (as shown by the scale bars). In the first row no surfactants are present in the turbulent flow, whereas the second row shows the (statistically stationary) situation after addition of 6 ppm Triton X-100. In the left photos the T³C apparatus can be seen.

bubbly flow. For lower Reynolds numbers, the velocity fluctuations become smaller, resulting in lower Weber numbers. We note that for the smaller bubbles the accelerations due to turbulent fluctuations are much larger than the centripetal accelerations. Therefore no bubble clustering close to the inner cylinder occurs [14].

From the figures we estimate the corresponding Weber numbers in the two cases as $We_{\text{without}} \approx 10$ and $We_{\text{with}} \approx 1$, implying that prior to injection of the surfactant the bubbles can deform [as indeed seen from Figs. 2(b) and 2(c)], whereas this is not possible after Triton X-100 was added [which is consistent with Figs. 2(e) and 2(f)]. As shown in Fig. 1(c), drag reduction is less pronounced at lower Reynolds numbers. The physical reason for this trend is that the Weber number of the bubbles decreases when reducing the Reynolds number.

Our findings give strong evidence that the bubble deformability is crucial in the drag reduction mechanism, as already speculated in Refs. [12,14,18], but disputed by other authors. We note that both the shape change of the bubble and the

bubble coating by the surfactant will also modify the lift force coefficient of the lift acting on the bubble [15,23,24,27,28] and thus the bubble distribution in the flow. Apparently, the large and deforming bubbles, which accumulate close to the inner cylinder [14], hinder the angular momentum exchange between boundary layer and bulk by partly blocking the emission of coherent structures from the boundary layer towards the bulk and reducing the Reynolds stress, thus leading to drag reduction [14,18,28,29].

Our results have strong bearing on the projected bubble drag reduction in the naval industry. Not only surfactants, but also ions of the various dissolved salts have a strong effect on coalescence properties of bubbles, either enhancing or suppressing coalescence [30]. As seen from our experiments, tests of bubbly drag reduction in fresh water facilities will therefore lead to very different results as in the salty ocean water.

Our results, however, also offer opportunities to enhance drag reduction in pipelines transporting liquified natural gases (LNGs) close to the boiling point by adding

appropriate surfactants *helping* coalescence [31]. Going beyond bubbly multiphase flow towards emulsions of e.g. oil in water [32], also here the global drag will be strongly affected by the local coalescence behavior of the droplets, thus opening opportunities to influence the overall drag by the use of surfactants.

We would like to thank Gert-Wim Bruggert and Martin Bos for their continuous technical support over the years. We acknowledge stimulation discussions with Dennis Bakhuis, and Rodrigo Ezeta Aparicio and Michiel van Limbeek. The work was supported by the Dutch Technology Foundation STW (ShipDRAC project) and by an ERC Advanced Grant.

