Sodium chloride inhibits effective bubbly drag reduction in turbulent bubbly Taylor–Couette flows

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Using the Taylor–Couette geometry we experimentally investigate the effect of salt on drag reduction caused by bubbles present in the flow. We combine torque measurements with optical high-speed imaging to relate the bubble size to the drag experienced by the flow. Previous studies have shown that a small percentage of air (4%) can lead to dramatic drag reduction (40%). In contrast to previous laboratory experiments, which mainly used fresh water, we will vary the salinity from that of fresh water to the average salinity of ocean water. We find that the drag reduction is increasingly more inhibited for increasing salt concentrations, going from 40% for fresh water to just 15% for sea water. Salts present in the working fluid inhibit coalescence events, resulting in smaller bubbles in the flow and, with that, a decrease in the drag reduction. Above a critical salinity, increasing the salinity has no further effect on the size of bubbles in the flow and thus the drag experienced by the flow. Our new findings demonstrate the importance of sodium chloride on the bubbly drag reduction mechanism, and will further challenge naval architects to implement promising air lubrication systems on marine vessels.

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1. Introduction

Most goods are transported over sea by large container ships. The largest contribution to the drag force on these ships is from skin friction on the ship hull [1,2]. Reducing the skin friction can lead to a substantial decrease in the ship’s fuel consumption. Not only is this financially attractive, but it also reduces the emissions of CO₂ substantially. One promising technique for reducing the skin friction is to inject air into the flow under the ship’s hull. Other advantages of this system are that it does not pollute the ocean or disturb marine fauna.

Drag reduction by air lubrication can be achieved in multiple ways, for example by using air layers [3–6] to reduce the contact area of water with the ship hull, or by using bubbles to alter the turbulent flow in the boundary layer below the hull. We will focus on the latter method, i.e. on bubbly drag reduction, which has been reviewed by Ceccio [7], Murai [8], Hashim et al. [9] and Lohse [10]. In those review papers, multiple possible mechanisms for bubbly drag reduction are discussed. In flat-plate experiments up to 80% of drag reduction has been observed using small bubbles at a Reynolds number of \( Re \approx 2 \times 10^6 \) [11,12]. Also in numerical simulations of channel flow [13] it was found that non-deformable micro-bubbles can reduce the drag by up to 6.2% for a moderate Reynolds number of \( Re = 3000 \). This indicates that the bubble size perhaps does not play an important role in the amount of drag reduction, suggesting that the void fraction is the determining factor [7,14]. Compressibility (e.g. [15]) and turbulent suppression (e.g. [16,17]) are also considered to be possible mechanisms for bubbly drag reduction. Furthermore, deformability of bubbles can play a major role in the effects of bubbly drag reduction [18–22].

Different drag-reducing mechanisms apply for low- and high-Reynolds-number Taylor–Couette flows. In low-Reynolds-number flows small bubbles rise due to gravity and destroy the Taylor vortices, removing a very efficient transport mechanism of angular momentum between the cylinders [23–25]. For high-Reynolds-number Taylor–Couette flows it was found by high-performance direct numerical simulations [26] that the deformability of bubbles plays an important role in the drag-reducing mechanism.

One open question is how bubbly drag reduction can be applied to marine vessels. A few ships have already been equipped with bubble-injection systems. Examples are the Silverstream project [27] and the Mitsubishi Air Lubrication System [28,29]. The latter achieved around 10% of power savings, already taking the energy needed for the air injection into account. Similar power savings were achieved using a hydrofoil on a variety of ships [30]. These power savings are, however, not nearly as large as the drag reductions measured in the laboratory. A possible explanation for the discrepancy between laboratory measurements and measurements on marine vessels could be size effects that come into play when scaling the flow from the laboratory to ships [7,31,32], surface details of the hull such as roughness [33–37], mineral/salt content of the water, particulate content or surfactants [22].

