Decreasing frictional resistance by air lubrication

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Abstract

The decrease of ship resistance is one of the most effective way to reduce operating costs and CO_2 production. The wave making resistance and form drag can be reduced by optimizing the hull form, but the frictional drag remains proportional to the wetted surface. The use of air as a lubricant in order to reduce that frictional drag is an active research topic and three techniques are identified: injecting air bubbles in the boundary layer, the use of air films along the bottom plating, and using air cavities in the ship's bottom. These approaches are the research topic for the Dutch joint-research project PELS and the EU project SMOOTH, both of which have the goal of not only predicting energy savings using numerical models and model tests, but proving it using full-scale demonstrator ships adapted for air lubrication. Although decreases in frictional resistance of nearly 20% have been obtained on model-scale ships, experience shows that the implementation of air lubrication can also easily increase the resistance of a ship.

Introduction

The increase in fuel costs and looming restrictions on carbon dioxide emissions are driving the ship owner into reducing the ship resistance and required installed power. The propulsive efficiency using the propeller is often good and it is difficult to gain a few percent. Thrust augmenting devices such as high-efficiency rudders and kites will undoubtedly be prevalent in the future. Reducing the required propulsive thrust is a more direct means to lower operating costs and can even be used in conjunction with thrust augmenters to further sharpen the competitive edge of the ship owner. The main components of ship resistance consist of resistance due to wave drag, pressure drag, and frictional drag. The wave and pressure (form) drag can be optimized by carefully manipulating the lines of the vessel, but frictional resistance remains proportional to the wetted surface and the square of the ship speed. As this resistance drag is by far the largest resistance component in normal operating speed ranges, any reduction of this component will have an immediate and favorable influence on the performance of the vessel. Such reductions can be achieved by compliant coatings, ribblets, polishing the surface, or polymer injection; measures that are not very practical for ships. A promising technique to obtain lower frictional resistance is using air as a lubricant to reduce the wetted surface of the ship.

Three distinct approaches are identified: the injection of bubbles, air films, and air cavity ships. The first technique, bubble injection, is a direct means to reduce the friction of the ship by positive interaction with the boundary layer. When the bubbles are within 300 viscous wall units —defined as $l = \nu / u_0^*$ and u_0^* the friction velocity of the fully-wetted flow $u_0^* = \sqrt{\tau / \rho}$ —the effect of air lubrication can be measured in laboratory tests, indicating a strong dependence on the boundary layer (Sanders et al., 2006). When the bubbles are farther away from the wall, no effect is measured. The use of air films is self-explanatory; the air film separates the water from the hull thus reducing friction. Air cavity ships are vessels that have a series of openings in the bottom where a free surface is formed. The downside of all three techniques is that it is surprisingly easy to increase, rather than to decrease, the resistance and that many aspects of the behavior of air in water are poorly understood. For example, the full-scale demonstrator vessel Seiun Maru showed a 2% decrease at only a limited speed range with an increase in required power over most over its speed range, notwithstanding huge resistance decreases tested at model scale.

The three approaches are the subject of two of MARIN's research projects, PELS (Project Energy-saving air-Lubricated Ships) and SMOOTH (Sustainable Methods for Optimal design and Operation of ships with air lubricaTed Hulls). PELS is a Dutch research consortium and SMOOTH is an EU-funded consortium both consisting of ship owners, ship yards, paint manufacturers, model basins, and universities. The main goal is not only to perform model experiments, but also to demonstrate the effect on full-scale ships. Simultaneously, MARIN is a partner in a PhD research project focusing on understanding the fundamental mechanisms of air lubrication together with the Laboratory of Hydro and Aerodynamics at the University of Delft and the Physics of Fluids department at the University of Twente.

