Reducing Friction with Passive Air Lubrication: Initial Experimental Results and the Numerical Validation Concept of AIRCOAT

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Abstract

The EU project AIRCOAT aims to develop a passive air lubrication technology for ships. Using self-adhesive foils instead of paints and inspired by the Salvinia effect, an air coated ship hull is meant to reduce friction, biofouling, corrosion and noise. This paper outlines the validation concept to quantify the potential friction reduction for a micro-structured air keeping surface for ships. It further describes the experimental setup of the visualization flow tank to investigate velocity profiles and the validation of the CFD code by simulating the HSVA HYKAT and preliminary friction reduction results from the SVA friction tunnel experiments.

1. Introduction

Active air lubrication is considered as an energy saving technology of high potential for the shipping industry. It is well known that frictional forces are proportional to fluid viscosity, giving rise to a strong motivation to lower the viscosity of the fluid. Without bubble size regulation and monitoring, inducing air in form of bubbles into the boundary layer mainly modulates the viscosity of water *Busse and Sandham (2012), Verschoof et al. (2016)*. Experiments with injecting small bubbles can produce a drag reduction of up to 22%, *Butterworth et al. (2015), Van den Berg et al. (2005)*. Active air lubrication system are already commercially available and demonstration tests show net average energy efficiency savings of up to 4.3 %, *Shell (2015)*. Such active air lubrication systems require injection of air upstream in order to maintain a finite mass flow, *Elbing et al. (2008)*.

1.1. A bioinspired air keeping surface

Contrary to active air lubrication, the aim of the current EU project AIRCOAT (Air Induced friction Reducing ship Coating) is to develop a passive air lubrication technology inspired by nature. The bioinspired technology mimics the floating water fern ‘Salvinia molesta’, which forms a permanent air layer when submerged in water *Barthlott et al. (2010)* and is able to maintain a stable air layer under pressure, *Gandyra (2020)*. The special surface structure and resulting properties of the coating suffice to establish and retain an air layer. This means that no additional air or energy have to be supplied and the air layer also remains effective when the ship is not moving, setting AIRCOAT apart from bubble inducing systems available on the market.

Based on this so called Salvinia effect, that is enabled by specific surface topology (and a combination of hydrophilic and hydrophobic areas), the team of nanotechnologists from the Karlsruhe Institute of Technology (KIT) developed an artificial surface that can maintain an air layer under water for several years. This technology was transferred onto self-adhesive foils in AIRCOAT and can be used to coat ships, boats and other marine structures, Fig.1. For an overview of the concept see Fig.2 in *Oeffner et al. (2020)*. The AIRCOAT foil creates a thin permanent air layer between the immersed hull and the surrounding water, resulting in two major benefits. On the one hand, there will be a significant reduction in frictional resistance. The potential is massive: Estimations assuming friction coefficient reduction scenarios from 2-20% for an AIRCOAT foil applied to the global IMO-registered fleet could reduce annual fuel cost by millions of Euros, *Oeffner et al. (2020)*. On the other hand, the air layer will form a physical barrier for marine organisms, preventing the attachment of biofouling and thus the increase of frictional resistance over time.

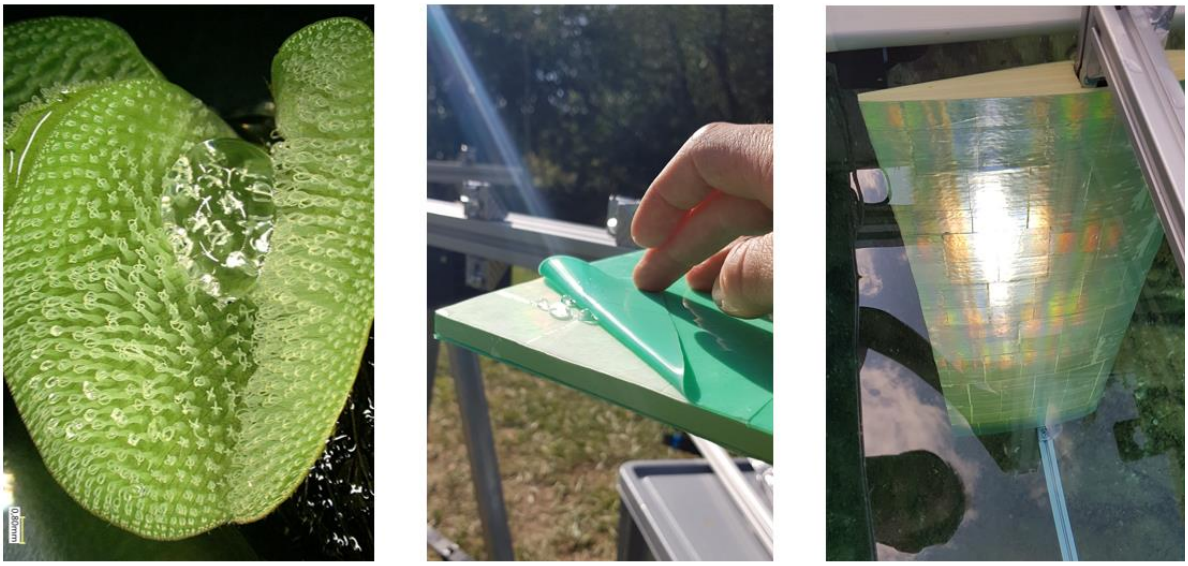

Fig.1: Images of the biological template (‘Salvinia molesta’) with a water droplet (indicating the Salvinia effect) on its surface with the characteristic eggbeater shaped structures (left); the AIRCOAT foil with a water droplet on its surface on land (middle) applied on a foil section and submerged in water (right). Here, the rainbow coloured reflections show the air layer.