Almost all laboratory studies are performed with tap water or even cleaner water [11,12,18,19,25,26,37–41]. Sea water, however, contains a large variety of chemicals and particles. Few laboratory studies have been performed with ‘contaminated’ water. For example, Winkel et al. [42] measured bubble size distributions in salt water in a horizontal water channel and found that the bubble sizes decrease monotonically for increasing salt concentrations. By contrast, Shen et al. [43] found that when injecting bubbles into solutions with salts or surfactants, the drag reduction is independent of the bubble size. Furthermore, Elbing et al. [3] measured the drag reduction in a surfactant solution in a water channel and found that the resulting size of the bubbles downstream of the injection and the drag reduction do not significantly depend on the surfactant concentration. In contrast, Verschoof et al. [22] found that the injection of only 6 ppm of surfactant had a dramatic effect on the drag reduction in a Taylor–Couette set-up, reducing it...
from 40% to just 4%, for a global air volume fraction of $\alpha = 4\%$. They estimated the Weber number $\text{We} = \rho u'^2 d_{\text{bubble}} / \gamma$, where $\rho$ is the fluid density, $u'$ represents the velocity fluctuations, $d_{\text{bubble}}$ is the bubble diameter and $\gamma$ is the surface tension. The Weber number quantifies the deformability of the bubbles, by comparing the drag force of a bubble with surface tension forces. Verschoof et al. [22] found that bubbles with higher Weber numbers, i.e. deformable bubbles, are much more effective for drag reduction. This was in accordance with earlier observations [19,20]. It is important to note that there are certain differences between a water channel and a Taylor–Couette set-up. Whereas in channel flow and flat-plate experiments there is a distinct gravitational force, in Taylor–Couette flow bubbles experience a centripetal force (and the effect of gravity is minimal for the fully turbulent case). Also, in Taylor–Couette flow there is no developing boundary layer as in channel flow or flat-plate experiments.

Salts have a marked effect on the kinetics and dynamics of bubbles in flows [44,45]. Bubble sizes in turbulent flows are governed by a dynamic equilibrium between bubble splitting and bubble coalescence events. This equilibrium can be affected by salts which inhibit the coalescence of bubbles. Some combinations of ions will inhibit the coalescence of bubbles, whereas others do not have an effect on bubble coalescence [44]. Sodium chloride is among those salts that inhibit bubble coalescence. With increasing salinity, the equilibrium bubble size decreases monotonically, indicating that the inhibition of coalescence becomes stronger. At a critical concentration, the equilibrium bubble size is not affected any more [46–49]. This critical concentration depends on the type of salt and on the bubble size [47,50].

In this paper, we investigate the effect of water quality, more specifically the sodium chloride concentration, on bubbly drag reduction. We employ the Twente Turbulent Taylor–Couette (T³C) facility [51], with which we have previously measured bubbly drag reduction in clean water [19]. The concentration of sodium chloride is varied from that of decalcified water to the concentrations found in ocean water. We measure the friction of the flow on a wall. The size of the bubbles is measured using high-speed imaging, and we relate the bubble size to the measured drag reduction.

The paper is organized in the following way. In §2, we introduce the T³C facility, the set-up and the experimental conditions. Section 3 discusses the results. We draw conclusions in §4.

2. Experimental set-up and control parameters

The Taylor–Couette geometry [52] consists of two concentric cylinders that can rotate independently. Taylor–Couette flow displays a wide variety of flow phenomena [53–55]. The system has been referred to as the hydrogen atom of fluid mechanics [56]. The Taylor–Couette geometry is a closed system and has, therefore, a well-defined energy balance, where all the energy inserted by driving the flow is dissipated by the turbulence [57].