Micro Bubbles

The application of micro bubbles is an often-named candidate for resistance reduction, as it ideally requires a small conversion of an existing ship hull and no resistance increase is experienced when the pump system fails. But there is some uncertainty on the size of what can be defined as a micro bubble. As the bubble increases in size, so does its tendency to deform in the shear and turbulent fluctuations of the flow (typically when their Weber numbers exceed unity) and it is no longer a micro-bubble. A distinction between bubble drag reduction and micro-bubble drag reduction is required. For the micro-bubbles, experiments with flat plates show a spectacular resistance decrease as large as 80%. This resistance decrease is thought to originate by favorable interaction with the boundary layer and not through the reduction of viscosity. In fact, viscosity increases by the injection of micro-bubbles. The production of these small and undeformable on a ship-wide scale is difficult and major scale effects are present.

The mechanisms by which friction is reduced is unclear. It can be simply a reduction in density, modifying turbulence or perhaps even by bubbles merging and splitting. At very low speeds, around 1m/s, bubbles with a diameter of only a few viscous length scales of the flow can generate a 10% decrease in resistance at only 1 volume percent of air in the boundary layer (Olivieri et al., 2005, Park & Sung, 2005). At more realistic flow speeds of 5m/s to 15m/s, this viscous length scale drops rapidly enforcing a small bubble that is difficult to produce in large quantities. Moriguchi & Kato (2002) used bubbles between 0.5mm and 2.5mm and measured up to a 40% decrease in resistance, but for air contents over 10%. Shen et al. (2005), using smaller bubbles between 0.03mm and 0.5mm, found a 20% drag reduction at an air content of 20%. No appreciable influence of bubble size was found.

Sanders et al. (2006) performed experiments with a very large flat plate over 10m in length with speeds up to 20m/s. This experiment allowed for tests at Reynolds numbers that were hitherto not obtainable at model scale with bubbles ranging from 0.1mm to 1.0mm. The experiments showed that the bubbles were pushed out of the boundary layer a few meters behind the air injectors, even when the bubbles were injected at the lower side of the plate. A nearly bubble-free liquid layer was formed near the wall and the effect of air lubrication almost vanished. It is hypothesized that the lift force experienced by a bubble in the boundary layer is more than sufficient to overcome the buoyancy of the bubble. This experiment indicates that a strong Reynolds-scale effect is present for model testing with bubble injection.

In order to increase our understanding of the behavior of bubbles in air layers, an extensive research program with Technical Universities of Delft and Twente has started. At the University of Twente, test will be performed with a Taylor-Couette setup, consisting of a thin water channel between to counter-rotating cylinders. This setup has the advantage that it allows for statistically stationary flow and accurate resistance measurements by means of the applied torque on the rotating drum. Moreover, the bubble distribution in this stationary case will be measured, and its effect on the overall torque will be theoretically analyzed. Research by van den Berg et al. (2005) showed that the resistance decreased only after exceeding a Reynolds number of nearly 1 million. At this point, the bubbles can no longer be considered undeformable. Kitagawa et al. (2005) found that bubbles deformed with a favorable orientation with respect to the flow, reducing turbulent stress as the flow field around the bubble is more isotropic. However, other mechanisms are possible, such as compression (Lo et al. 2006) or bubble splitting (Meng & Uhlman 1998). At the University of Delft, the drag reduction will be studied in a non-stationary flow over a flat plate. The stability of the air film, the breaking up in bubbles and the injection of bubbles will be visualized with high-speed cameras and measured by means of Particle Imaging Velocimetry. The drag reduction itself will be measured with existing and experimental shear stress sensors.

The advanced inland shipping concept of the Futura carrier is the topic of research on the EU-funded program SMOOTH, displayed in Figure 1. This vessel, christened the *Till Deymann*, is fitted with an air injection system. It is propelled by four thrusters, two at the stern and one in a tunnel in each of the two bows of this semi twin-hull bow. These forward thrusters give the *Till Deymann* exceptional maneuvering characteristics, but an increase in skin friction at the tunnel due to the high speeds induced by the propeller. Local air injection is therefore a viable option to improve performance,

Figure 1 The Futura carrier *Till-Deymann*, a full-scale test ship for bubble injection, showing its typical semi twin-hull bow.