Transferring the small microstructure characteristics of a Salvinia plant onto sea going ships (e.g. container ships) – which are among the largest maritime macrostructures – and demonstrating its effectivity is an ambitious task that involves a well-defined validation method. The AIRCOAT project does this by means of combining experimental and numerical methods to upscale results from laboratory prototypes to application of full-scale solutions in operational environments. Here, small- and large-scale laboratory experiments will investigate the air retaining and friction reducing capabilities of the surface. Visualisation techniques will be used to determine the phenomena occurring at the air-water interface. In parallel, a set of numerical studies at different levels (small, large and full scale) will be carried out to estimate the drag reduction for a sea going ship coated with AIRCOAT.

1.2. Friction Reduction of AIRCOAT

A fluid flowing along an immovable solid wall is subject to the no-slip condition and thus forms a boundary layer through which the fluid velocity increases from zero (at the wall) to freestream velocity normal to the surface. If the fluid flows along a liquid/gas interface the conditions differ. In the case of AIRCOAT, where an air layer exists between liquid and solid surface, a reduction in normal velocity gradient occurs. One can say, that part of the boundary layer lies within the air layer which allows a certain amount of slip between the wall and the water, the so-called slip velocity, Fig.2.

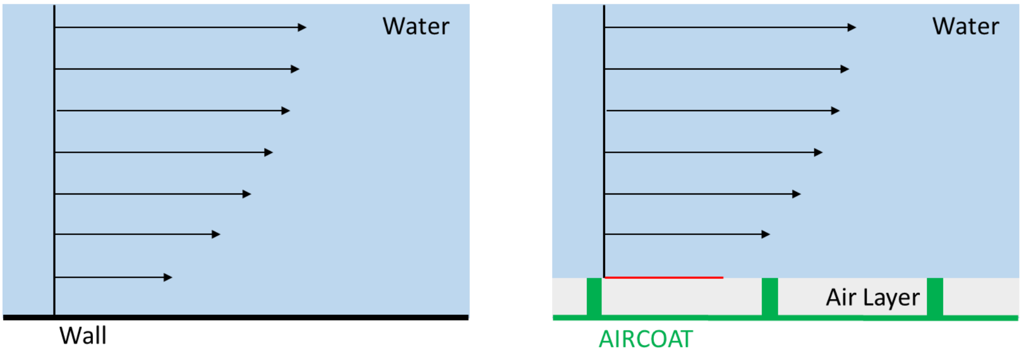

Fig.2: Boundary layer of surface without and with AIRCOAT applied. Black arrows indicate velocity profile normal to a solid wall with zero velocity due to no-slip-condition (left) and normal to an air layer (right), where slip velocity (red)occurs at the air/water interface.

Since the velocity gradient at the phase boundary determines the shear stress and the gradient is at its maximum at the wall, friction is reduced, *Busse and Sandham (2012)*. Ideally, the boundary layer would be entirely contained in the air layer. However, the resulting air layer would be unstable. Additionally, the air needs to adhere to the hull which necessitates areas of contact between the hull and the water on the microscopic scale. This physical constraint further lowers the achievable reduction in friction, the quantification of which is a major task of the AIRCOAT project.

1.3. Validation difficulties

One of the major challenges in this validation process is reaching Reynolds numbers in the order of magnitude typical for ships (approx. 10^9). In model tests a low viscosity fluid can be used to increase the Reynolds number for friction experiments. Since the air water interface is of particular importance in this case, changing the fluid is not an option which limits the achievable Reynolds number during experiments to about 10^7. The second experimental option would be to build a full-scale prototype which is not realistic within the time and budget of the project.

Due to the novelty of the AIRCOAT technology, the laws for scaling the effects from small to full scale application are yet to be determined. Thus, it is not known if and how the effects of AIRCOAT depend on the Reynolds number.

It was therefore decided to employ numerical methods and simulate a ship at full scale to demonstrate the efficiency of the technology. However, resolving the microscopic surface structure and associated physics in such a macroscopic model is practically impossible. To overcome this drawback, the properties of the coating will be incorporated into a wall function. A combination of computational fluid dynamics (CFD) and experiments is utilised to design and validate this wall function.

2. AIRCOAT's drag reduction validation concept

Starting from low Reynolds numbers (10^0) and small probe lengths (10^{-2} m), test body dimensions and flow speed during the experiments will be gradually increased for the various experiments until reaching the maximum lengths of 8 m and Reynolds numbers of Re = 10^7, respectively.

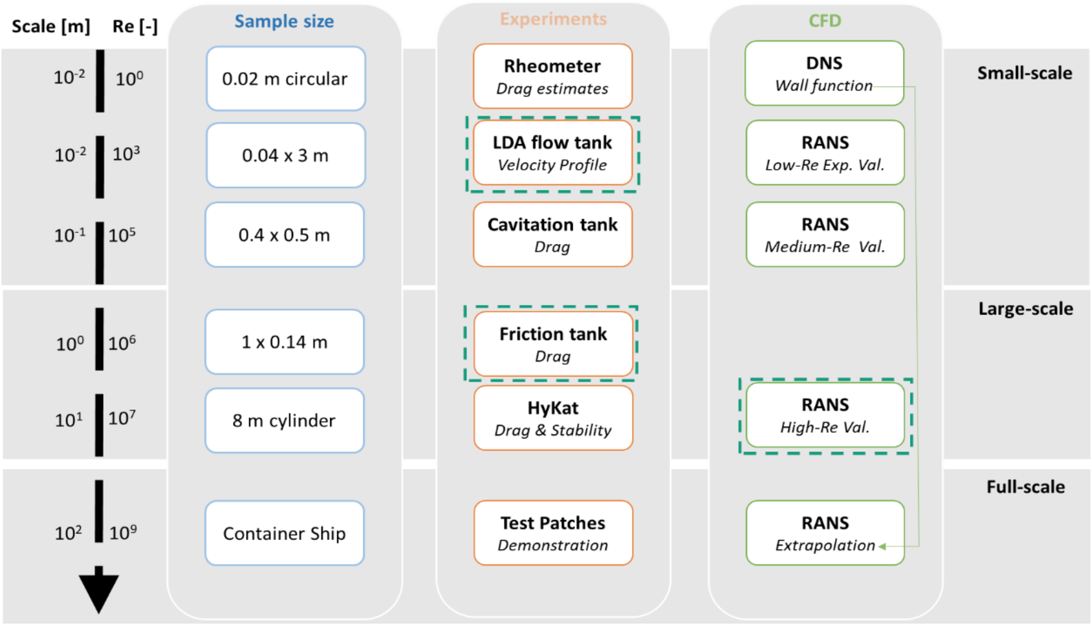

Fig.3: AIRCOATs validation process chain from micro to macroscopic scales (top to bottom) by means of increasing sample sizes and Reynolds numbers at different experiments which are validated by numerical simulations (CFD) in order to allow for a final full-scale extrapolation. Green dashed boxes represent the focus items of this paper.