In analogy with Rayleigh–Bénard convection (the flow between a heated bottom plate and a cooled top plate), where heat is transported [58], in Taylor–Couette flow angular velocity is transported [57]. In Rayleigh–Bénard convection the heat transport is characterized by the Nusselt number (the convective heat transport over the conductive heat transport) and, in analogy, in Taylor–Couette flow the angular velocity transport can be characterized by the angular velocity Nusselt number, $\text{Nu}_\omega$, which is the ratio of the angular velocity transport to the angular velocity transport in the laminar, non-vortical, flow state. This Nusselt number can be expressed as $\text{Nu}_\omega = \tau / \tau_{\text{lam}}$, where $\tau$ is the torque measured on the inner cylinder and $\tau_{\text{lam}} = 4\pi L \nu l (\omega_i - \omega_o) (r_i^2 r_o^2) / (r_o^2 - r_i^2)$ is the torque on the inner cylinder for the laminar (non-vortical) case, with $L$ being the length of the inner cylinder, $\nu_i$ and $\rho_i$ the viscosity and density of the fluid, respectively, $\omega$ the angular velocity and $r$ the radius of the cylinder; here the subscripts $i$ and $o$ refer to the inner and outer cylinders, respectively.
Figure 1. Schematic of the T³C set-up [51] (bubbles not to scale). The solid lines on the inner cylinder show the three sections of the inner cylinder. The torque is measured on the middle section. Red dashed lines show the field of view (30 mm × 30 mm) of the camera, which is positioned at midheight, \( z = L/2 \).

Whereas in Rayleigh–Bénard convection the (thermal) driving is given by the Rayleigh number, in Taylor–Couette flow the (mechanical) driving is given by the Taylor number:

\[
Ta = \frac{1}{4} \sigma \frac{(r_o - r_i)^2(r_o + r_i)^2(\omega_i - \omega_o)^2}{\nu^2},
\]

where \( \nu \) is the kinematic viscosity of the working fluid and \( \sigma = (1 + \eta)^4/(16\eta^2) \) can be seen as the quasi-Prandtl number [57], which is solely determined by the radius ratio \( \eta = r_i/r_o \). For measurements where the working fluid contains bubbles, we correct the density and the viscosity using the Einstein equation [59], as was done previously [19,22,34,35,38]:

\[
\rho = (1 - \alpha) \rho_l \tag{2.2}
\]

and

\[
\nu = \left(1 + \frac{5}{2} \alpha \right) \nu_l \tag{2.3}
\]

where \( \rho_l \) and \( \nu_l \) are the density and the viscosity of the carrier liquid (see table 2), respectively, and \( \alpha \) is the global air volume fraction.

The experiments are performed in the T³C set-up [51]; see figure 1 for a schematic. The acrylic outer cylinder allows good optical access to the flow. Multi-phase flows have been widely studied in the Taylor–Couette geometry [60–64], often in the context of drag reduction by air lubrication [18,19,22–25,33–35,65].

In the current study, only the inner cylinder of the T³C set-up is rotated, while the outer cylinder is kept stationary. The inner and outer cylinders have radii of \( r_i = 0.2000 \text{ m} \) and \( r_o = 0.2794 \text{ m} \), respectively, resulting in a gap width of \( d = r_o - r_i = 0.0794 \text{ m} \) and a radius ratio of \( \eta = r_i/r_o = 0.716 \). The height of the set-up is \( L = 0.927 \text{ m} \), giving an aspect ratio of \( \Gamma = L/d = 11.7 \).

As indicated in figure 1, the inner cylinder is divided into three sections. We measure the torque only on the middle section of the inner cylinder to prevent any influence of the (stationary)
end plates. We connect the driveshaft with the middle inner cylinder using an Althen hollow axis torque transducer with a range of ±225 Nm and 0.25% accuracy. For more details on the T³C set-up see [51].

The measurement volume is cooled by actively cooling the bottom and top end plates. The temperature inside the measurement volume is measured with three Pt100 temperature sensors mounted flush in the inner cylinder. During a measurement the temperature of the working fluid is kept constant to within 1 K. The viscosity and density of the working fluid are calculated using the measured mean temperature, and their values at $T = 21^\circ C$ are listed in table 2.