Air layers

The air layer concept can be seen as a combination of micro bubbles techniques and air cavity ships. An air stream is injected into the bottom region of a ship and an air film forms. This air layer is subjected to influences as turbulence and the natural instabilities that occur on any fluid-liquid interface. Fukada et al. (2000) compared the effect of air injection for a series of objects with a water repellant paint applied to the test objects. With an air film of half a millimeter thick, a drag reduction of 90% was obtained although no Reynolds effects were taken into account. Shimoyama carried out experiments with air film lubrication on a flat plate and for model ships, all without a water-repellent coating (His results are described by Kato & Kodama, 2003). They managed to obtain drag reduction, but had difficulties in obtaining a stable air film, especially at higher flow Reynolds numbers. They noted that the air layer can increase the frictional drag when the liquid-gas interface become instable, resulting in breaking up the layer in larger sized bubbles that also may reduce frictional drag. On the other hand air injection of bubbles may also lead to patches of air films and therefore the two techniques are closely related with the properties of the surface treatment (coating) as a main parameter influencing the results. The application of such so-called hydrophobic coating explains the participation of paint manufacturers in may research programs for drag reduction by air.

Air cavity ships

The air cavity ship or ACS, is a vessel with several recesses in its bottom that need to be filled with air, see Figure 2. Of course, these cavities can only be fitted to a flat horizontal surface. For the length of the air cavity no wetted surface is present whatsoever, leading to a local but effective drag reduction. However, a standing wave is created in the air cavity and the fluid-air interface must re-attach smoothly at the end of the cavity. A simplified model of a two-dimensional cavity is given by Matveev (1999) and MARIN calculated the wave pattern in a barge with many air cavities with RAPID, a fully non-linearized potential flow code. Obtaining correlation with model experiments, however, proved to be less straight forward than expected.

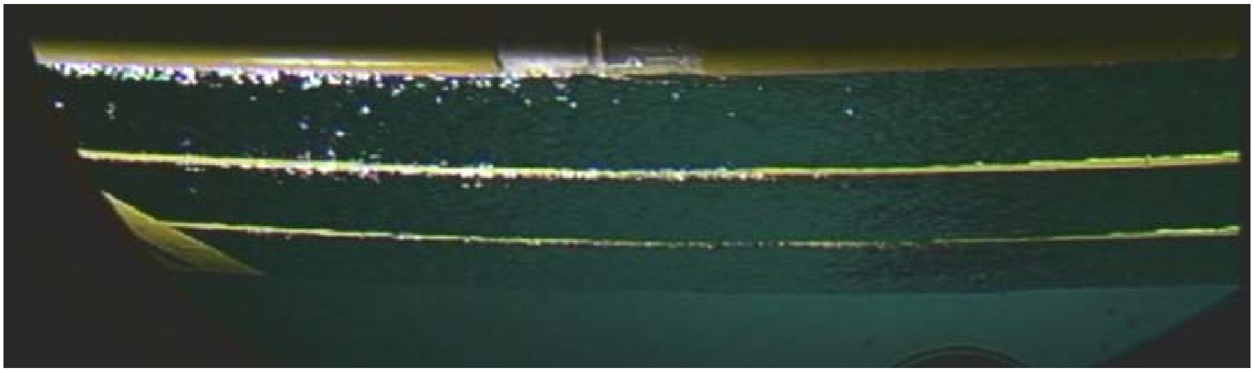

Figure 2 Side-view of an ACS tested for SMOOTH at SSPA, Sweden, with three large air cavities per section. Flow direction from left to right.

A distinct disadvantage of the ACS is that air can escape from the cavities when the ship is pitching and rolling in seaway and that its stability is negatively affected by the creation of additional free surfaces. This means that the ACS is a technique that can be ideally suited for inland ships, a sector where exhaust and carbon dioxide emissions restriction regulations are expected to be imposed in the near future. The ACS has the added advantage that it can actively improve its stopping behavior by releasing air from the cavities, a feature relevant for the busy inland traffic.