Investigations will be conducted at three scales: Small- and large-scale laboratory experiments will investigate the air retaining and friction reducing capabilities of the surface. Visualization techniques will be used to determine the phenomena occurring at the air-water interface. In parallel, a set of numerical studies at different levels (small-, large- and full-scale) will be carried out in order to validate the codes and gain additional insight into the flow phenomena around the phase boundary. Experiments and Numerical simulations complement each other.

The final full-scale validation to estimate the drag reduction for a sea going ship virtually coated with AIRCOAT will be conducted with a RANS code equipped with an AIRCOAT specific wall function. The entire process chain for validation of AIRCOAT is depicted in Fig.3 and further described in the following subchapters.

This paper will focus on three items of the above explained process chain for which Fraunhofer CML is in charge within the AIRCOAT project: LDA flow tank design, friction tank experiments and AIRCOAT RANS model validation (see dashed green boxes in Fig.3).

2.1. Small-scale

Small-scale experiments with max samples size of 0.2 sqm allow for quick testing in incremental steps while the AIRCOAT surface is constantly readjusted in parallel based on test results. Very low Reynolds number experiments (Re ~ 6) with Rheometer will be done to get drag estimates. To develop the wall function, results from rheometer measurements, DNS simulations and advanced visualization techniques will be coupled. For the latter, Laser Doppler Anemometry (LDA) experiments at low Reynolds numbers (Re ~ 9000) will be done to determine an actual velocity profile normal to the AIRCOAT surface. Furthermore, cavitation tank experiments at medium Reynold number ($Re = 2.27 \cdot 10^6$) shall give initial information on drag reduction at medium Reynolds numbers.

2.1.1. LDA flow tank design

In order to perform the LDA experiments, a gravity driven flow tank has been designed by Fraunhofer CML, Fig.4. A main objective with this experiment is gathering information on the velocity profile, which requires establishing an undisturbed, fully developed flow in the measurement section. Consequently, the tank is designed to reach a maximum flow velocity of 0.5 m/s. Water is supplied to the main inlet from an overflow tank which is fed by a pump. Excess water is lead into another overflow basin to keep the water level in the main inlet constant, Fig.4, top left. These measures are taken to avoid inducing any turbulence and create a constant flow velocity. After acceleration in the vertical tube the flow is deflected to a horizontal direction and led through a rectifier to eliminate any off-axis flow. The length of the rectifier is defined by the diameter of the pipe and has to be minimum two times dI.

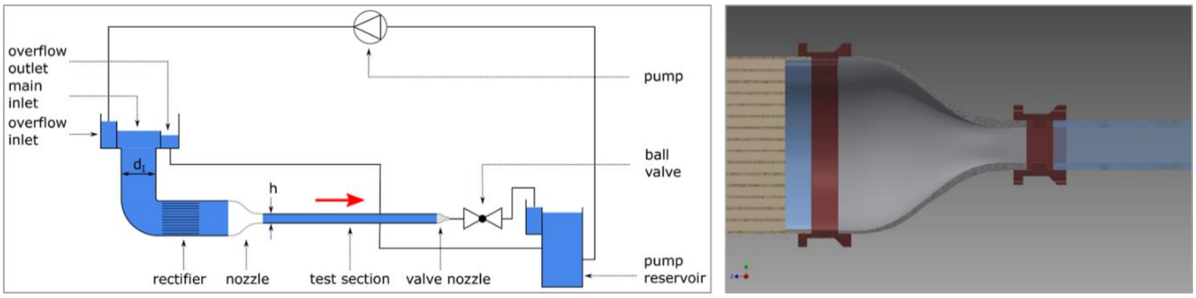

Fig.4: Schematic drawing of the LDA flow tank with major parts and flow paths. The red arrow indicates main flow direction (top left) and detailed rendering of the nozzle with 3D-printed connectors and adjacent parts (top right).

Before entering the test section, a specially manufactured nozzle (see Fig.4, top right) changes the cross section from the round pipe to a square channel. The nozzle is specially designed to accelerate the water as homogenously as possible. The test section is a tube of 3 m length with quadratic cross section (4 x

4 cm). This length (75h) is required to ensure a fully developed boundary layer at its end where the LDA measurement will be performed. The lid of the test section can be removed and will be coated with AIRCOAT. A valve is located behind the test section to adjust the flow speed before the water exits into a tank from where it overflows into the pump reservoir. The setup was designed to the needs of fitting an LDA profile sensor (ILA, LDV fp50 unshifted system) to determine a velocity profile. The boundary layer size was estimated based on the channel height, the flow speed and fluid properties. Based on the minimal resolution of the LDA five to ten measurement points are expected to be located inside the viscous sublayer, allowing for extrapolation of the speeds towards the air-water phase boundary.

2.2. Large-scale

Large-scale hydrodynamic tests allow for high precision measurement of friction drag reduction in a near-operational environment. Here, AIRCOAT surface is investigated with two different setups with different benefits: The SVA friction tunnel reaches relatively large Reynold numbers with small sample sizes, the HSVA HYKAT allows for operational tests, visual control and hydrodynamic conditions closer to real conditions.

