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From nature to green shipping: Assessing the economic and environmental potential of AIRCOAT on low-draught ships.

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Abstract

Air pollution from ships have been recently shown to contribute to human health effects by over 250 000 premature deaths annually even with the global 0.5% Sulphur cap which enters in force by Jan 1st 2020 (Sofiev et al., 2018). This paper introduces a passive air lubrication application for ship hulls, which has potential to reduce frictional resistance, fuel oil consumption and atmospheric emissions. The AIRCOAT approach is based on a biomimetic ship hull coating that introduces a permanent layer of air on a surface under water. This avoids direct contact of the ship and water, which reduces drag, corrosion and fouling of the hull and may lead to significant fuel savings at global level. Estimations revealed that applying AIRCOAT on low-draught boats and partly coated high-draught vessels of the global IMO-registered fleet could reduce annual fuel cost by millions of Euros depending on friction reduction performance of AIRCOAT.

Keywords: Air lubrication, Salvinia effect, drag reduction, biomimetics, ship emission modeling, fuel efficiency

1. Introduction

1.1. The AIRCOAT project

AIRCOAT aims at reducing energy consumption and emissions of ships to make Europe's waterborne transport more sustainable. It is a European project that received a total grant of 5.3 million Euros from the European Commission within the Horizon 2020 framework. AIRCOAT is short for *Air Induced friction Reducing ship COATing* and aims at developing a biomimetic *passive* air lubrication technology that was inspired by the Salvinia effect.

The Salvinia effect benefits from a hierarchically structured surface with specialised micro- and nanostructures in combination with hydrophilic and hydrophobic areas. This structure allows long-term air retention and simultaneously prevents the loss of air even in turbulent flow conditions (Barthlott et al., 2010; Bottaro, 2014; Brede et al., 2017). Fig. 1 (a) shows a image of of a Salvinia plant while retaining thin layer of air through the Salvinia effect. A detailed image of the complex egg-beater-like trichome structure can be seen in 1(b). The overall hydrophobic surface repells a droplet of water. The AIRCOAT project aims to develop a passive air lubrication technology for application on ship hulls which utilises the Salvinia effect. The project technologically implements this effect on a self-adhesive foil system.

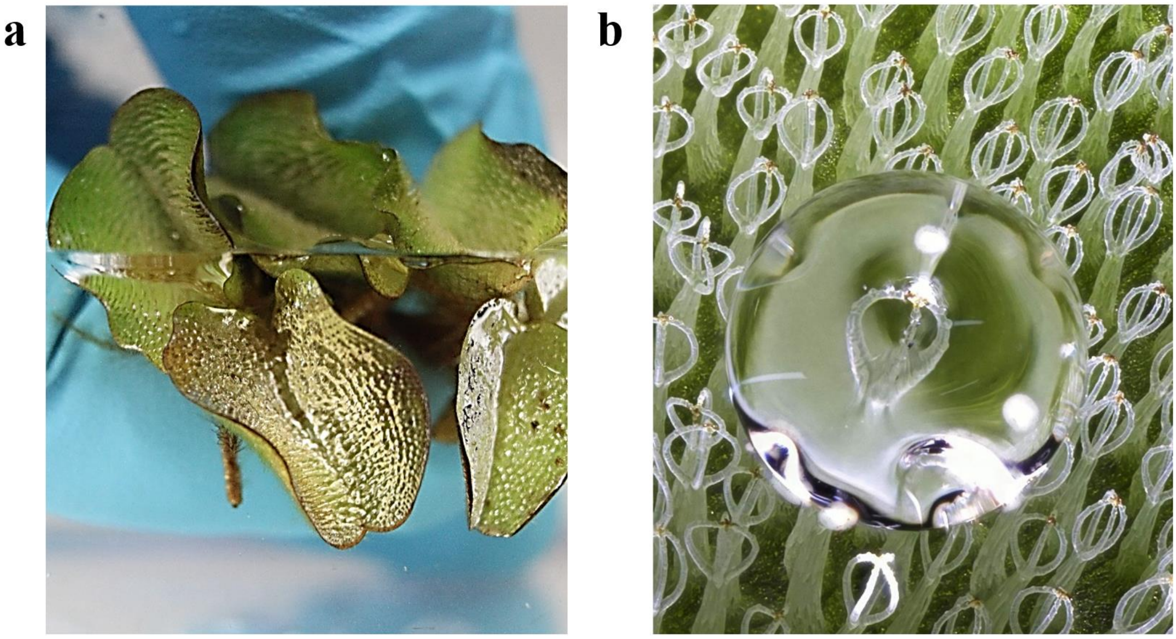

Fig. 1 (a) Image of half way submerged Salvinia molesta plant. The silvery shining reflection of the air water interface is clearly visible in the lower part of the image. (b) The top surface of the plant is covered by wax coated trichomes. The eggbeater-shaped trichomes are hydrophobic, while the four brown top cells are hydrophilic and attract water. The water droplet in (b) is only hold by these hydrophilic top cells. This property represents the air-retaining Salvinia effect.

Applying a ship with such an AIRCOAT foil will provide a thin permanent air layer, when submerged in water (Fig. 2). This reduces the overall frictional resistance while acting as a physical barrier between water and hull surface. Therefore, besides reducing energy consumption, the air barrier further inhibits the attachment of maritime organisms (biofouling).