The project PELS and its successor PELS II focus on the application of air cavities on a full-scale ship, in this case a barge. The vessel from the project PELS-I is presented in Figure 3 with a good view of its bottom in Figure 4. But from an initial series of model tests it became readily apparent that it is far easier to increase the resistance, even after an optimization of the air cavities using computational fluid dynamics. Several configurations were tested, changing the number and size of the cavities along both the length and width of the vessel, but none reduced the resistance of the model. A careful appraisal of the results led to the conclusion that the flow over the bow of the vessel distorted the flow over the bottom to such an extent that no good configuration of air cavities was possible at all.

Figure 3 The segmented ACS vessel for the project PELS-I

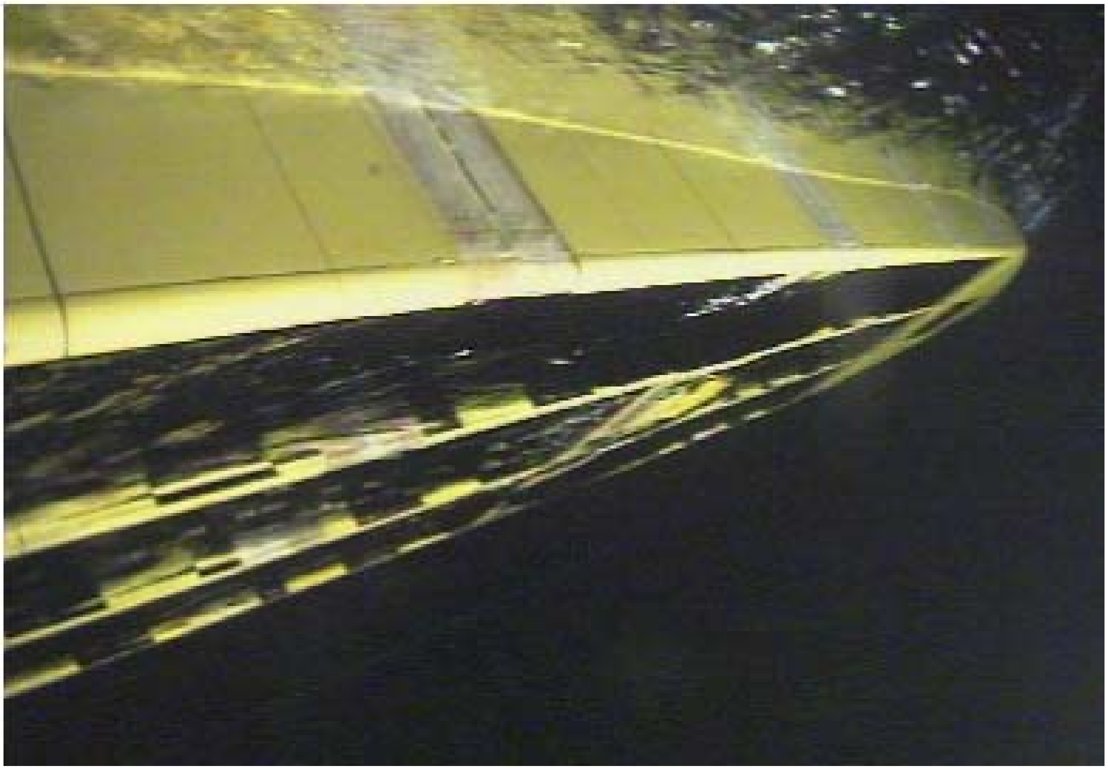

Figure 4 A submerged view the PELS-I vessel at speed, clearly showing the air layer trapped in the bottom.

To test this hypothesis, the barge was fitted with a new bow and the tests were repeated. This time the frictional resistance dropped 20% leading to an overall drag reduction well over 10%. This leads to the important conclusion that the application of air cavities to just any hull form without consideration and understanding of the local dynamics of the flow can have counterproductive results. It also underscores to ongoing need for verification, be it on model or full scale.