As the working fluid we use decalcified water. The water was analysed using ion chromatography to measure the concentrations of ions already present in it (see table 1). The water contains little calcium and magnesium, but does contain sodium and chloride. However, we found these concentrations to be negligible relative to the concentrations used in our experiments. Initial experiments by us using ultrapure MilliQ water have yielded results no different from those with decalcified water. The measurement volume is filled entirely with water for the reference case. In the drag-reduction cases, we fill 96% of the volume with water and leave 4% filled with air, i.e. the average air volume fraction is $\alpha = 4\%$. The turbulence is strong enough to entrain all the air and distribute the bubbles throughout the entire domain. We add industrial-grade sodium chloride to the system in concentrations of up to 35 g NaCl/kg solution (3.5% (w/w)), corresponding to the concentration of salt present in standard ocean water. We use the relative salinity, defined in equation (2.4), where $\tilde{S}$ is the salinity in the measurement and $S_{\text{ocean}}$ is a salinity of 35 g of salt per kilogram of solution:

$$\tilde{S} = \frac{S}{S_{\text{ocean}}}. \quad (2.4)$$

We use high-speed photography, simultaneous to our torque measurements, to measure the sizes of bubbles in the flow (see figure 1). We use a Photron Mini AX200 high-speed camera with

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**Table 1.** Concentration of different cations and anions present in our working fluid (decalkified water).

| ion     | concentration (mg kg⁻¹) |
|---------|-------------------------|
| Na⁺     | 86.27                   |
| K⁺      | 3.23                    |
| Ca²⁺    | 0.69                    |
| Mg²⁺    | 0.052                   |
| Cl⁻     | 19.84                   |
| NO₃⁻    | 2.63                    |
| SO₄²⁻   | 45.48                   |

**Table 2.** Material properties for our working fluid at $T = 21^\circ C$: $\rho_l$ and $\nu_l$ are from Pereira et al. [71] and Aleksandrov et al. [72], respectively, $\gamma$ is taken from the model of Dutcher et al. [70], and $\rho$ and $\nu$ (thus including the effects of bubbles) are calculated according to equations (2.2) and (2.3), respectively, using $\alpha = 0.04$.

| $\tilde{S}$ | $\rho_l$ (kg m⁻³) | $\nu_l \times 10^{-6}$ (m² s⁻¹) | $\gamma'$ (mN m⁻¹) | $\rho$ (kg m⁻³) | $\nu \times 10^{-6}$ (m² s⁻¹) | $\rho / \gamma'$ | $10^4$ (l² m⁻³) |
|-------------|------------------|-------------------------------|-------------------|----------------|----------------------------|----------------|----------------|
| 0           | 998.1            | 0.9778                        | 72.8              | 958.2         | 1.0756                   | 1.317          |
| 0.5         | 1011.1           | 1.0034                        | 73.2              | 970.6         | 1.1038                   | 1.325          |
| 0.75        | 1017.6           | 1.0163                        | 73.5              | 976.9         | 1.1179                   | 1.330          |
| 1           | 1024.1           | 1.0299                        | 73.7              | 983.1         | 1.1329                   | 1.334          |
Figure 2. Torque measurements performed in the T3C set-up. The black line indicates the reference measurement with no air or salt, and the blue lines indicate measurements with an air volume fraction of $\alpha = 4\%$. The shade of the blue lines indicates the salinity, where the light blue line represents the decalcified water case and darker lines correspond to higher salinities. (a) Angular velocity Nusselt number, with the black dashed line representing the effective scaling $N_{\omega} \propto T_a^{0.4}$. (b) Drag reduction compared with the reference case, calculated according to equation (3.1).