2.2.1. Friction tank experiments

The friction tank of SVA Potsdam creates a narrow (~ 12 mm thick) rectangular channel by means of two opposing test plates and determines drag reductions via pressure difference measurement. A full test series allows measuring at a number of pre-set steps in a speed range from 1 m/s up to 18 m/s. The measurement cycle is repeated three times. Twelve pressure sensors measure the pressure. From the pressure difference, the shear stress is derived, which is then translated to a drag coefficient by dividing by dynamic pressure. This allows comparison to the ITTC friction line (*ITTC, 2002)*, which in turn enables extrapolating the results to ship operation conditions, see *Schulze & Klose, 2017* for details.

A production process specifically designed for AIRCOAT was used by KIT to produce air keeping surfaces by structuring thermoplast foils. Additionally, the same production process was used to produce unstructured foils of the same material that act as control for the experiments. Aluminum plates with the dimension of 1m x 0.16 m were coated with the samples using tesa® 4967 double sided tape (0.05 m rolls). Stripes of tesa had to be aligned and samples were carefully applied, however small air bubbles between coating and plates could not prevented. The leading edge of the samples were bend around the sharp leading edge and fixed on the other side. Test plates were installed in the friction tank and measurements were performed.

2.2.2. HYKAT cavitation tunnel

The HYKAT at HSVA, *Weitendorf and Friesch (1990)*, is a closed circulating cavitation tunnel with test section dimensions of (L x W x H) 11 m x 2.8 m x 1.6 m. It can be equipped with a 7.5m long axisymmetric underwater test body located in the center of the test section to conduct friction experiments at medium to large Reynolds numbers ($Re = 10^8$) with respective water speeds of 20 kn. The flow conditions are close to those of real ocean-going ships. The HYKAT allows to coat a larger area with AIRCOAT and the ability to adjust the pressure (between 2.5 and 0.15 bar) facilitates investigating air layer thickness, air retention, air reloading and foil adhesion at varying application depths.

The test body of the HYKAT will be covered with AIRCOAT foil to investigate the drag reduction effect of the air keeping surfaces. Reference measurements with a flat coated test body have been done and act as a validation instrument for the CFD code development as described in the following.

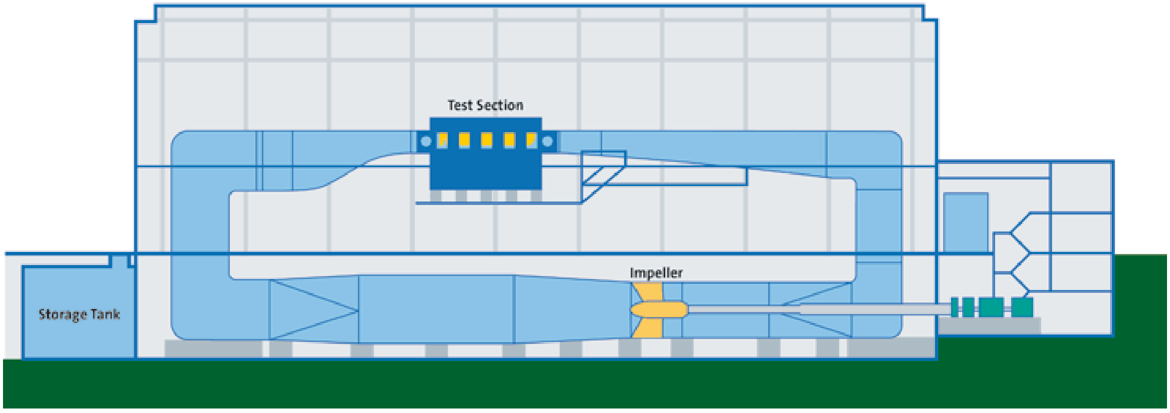

Fig.5: Schematic drawing of the HYKAT cavitation tunnel setup

2.3. Full-scale

Normally, in order to determine the total resistance of a ship, model tests are conducted in ship model basins and results are upscaled to full-size. The associated scaling process has been standardized by the International Towing Tank Conference, *ITTC (2002)*. Therefore, towing tank tests are carried out at Froude similarity, which enables direct transfer of the measured residuary resistance coefficient from the model to the ship. In such an experiment, viscous forces such as friction will not be captured to scale since they depend on the Reynolds number and it's not possible to fulfil Froude and Reynolds similarity simultaneously in a model test. To overcome this issue, friction correlation formulas (such as the ITTC friction line) have been derived which are used to separate residuary from frictional resistance components for the model and determine the frictional resistance of the full-scale ship. The total resistance of the ship is then determined by applying the residuary resistance from the model test and the frictional resistance from the friction correlation formula.

This is not applicable to AIRCOAT as the laws for scaling the effects from small-scale experiments to full-scale are yet to be determined for air keeping surfaces. As AIRCOAT can only reduce viscous resistance, towing tank experiments – which have a significant wave drag component, and are restricted in Reynolds numbers range – are not feasible. Hence, to maximise the measurable effect, AIRCOAT will only be analysed in closed loop cavitation tank experiments (such as the HYKAT), where wave drag components are not existent and total forces are directly related to friction forces. Hence, a reduction of forces would directly represent AIRCOAT friction reduction. Results will be cross-validated by a CFD code that targets to estimate the total effect on a real ship.

Numerically simulating the interaction of the microstructured AIRCOAT surface with a turbulent flow in a three-dimensional volume at transient and two-phase (water and air) flow conditions comes at very high-computational cost. Nevertheless, to understand the drag reducing effect it is crucial to investigate the influence of AIRCOAT on turbulent structure and momentum transfer from water to the surface. Therefore, it will be done on very small scales via Direct Numerical Simulation (DNS) at small Reynolds numbers of Re ~ 300 within the project.

As the final goal is to verify the drag reducing effect, it will be extrapolated and scaled-up to large ocean-going ships numerically. Such ships operate at high Reynolds numbers (Re ~ 10^9), hence a RANS CFD code including a turbulence model will be used. The designed wall function will be incorporated in the developed AIRCOAT RANS model.