Extrapolation

The extrapolation of model-scale data to full-scale data for ships is a well-known procedure. The measured total resistance C_T—made dimensionless by dividing by $\frac{1}{2}\rho V^2 S$ with S the wetted area of the ship—is the sum of friction drag, form drag, and wave drag whereby the form drag is expressed as a fraction k of the frictional drag, so that the wave resistance is determined by

$$C_W^{REF} = C_T^{REF} - (1+k)C_F^{REF}$$

Customary with Froude-identity tests, the wave resistance coefficient remains the same at all scales and the frictional resistance is estimated by friction lines (e.g., ITTC ’57). For an air-lubricated ship, the reduction in resistance can be found by comparing the air-lubricated ship with the fully-wetted ship. For the ACS, the means that the air cavities during the model test must be fully closed off. Assuming for a moment that form drag and wave drag do not change for the air lubricated ship, then a new frictional resistance with air lubrication can be determined as

$$C_F^{AIR} = C_T^{AIR} - kC_F^{REF} - C_W^{REF}$$

From the combination of the reference and air lubricated test, a new frictional resistance curve can be determined. The change in frictional resistance is expressed in a second coefficient k_2 so that

$$k_2 = \frac{C_F^{AIR}}{C_F^{REF}}$$

It is noted that any effect of waves in the air cavities is fully considered an effect on frictional resistance at this point. The wave length in the air cavity is known to be Froude-dependent but the effect of both the reduction in drag in the change in wave resistance cannot be determined simultaneously for a resistance test. However, an example of the maximum spread in k_2 of one ACS configuration is plotted in Figure 5. Some variation is visible in k_2, which is not surprising considering the velocity-dependent drag of the waves in the air cavities, variations in wetted surface (i.e., degree of filling in the air cavity), or variations in model heel angle. The optimum configuration showed a value of $k_2 = 0.82$. The total resistance is now extrapolated to full scale as