3. Results and discussion

The torque on the inner cylinder is directly related to the skin friction on the inner cylinder, which is of key interest for marine applications. From the measured torque we calculate the drag. Using high-speed imaging we measure the sizes of the bubbles in the flow, which are used to estimate the Weber number characterizing the deformability of the bubbles. We relate the deformability to the measured drag reduction, since deformability has proven crucial for effective drag reduction [10,19–22].

(a) Torque measurements

We measure the drag experienced by the flow for salinities in the range of $0 \leq \tilde{S} \leq 1$ (see figure 2). The black line shows the response of the system in the reference case, where there is no air or salt ($\tilde{S} = 0$) in the system. The blue lines represent the measurements with an air volume fraction of $\alpha = 4\%$. Darker lines indicate a higher sodium chloride concentration.

Figure 2a shows the measured Nusselt number. For the reference case without bubbles and without salts, we observe an effective scaling of $N_{\omega} \propto T_a^{0.4}$, indicated by the black dashed line, as observed previously [66–69]. Air present in the system leads to reduction of the Nusselt number for all salt concentrations measured. The case of $\tilde{S} = 0$ has the lowest Nusselt number, i.e. the lowest drag. With increasing salinity the Nusselt number increases, so the angular velocity transport, and thus the drag, increases. Above $\tilde{S} = 0.75$ no significant difference in the Nusselt number is observed with further increases in the salinity. This could suggest that there is a critical concentration above which increasing the salinity has no additional effect.

The drag reduction is calculated by comparing the cases with bubbles to the reference case, i.e. using decalcified water as the working fluid with no bubbles or salt. All other measurements are compared with the reference data. The drag reduction (DR) is calculated as

$$\text{DR}(T_a) = \frac{N_{\omega}(T_a, \alpha = 0\%) - N_{\omega}(T_a, \alpha = 4\%)}{N_{\omega}(T_a, \alpha = 0\%)}; \quad (3.1)$$
The highest drag reduction is achieved for fresh water, i.e. $\tilde{S} = 0$, where we observe drag reduction of up to 40%, as previously reported [22]. The drag reduction becomes less effective with increasing salinity. No clear difference is observed when the salinity is increased above $\tilde{S} = 0.75$. For $\tilde{S} \leq 0.5$, the drag reduction increases with increasing Taylor number, whereas for $\tilde{S} \geq 0.75$, the drag reduction decreases with increasing Taylor number. We therefore find that in the current Taylor number regime there exists a critical salinity $0.5 \leq \tilde{S}_{\text{crit}} \leq 0.75$ at which we switch from increasing drag reduction to decreasing drag reduction with increasing Ta.

(b) Estimates of the Weber number

We capture images of the bubbles in the flow using a high-speed camera. We focus on bubbles close to the outer cylinder at $r \approx 0.275 \text{ m}$, since direct optical access close to the inner cylinder is limited because of the bubbles in the flow. The images are captured at a low frame rate, 50 fps, so as to obtain uncorrelated images and uncorrelated size distributions.

Typical images captured during the experiment are shown in figure 3. Images are captured at $Re \approx 10^6$ (shown in figure 3) and $Re \approx 2 \times 10^6$ (not shown). Increasing the salinity leads to smaller bubble sizes in the flow, due to the inhibition of coalescence. The larger bubbles, when $\tilde{S} = 0$, move in bubble clouds and are therefore not homogeneously distributed throughout the volume.

The bubble size is directly connected to the Weber number

$$\text{We} = \frac{\rho u^2 d_{\text{bubble}}}{\gamma},$$  \hspace{1cm} (3.2)

where $\rho$ is the fluid density, $u'$ represents the velocity fluctuations (the standard deviation of $u$), $d_{\text{bubble}}$ is the diameter of the bubble and $\gamma$ is the surface tension. For salt water, the presence of the ions will slightly modify the surface tension, and we use the model of Dutcher et al. [70] to find the surface tension of the salt water (see table 2). The smaller the size of the bubbles, and hence the smaller their Weber number, the more dominant surface tension becomes over the forces the bubbles experience in the flow. Therefore, the bubbles will deform less. The reduced size of the bubbles also decreases their Stokes number and thus increases their mobility, allowing for better mixing inside the flow. The bubbles will, therefore, be distributed throughout the measurement volume more uniformly.