2.3.1. AIRCOAT RANS model

OpenFOAM v1806 is used to solve the Reynolds-Averaged Navier-Stokes equations. Turbulence is modelled using the k-ω-SST turbulence model and wall functions are used to resolve the boundary layer. The simpleFoam solver with second-order Gauss linear upwind schemes is employed.

A finite-volume approach has been utilized in this study, *Ferziger and Perić (2002)*. Fully unstructured hex-dominant meshes are generated using CFMesh, *Juretic (2015)*. The six steps as shown in Table I will be performed to validate the model.

Table I: The six steps of the AIRCOAT RANS code validation

#	Setup	Re	Flow	Surface	Validation of
1	HYKAT	High	Single-phase	unstructured	AIRCOAT RANS code
2	Container Ship	Very High	Two-phase	unstructured	Literature data (KCS model)
3	Cavitation tank	Medium	Two-phase, WF	AIRCOAT	RANS + Wall function
4	LDA flow tank	Low	Two-phase, WF	AIRCOAT	Velocity profile
5	HYKAT	High	Two-phase, WF	AIRCOAT	Drag Reduction
6	Container Ship	Very High	Two-phase, WF	AIRCOAT	AIRCOAT full-scale

2.3.2. High-Re Validation

In this paper the first step will be described which is to verify the established CFD model by comparing experiment and simulations, this being the prerequisite to use the code for future simulations. Therefore, HYKAT experiments with smooth surface, which represents the facility with hydrodynamic conditions as closest as possible –but controllable– to real operation are to be validated. If model and experiment align, results from experiments with AIRCOAT surface can be numerically upscaled to allow estimating the full-scale AIRCOAT potential.

Only the test section of the HYKAT experiment, Fig.5, has been replicated for the simulations. A sketch of the setup can be seen in Fig.6. The underlying coordinate system is right-handed rectangular cartesian. The origin lies in the center of the numerical tank. The positive z-axis points upwards and the positive x-axis points towards the inlet. The flow enters the test section from the left, i.e. along the negative x-direction.

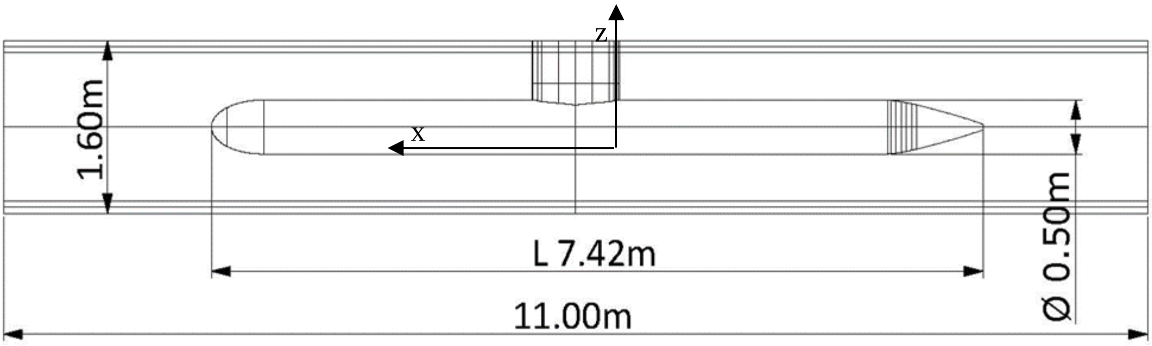

Fig.6: Sketch of case setup with the test body located inside the test section

A grid study with five different meshes was done to investigate the sensitivity of the solution towards the resolution of the geometry at a Reynolds number of Re = $1.6 \cdot 10^7$. The mesh size with the best resolution to computational cost ratio was used for a validation study, which was performed at five speeds to cover the entire range of the experimental tests from Re = $1.6 \cdot 10^6$ to Re = $7.5 \cdot 10^7$. In order to keep the non-dimensional wall distance y+ constant, five grids (one per speed) were created ranging from 12 up to 15 million cells.

3. Results

3.1.1. LDA flow tank design

The flow tank was constructed based on the described design, Fig.7. Validation experiments without AIRCOAT are currently undertaken in order to verify the setup. Later, the lid of the test section will be coated with AIRCOAT foil and LDA measurements will be done in order to investigate the velocity profile and obtain valuable information on slip length and drag reduction effects and to cross-validate the above described CFD code.

Fig.7: Image of the constructed the LDA flow tank with major parts and flow paths. The red arrow indicates main flow direction (top left) and detailed rendering of the nozzle with 3D-printed connectors and adjacent parts (top right).

3.1.2. Friction Tank

Standard test procedures (for details see *Schulze & Klose, 2017)* were used for the control at speeds ranging from 2 to 17 m/s, corresponding to Reynolds number between Re = $6.3 \cdot 10^5$ and Re = $5.62 \cdot 10^6$. During first measurements with higher speeds, the control foil detached from the plate, water flowed under the foil and the foil locally ruptured. The reason for this failure was likely bending of the relatively stiff thermoplast at leading edge, where small cracks were visible before installation. Hence, control measurements existed only up to Re = $2 \cdot 10^6$.

Therefore, the test procedure for the AIRCOAT samples installed in the tank, Fig.8, was modified, and runs with reduced speed up to 6.5 m/s, reps. Re = $3.16 \cdot 10^6$ to were successfully performed. The air layer was still intact after these runs. Another test with standard test procedures revealed detachment of the foil, Fig.8.

Fig.8: Images of the friction tank experiments at SVA. Left: Flat control installed in the friction tank. Middle: AIRCOAT foil submerged in water after experiments done at 6 m/s – note the clearly visible, silvery shining air layer. Right: AIRCOAT foil installed in the friction tank before (top) and after the last experiment with maximum velocity of 17 m/s (below).

Comparing the drag coefficient values of control and AIRCOAT for the speed range with successful measurements resulted in drag reduction (DR) values between 1% and 3 % drag reduction, Table II.

Table II: Drag reduction (DR) of AIRCOAT foil compared to unstructured control at different Reynolds number (Re) range in the friction tank. Negative values indicating reduction.