$$C_T^{FS} = (k + k_2)C_F^{FS} + C_W^{REF} + C_A$$

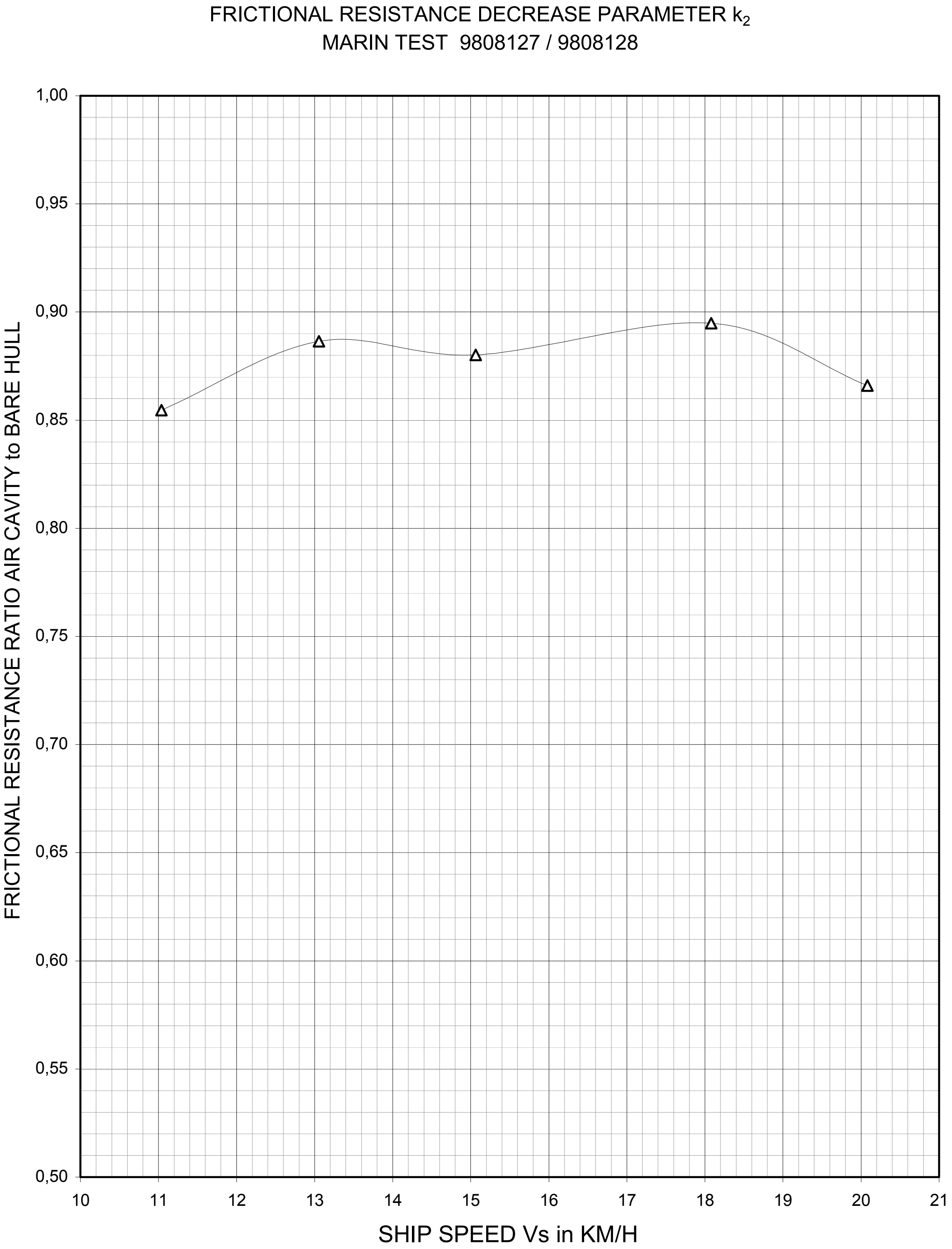

Figure 5 Ratio of frictional of an air cavity ship versus full hull, showing a 10.5% to 14.5% decrease in frictional resistance. Values up to 18% have been measured.

The correlation C_A can be estimated using an emperical function or regression analysis on the database of a model basin. From the constant value of k_2, an important conclusion can be drawn. The wave resistance is known to increase exponentially as the velocity of the ship increases, but the waves in the air cavity prefer a high ship speed to obtain a long wave length. This means that the application of air cavities results in a minimum ship velocity whereby the wave pattern is still favorable and a maximum ship velocity whereby the improvement in frictional resistance is still significant compared to the total resistance. This means that application of air cavities is only viable for a restricted speed range. For the optimum air cavity configuration of the model, the total resistance decreases 3% at model scale from a 11.5% to 12.5% range during extrapolation. Nevertheless. a total full-scale resistance decrease of a 8.5% to 9.5% range is an impressive reduction. This figure does not yet include the power losses required by the air compressors and ideally no or little air is lost with the ACS. Both air cavities and micro bubbles should be configured such that no air should enter the propeller as the reduction in density results in a reduction of thrust or increase in required power.

But uncertainties remain. Does the friction scale with plate-friction line formulae and to what extent is the correlation coefficient C_A valid for an air-lubricated vessel? This coefficient can easily comprise of 20% of the vessel resistance, more than able to negate any favorable resistance reduction by air lubrication. Without a full understanding of the mechanisms of air lubrication and its scaling mechanisms, tests with full-scale ships are required. From these tests it can be determined how effective the various approaches in air lubrication are and how much air and pumping power is required in service conditions

Future outlook

Drag reduction by air lubrication is a very active and actual research topic. MARIN is participating with universities to investigate the interaction between bubbles, turbulence, and boundary layers to from an understanding of the mechanisms of bubble drag reduction. Model scale tests for both resistance and propulsion, and maneuvering and sea keeping are being performed with all types of air lubrication. Full-scale trials are planned for both an air cavity ship and a vessel with bubble-injection.

For sailing yachts, air cavities and air films do not seem readily applicable considering the large heeling angle during sailing and the absence of any flat bottom. But the application of special paints and bubble-injection of a ship is a promising application. The Reynolds effects of yachts are several order of magnitude less than for a bulk carrier or container ship. For larger ships, unknowns remain on both ends of the scale ladder, ranging from uncertainties in bubble-boundary layer interaction to the extrapolation to high Reynolds numbers.

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