We obtain the velocity fluctuations, which are needed to calculate the Weber number, from the measurements of van Gils et al. [19]. These authors measured the velocity fluctuations for a global air volume fraction of 3% in the same set-up as we use for our experiments. The velocity fluctuations at the position of the focal plane of the camera are estimated at 2.5% of the velocity of the inner cylinder.

We obtain the probability distribution of the Weber numbers of the bubbles captured by the camera (see figure 4). The top and right axes represent the bubble size distribution calculated with the density and surface tension of the decalcified water case. The axes are slightly off for the cases with salt, due to a slightly different conversion factor $\rho/\gamma$ in equation (3.2) for salt water (see table 2). The grey areas indicate regions where bubbles are too small to be (accurately) detected. The vertical dashed lines indicate the average values of the Weber number for the corresponding measurements. At $Re \approx 10^6$, figure 4a, the probability of the Weber number of all salinity cases peaks around $\text{We} \approx 0.6$. The range of Weber numbers is the widest at $\tilde{S} = 0$. At higher salinities the bubbles become more monodisperse. The long tail at high Weber numbers seen in the probability distribution for decalcified water disappears when salt is added to the system.

At $Re \approx 2 \times 10^6$, figure 4b, again we observe the highest Weber numbers in the fresh water case. For $\tilde{S} \geq 0.75$ most bubbles are too small to be accurately detected. Therefore, we could not obtain an accurate bubble size distribution and the corresponding Weber number distribution. The images for $\tilde{S} = 0.75$ and $\tilde{S} = 1$ seem to have very similar bubble size distributions when inspected by eye. We estimate that the mean bubble size is $d_{\text{bubble}} \approx 0.3 \text{ mm}$, corresponding to a Weber number of $\text{We} \approx 1.6$, as indicated by the corresponding vertical dashed line in figure 4b.
Figure 3. Representative images during measurements with (a) $\tilde{S} = 0$, (b) $\tilde{S} = 0.5$, (c) $\tilde{S} = 0.75$ and (d) $\tilde{S} = 1$. Images are captured at $Re \approx 10^6$ and a global air volume fraction of $\alpha = 4\%$ at midheight, $z = L/2$, close to the outer cylinder, $r_{focal} \approx 0.275$ m. The field of view is approximately $30 \text{ mm} \times 30 \text{ mm}$. Corresponding videos are included in the electronic supplementary material.

We find that the sizes of the bubbles and their corresponding Weber numbers are not further affected when the salinity is increased above $\tilde{S} = 0.75$. This would suggest that the coalescence is not further inhibited by the presence of extra salts. The resulting critical coalescence concentration ($\tilde{S}_{\text{CCC}}$) would be $0.5 \leq \tilde{S}_{\text{CCC}} \leq 0.75$. This is the same range in which we found $\tilde{S}_{\text{crit}}$, corresponding to the salt concentration at the transition of increasing drag reduction to decreasing drag reduction with increasing $Ta$. These two critical concentrations are deduced from two different observations, so we will treat them as two separate critical concentrations. It is also unclear whether the critical concentrations will always lie within the same range of salinity. The range in which we find the critical coalescence concentration $\tilde{S}_{\text{CCC}}$ agrees with the critical coalescence concentration found in Quinn et al. [48] for bubbles with sizes of the same order of magnitude in a flotation cell.