Re [-]	$6.3 \cdot 10^5$	$7.1 \cdot 10^5$	$7.9 \cdot 10^5$	$8.9 \cdot 10^5$	$1.0 \cdot 10^6$	$1.1 \cdot 10^6$	$1.3 \cdot 10^6$	$1.4 \cdot 10^6$	$1.5 \cdot 10^6$	$1.8 \cdot 10^6$	$2.0 \cdot 10^6$
DR [%]	-3.0%	-1.6%	-1.2%	-1.3%	-1.5%	-1.6%	-1.5%	-1.2%	-1.0%	-1.2%	-2.4%

3.1.3. High-Re Validation

Deviations from 1% to 10% are found between experiment and simulation, Fig.9, depending on flow speed. Furthermore, the accuracy of the numeric solution is found to increase significantly with speed, Fig.10, which is ascribed to the presence of laminar flow in the experiment, especially at lower speeds.

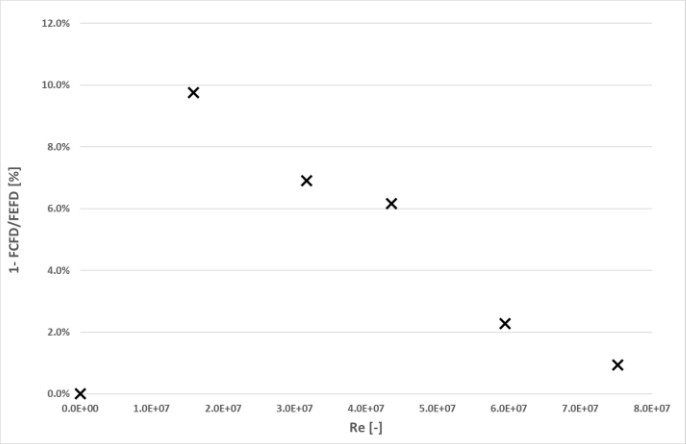

Fig.9: Results of the validation of simulation and experiment. Relative resistance difference of simulation to experiment per Reynolds number.

The decrease of the frictional resistance coefficient with Reynolds number is well documented, *Spurk and Aksel (2010)*, and used in empirical friction correlation formulas such as the ITTC'57 friction line, *ITTC (2002)*. A relatively lower frictional resistance will also reduce viscous pressure resistance.

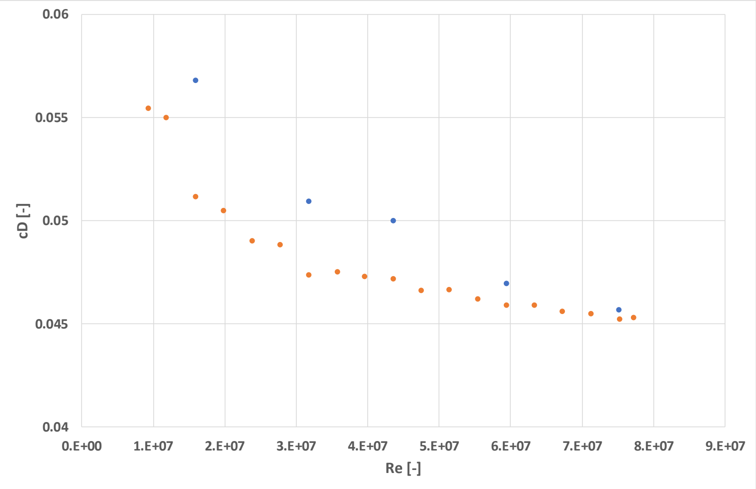

Fig.10: Results of the validation of simulation and experiment. Drag coefficient c_D over Reynolds number for experiment (orange dots) and simulation (blue dots).

If the fluid loses less momentum along the body the pressure peak at its end rises. However, when looking at Fig.12, which shows a comparison of the pressure fields normalized with dynamic pressure in order of increasing Reynolds number, this cannot be observed. The pressure field around the back half of the body remains unchanged. Instead, the pressure around the front and below the front half of the test body decreases with increasing Reynolds number. Furthermore, there is a low-pressure region below the test body that coincides with the longitudinal position of the attachment strut and increases in size with increasing Reynolds number.