*chaosun@tsinghua.edu.cn

†d.lohse@utwente.nl

- [1] S. L. Ceccio, *Annu. Rev. Fluid Mech.* **42**, 183 (2010).
- [2] N. K. Madavan, S. Deutsch, and C. L. Merkle, *Phys. Fluids* **27**, 356 (1984).
- [3] N. K. Madavan, S. Deutsch, and C. L. Merkle, *J. Fluid Mech.* **156**, 237 (1985).
- [4] V. S. L'vov, A. Pomyalov, I. Procaccia, and V. Tiberkevich, *Phys. Rev. Lett.* **94**, 174502 (2005).
- [5] Y. Murai, *Exp. Fluids* **55**, 1773 (2014).
- [6] I. Kumagai, Y. Takahashi, and Y. Murai, *Ocean Eng.* **95**, 183 (2015).
- [7] E. J. Foeth, in *20th International Hiswa Symposium, Yacht Design Yacht Construction. Amsterdam, The Netherlands, 2008*, (2008).
- [8] W. C. Sanders, E. S. Winkel, D. R. Dowling, M. Perlin, and S. L. Ceccio, *J. Fluid Mech.* **552**, 353 (2006).
- [9] S. Deutsch, M. Moeny, A. A. Fontaine, and H. Petrie, *Exp. Fluids* **37**, 731 (2004).
- [10] K. Sugiyama, T. Kawamura, S. Takagi, and Y. Matsumoto, in *Proceedings of the 5th Symposium on Smart Control of Turbulence, Tokyo, Japan* <http://www.nmri.go.jp/turbulence/PDF/symposium/FY2003/Sugiyama.pdf> (2004), pp. 31–43.
- [11] T. H. van den Berg, S. Luther, D. P. Lathrop, and D. Lohse, *Phys. Rev. Lett.* **94**, 044501 (2005).
- [12] T. H. van den Berg, D. P. M. van Gils, D. P. Lathrop, and D. Lohse, *Phys. Rev. Lett.* **98**, 084501 (2007).
- [13] B. R. Elbing, E. S. Winkel, K. A. Lay, S. L. Ceccio, D. R. Dowling, and M. Perlin, *J. Fluid Mech.* **612**, 201 (2008).
- [14] D. P. M. van Gils, D. Narezoz Guzman, C. Sun, and D. Lohse, *J. Fluid Mech.* **722**, 317 (2013).
- [15] B. R. Elbing, S. Mäkiharju, A. Wiggins, M. Perlin, D. R. Dowling, and S. L. Ceccio, *J. Fluid Mech.* **717**, 484 (2013).
- [16] C. Merkle and S. Deutsch, in *Frontiers in Experimental Fluid Mechanics, Lecture Notes in Engineering*, edited by M. G. el Hak (Springer, Berlin, 1989), Vol. 46, p. 291.
- [17] A. Ferrante and S. Elghobashi, *J. Fluid Mech.* **503**, 345 (2004).
- [18] J. C. Lu, A. Fernandez, and G. Tryggvason, *Phys. Fluids* **17**, 095102 (2005).
- [19] M. A. Fardin, C. Perge, and N. Taberlet, *Soft Matter* **10**, 3523 (2014).
- [20] S. Grossmann, D. Lohse, and C. Sun, *Annu. Rev. Fluid Mech.* **48**, 53 (2016).
- [21] D. P. M. van Gils, G. W. Bruggert, D. P. Lathrop, C. Sun, and D. Lohse, *Rev. Sci. Instrum.* **82**, 025105 (2011).
- [22] A. Einstein, *Ann. Phys.* **324**, 289 (1906).
- [23] S. Takagi, T. Ogasawara, and Y. Matsumoto, *Philos. Trans. A. Math. Phys. Eng. Sci.* **366**, 2117 (2008).
- [24] S. Takagi and Y. Matsumoto, *Annu. Rev. Fluid Mech.* **43**, 615 (2011).
- [25] J. Göbel and G. Joppien, *J. Colloid Interface Sci.* **191**, 30 (1997).
- [26] S. G. Huisman, D. P. M. van Gils, S. Grossmann, C. Sun, and D. Lohse, *Phys. Rev. Lett.* **108**, 024501 (2012).
- [27] J. Magnaudet and I. Eames, *Annu. Rev. Fluid Mech.* **32**, 659 (2000).
- [28] M. Muradoglu and G. Tryggvason, *J. Comput. Phys.* **274**, 737 (2014).
- [29] A. Kitagawa, K. Hishida, and Y. Kodama, *Exp. Fluids* **38**, 466 (2005).
- [30] V. S. J. Craig, *Curr. Opin. Colloid Interface Sci.* **9**, 178 (2004).
- [31] W. C. Ikealumba and H. Wu, *Energy Fuels* **28**, 3556 (2014).
- [32] S. F. Wong, J. S. Lim, and S. S. Dol, *J. Pet. Sci. Eng.* **135**, 498 (2015).