We compare the measured drag reduction with the Weber numbers observed at $Re \approx 2 \times 10^6$. The highest drag reduction is observed for the fresh water measurements, where also the highest bubble Weber numbers are observed. Increasing the salinity decreases the Weber numbers of the bubbles, and correspondingly the drag reduction decreases. When the salinity is increased above $\tilde{S} = 0.75$, the bubble sizes and their corresponding Weber numbers are not further affected. This coincides with the observation that the measured drag reduction is not affected by an increase of
salinity above $\tilde{S} = 0.75$. These observations confirm that bubble size and deformability are of key importance for effective bubbly drag reduction.

The near-wall void fraction is often considered to be an important parameter for bubbly drag reduction (see e.g. [7, 14]). Although we have not measured the local void fraction, we can obtain values in the case of decalcified water from the measurements of van Gils et al. [19]. From these measurements, we see that the local void fraction near the inner cylinder is higher than in the bulk of the flow. For the cases with higher salinity, the bubbles are smaller and are therefore less affected by the centripetal forces and more easily transported by the turbulence. It is likely that these bubbles are more evenly distributed throughout the measurement volume. We cannot exclude the possibility that a change in the distribution of the bubbles also plays a role in the observed change in drag reduction, as we are unable to alter the Weber number of the bubbles without changing the Stokes number as well. Numerical investigations could offer more insight in this regard.

Comparison with the results of Verschoof et al. [22] indicates that sodium chloride has a less strong effect on the observed Weber numbers and drag reduction than surfactants. While sodium chloride is not as effective as surfactants in decreasing the drag reduction, it still has a non-negligible effect.

4. Conclusion

We have experimentally investigated the effect of salt on bubbly drag reduction in Taylor–Couette turbulence. By adding sodium chloride to the system, the salinity of the working fluid is increased from that of fresh water to the average salinity of ocean water. We perform torque measurements combined with high-speed imaging to relate the change in drag reduction to the size of bubbles in the flow.

Whereas in fresh water, for a global air volume fraction of 4%, a drag reduction of up to 40% is achieved, the drag reduction becomes less effective with increasing salinity. We observe a critical salinity, $0.5 \leq \tilde{S}_{\text{crit}} \leq 0.75$, where we switch from increasing drag reduction to decreasing drag reduction with increasing $Ta$. Above $\tilde{S} = 0.75$, increasing the salinity has no further effect on the measured torque and drag reduction.
From the high-speed recordings we obtain the bubble size distribution and calculate the Weber numbers of the captured bubbles. Salts inhibit bubble coalescence; therefore, the bubbles observed in flows containing salts are smaller and have lower Weber numbers. Above $S \approx 0.75$, an increase in salinity has no further significant effect on the bubble sizes observed in the flow. This indicates a critical coalescence concentration in the range of $0.5 \leq S_{\text{CCC}} \leq 0.75$. This range agrees with the critical coalescence concentration of sodium chloride observed in other experiments [48].

We relate the Weber number of the bubbles, which characterizes their ability to deform, to the measured drag reduction. Flows with high-Weber-number bubbles have high drag reduction, whereas flows with lower-Weber-number bubbles have less effective drag reduction. For salinities of $S \geq 0.75$, an increase in salinity has no significant effect on the measured drag reduction and Weber numbers of the bubbles in the flow. These findings confirm the importance of bubble size and deformability for effective bubbly drag reduction [19,22].

Our new findings show that considering the mineral content of water is important when investigating bubbly drag reduction for marine applications. In future investigations, we plan to look into the effects of other salts present in ocean water on bubbly drag reduction. Our aim is to characterize the effects of the salts individually and all combined to mimic seawater more closely.

Data accessibility. Data for figures 2 and 4 are provided in the electronic supplementary material [73].

Authors’ contributions. L.J.B.: data curation, formal analysis, investigation, writing—original draft, writing—review and editing; D.L.: conceptualization, funding acquisition, supervision, writing—review and editing; S.G.H.: conceptualization, funding acquisition, supervision, writing—review and editing.

All authors gave final approval for publication and agreed to be held accountable for the work performed therein.

Conflict of interest declaration. We declare we have no competing interests.

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