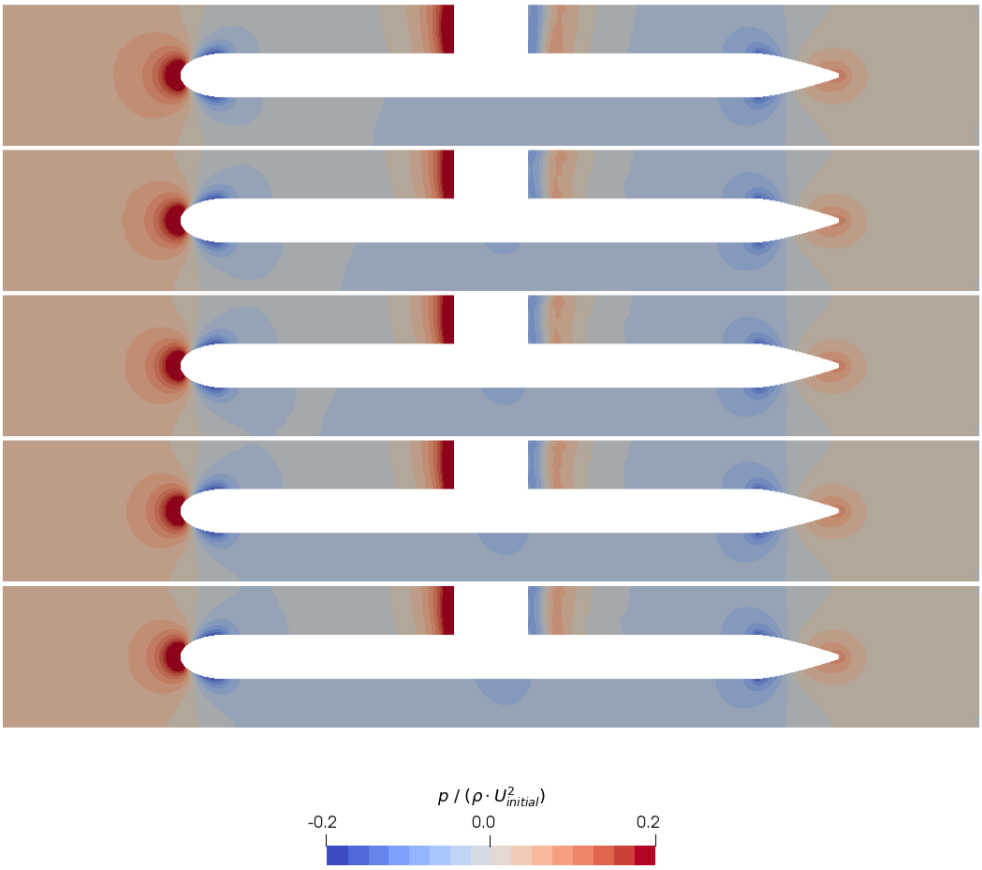

Fig.11: Normalized pressure fields around test body for Reynolds numbers ranging from $1.59 \cdot 10^7$ (top) to $7.5 \cdot 10^7$ (bottom).

Fig.12 shows a comparison of the pressure fields around the nose of the test body between the two extremes of the Reynolds number range investigated in this study. At $Re = 7.5 \cdot 10^7$ there is relatively lower pressure around the nose, which is associated with lower pressure resistance.

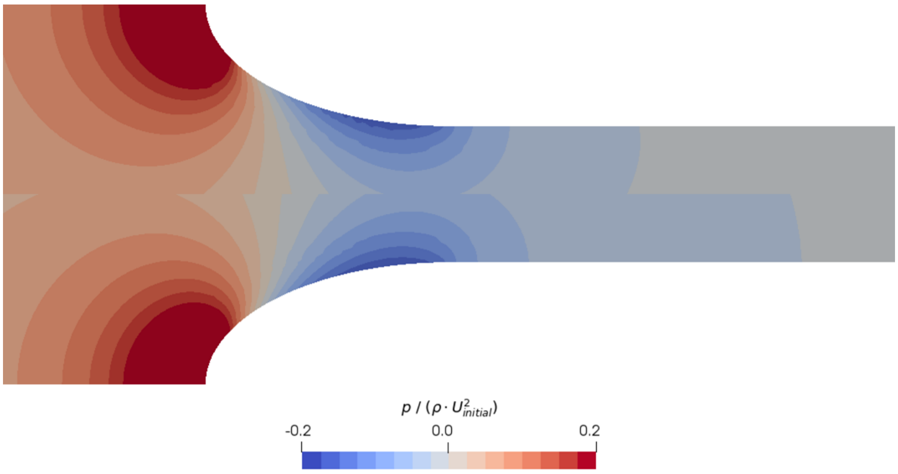

Fig.12: Comparison of pressure field above nose of test body between $Re = 1.59 \cdot 10^7$ (top, inverted) and $Re = 7.5 \cdot 10^7$ (bottom)

Hence, experiments can be replicated more accurately at higher Reynolds numbers, which are closer to the actual operating conditions of ships and are therefore of particular interest for the final full-scale validation. The code can be considered as validated for unstructured surfaces in the used setups. Hence, the first step of Table I is done. Subsequently, two-phase, freestream simulations of ships under operational conditions will be simulated (Table I, step 2). Furthermore, the customized wall functions will be included into the code and then compared to experiments with AIRCOAT surface from the cavitation tank, LDA flow tank and HYKAT to validate the final code necessary to perform the full-scale container ship validation.

4. Conclusion & Outlook

The AIRCOAT RANS code was validated with experimental data of the HYKAT. This is the prerequisite to compare the still-outstanding large-scale AIRCOAT HYKAT experiments with the still-outstanding numerical simulation that include a wall function to simulate the effect of AIRCOAT. The pure viscous drag coefficients retrieved from the simulation showed good alignment with the ITTC'57 friction line, following the curve with slightly higher drag coefficients. Furthermore, experiments at SVA friction tunnel resulted in drag coefficients also following the ITTC'57 friction line, Fig.13. Therefore, the experimental and numerical tools considered and the validation concept designed seem a promising approach to tackle the large set of challenges accompanying the novelty of passive air lubrication with bioinspired technologies.

It was validated that AIRCOAT does reduce frictional resistance. However, friction tunnel experiments only showed a slight reduction of maximum 3% to the control. The experimental setup gives a first drag estimate but may be not perfectly suitable for the investigated samples. The structured and unstructured samples were made of thermoplasts in a laboratory setup, which resulted in thickness changes of about 0.4 mm across the entire sample area. Furthermore, the application processes led to trapped air bubbles between sample backside and aluminium, which created further unwanted surface height changes. In a nutshell, samples were not completely level. This created an unknown parameter for calculating drag force calculations of the test setup with a 12 mm narrow channel breadth.

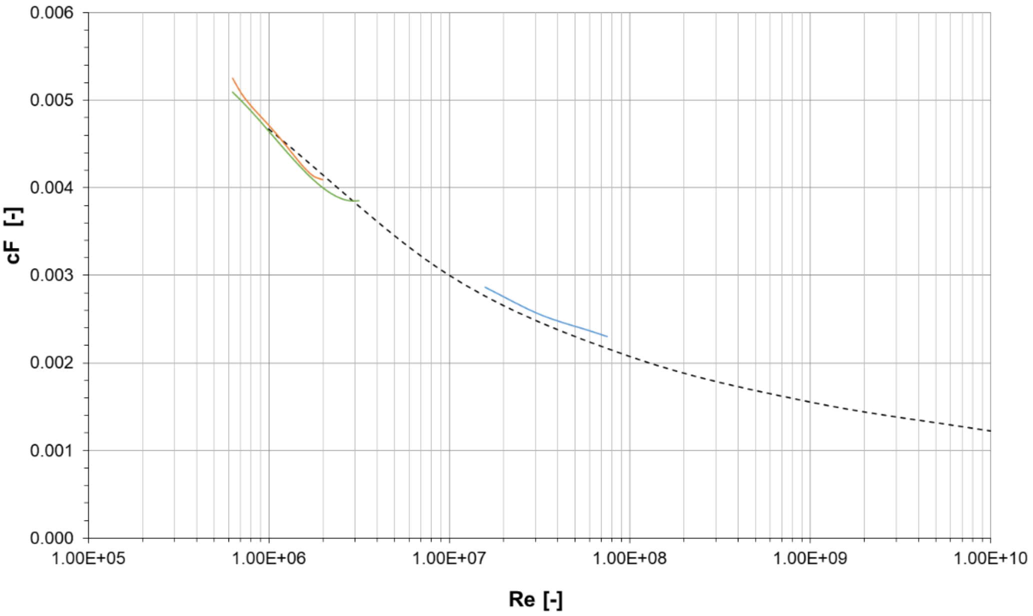

Fig.13: Comparing viscous friction drag (cF) values from friction tank experiments with AIRCOAT (green line) and with the unstructured control (orange line) as well as from numerical simulations of a HYKAT experiments with flat (unstructured) surfaces (blue line). Here, the results for the third grid with slightly higher cF values are not shown. The black dotted line represents the friction ITTC'57 friction line, *ITTC (2002).*

The entire test section is enclosed by the aluminium plates, hence there is no possibility to visually control the behaviour of the AIRCOAT surface during the experiment. It is possible that the air layer was not existent during these experiments as the run-in time of the experiments with undersaturated water (~ 89 % Oxygen saturation), that is necessary to fill the pressure sensor chambers, may have resulted in air layer loss. Both AIRCOAT and control show an increase of drag coefficient values after a critical Reynolds number (rising above the ITTC line). This is typical for coatings with surface roughness's, and show that both surfaces are not completely smooth and could even back the hypothesis that the air layer was lost and that the drag reduction was only due to the remaining (but now wetted) surface structures of AIRCOAT.

To get deeper insight into this, experiments with visible controls such as with the LDA flow tank and the cavitation tunnel are necessary to get a better understanding of the drag reduction capabilities of AIRCOAT. Those should be backed by future friction tunnel experiments with AIRCOAT that are level and already have a self-adhesive backside in order to reduce surface height changes and thus foil detachment. Finally, future HYKAT experiments at high Reynolds number will give insights to both drag reduction as well air layer stability (via visual control) to extrapolate the effect by "virtually coating" a ship with AIRCOAT in order to evaluate the true potential of AIRCOAT.

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References

BARTHLOTT, W.; SCHIMMEL, TH.; WIERSCH, S.; KOCH, K.; BREDE, M.; BARCZEWSKI, M.; WAHLHEIM, S; WEIS, A.; KALTENMAIER, A.; LEDER, A.; BOHN, H.F. (2010), *The Salvinia paradox: superhydrophobic surfaces with hydrophilic pins for air retention under water,* Advanced Materials *22*(21), pp.2325–2328

BUSSE, A.; SANDHAM, N. D. (2012), *Influence of an anisotropic slip-length boundary condition on turbulent channel flow,* Physics of Fluids *24*(5), pp.55111

BUTTERWORTH, J.; ATLAR, M.; SHI, W. (2015), *Experimental analysis of an air cavity concept applied on a ship hull to improve the hull resistance,* Ocean Engineering 110, pp.2-10

ELBING, B.R.; WINKEL, E.S.; LAY, K.A.; CECCIO, S.L.; DOWLING, D.R.; PERLIN, M. (2008), *Bubble-induced skin-friction drag reduction and the abrupt transition to air-layer drag reduction,* J. Fluid Mechanics 612, pp.201-236

FERZIGER, J.H.; PERIĆ, M. (2002), *Computational methods for fluid dynamics,* Springer

GANDYRA, D.; WALHEIM, S.; GORB, S.; DITSCHE, P., BARTHLOTT, W. SCHIMMEL, T. (2020), *Air Retention under Water by the Floating Fern Salvinia: The Crucial Role of a Trapped Air Layer as a Pneumatic Spring,* Small, 2003425

ITTC (2002), *Guidelines: Testing and Extrapolation Methods: Resistance-Uncertainty Analysis, Example for Resistance Test,* Int. Towing Tank Conf.

JURETIC, F. (2015), *cfMesh v1.1 user Guide,* Creative Fields, Ltd., Zagreb,

OEFFNER, J.; JALKANEN, J.P.; SCHIMMEL, T. (2020), *From nature to green shipping: Assessing the economic and environmental potential of AIRCOAT on low-draught ships,* Transport Research Arena, Helsinki

SCHULZE, R.; KLOSE, R. (2017), *Friction Measurements of different Coatings in a Friction Tunnel,* 2nd Hull Performance & Insight Conf. Ulrichshusen

SHELL (2015), *Silverstream Air Lubrication Technology delivers significant energy savings*. https://www.shell.com/business-customers/trading-and-supply/trading/news-and-media-releases/silverstream-air-lubrication-technology.html

SPURK, J. H.; AKSEL, N. (2010), *Strömungslehre: Einführung in die Theorie der Strömungen*, Springer

VAN DEN BERG, T.H.; LUTHER, S.; LATHROP, D.P.; LOHSE, D. (2005), *Drag reduction in bubbly Taylor-Couette turbulence*, Physical Review Letters 94(4), pp.44501

VERSCHOOF, R.A.; VAN DER VEEN, R.C.A.; SUN, C.; LOHSE, D. (2016). *Bubble Drag Reduction Requires Large Bubbles*, Physical Review Letters 117(10), pp.104502

WEITENDORF, E.; FRIESCH, J. (1990), *Der HYKAT die neue Versuchsanlage der HSVA-Einsatzmöglichkeiten und erste Ergebnisse*, Jahrbuch der Schiffbautechnischen Gesellschaft