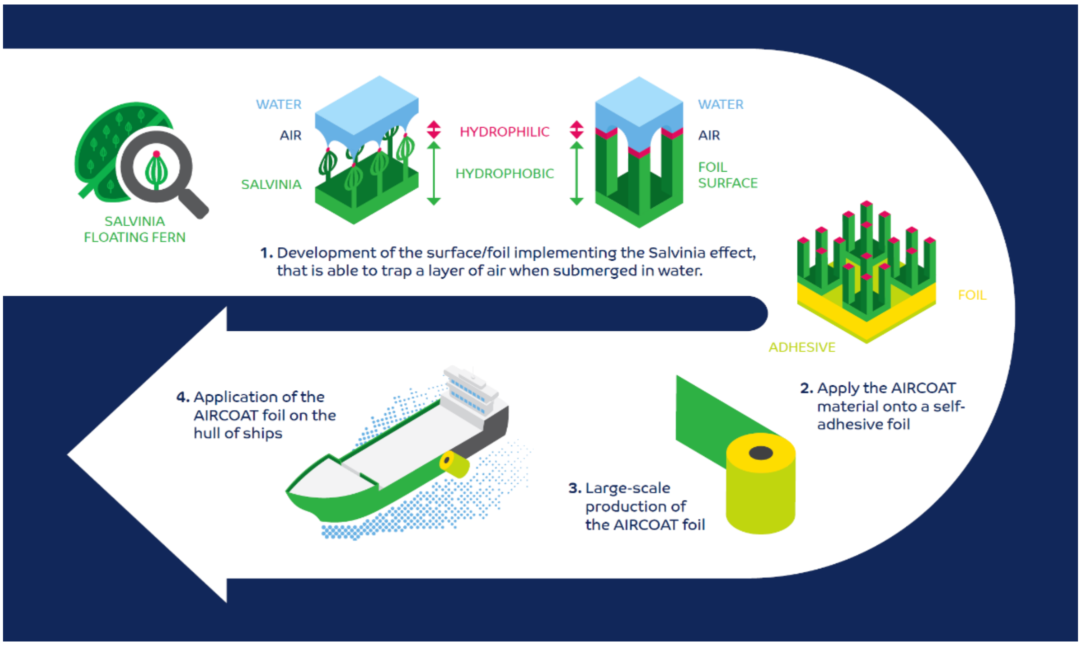

Fig. 2 Overarching concept of the AIRCOAT project with the intention to mimic the Salvinia effect on self adhesive foil systems. Applying the AIRCOAT technology on ship hulls lead to a passive air layer.

1.2. Passive vs. Active Air Lubrication

The idea to reduce ship drag by supplying air to the hull has been proposed in the 19th century and was described in 1967 by Butuzov using cavitation theory (Butuzov, 1966). Thereupon various studies have been done on ***active*** air lubrication (Matveev, 2003) for shipping. Skin friction resistance is roughly proportional to the wetted surface area, thus by covering the hull surface with air, the wetted surface area decreases and so does the friction resistance. It has been shown that a wetted surface area reduction of only 5% through air injection could already reduce 22% of the gross energy of a container ship (Butterworth et al., 2015), including the costs for constant air injection. As lubricating the ship hull with air has a high potential for skin friction reduction (Butterworth et al., 2015) a number of commercial systems such as MALS (MALS, 2019), Effectships (Effectships, 2019) and SILVERSTREAM® (Silverstream, 2015, 2016) are available on the market.

Contrary to active air lubrication technologies, AIRCOAT is a passive solution that has no hull application limit (flat bottom), does not require extra energy for compressed air supply and does not need refit adaptions to the ship hull (air outlet) and machinery (air compressors), hence not occupying valuable cargo space. It also does not constantly shed air bubbles – which can impair propeller efficiency – and does not increase underwater noise (bubble noise) but mitigates ship hull noise emissions (soft permanent air layer) that potentially effecting marine mammals.

1.3. Drag reduction in AIRCOAT and dependence to speed, ship type and draught.

AIRCOAT reduces skin friction, which is the major component of viscous drag. It is assumed that the presence of an air layer between ship and water serves as a slip agent and the velocity at the phase boundary layer is increased. This leads to reduced shear stress and ultimately reduced skin friction. The contribution of the passive air layer to the overall drag is minimal as the viscosity of air is 55 times lower than in water (Barthlott et al., 2017). The friction drag reducing effect of a passive-air lubricating coating is dependent on its slip-length, which is the fictitious distance below the surface where the no-slip boundary condition would be satisfied (Lauga et al., 2007). The larger the slip length, the larger the drag reduction. The slip length in turn decreases with decreasing distances between filamentous structures and gas area fraction, hydrostatic pressure and fluid speed. Therefore, the surfaces need to be optimised, depending on their use. A *passive* air layer further reduces the pressure fluctuations and thereto dampens instabilities in the boundary layer (similar as in compliant coatings (Gad-El-Hak et al., 1984)). Reducing friction drag with *passive* air lubricated surface in small-scales has been shown in different studies (e.g. (Dong et al., 2013; Du et al., 2017; Melskotte et al., 2013; Taghvaei et al., 2017)).
Ship drag consists of two predominant components: viscous and wave drag. At low speeds up to 15 knots (kn) it almost entirely consists of viscous drag. At speeds between 15 and 25 kn the viscous drag is dominating with wave drag increasing exponentially and being predominant at higher speeds (ABS, 2013). Different ship types operate in very different speed range. Hence, the slower a ship sails, the larger the expected benefits.

In order to reduce drag, the air layer needs to be stable. One factor that defines the stability of the air layer is pressure. On a ship hull, the pressure fluctuates locally and increases with draught. The higher the pressure, the smaller the surface structures have to be. However, a decreasing structure size towards micro- and submicron structures increases the effort for production and development. Hence, the higher the intended operation depth, the higher the production and innovation cost.

This paper will elaborate the correlation of ship types, draughts levels and CO_2 emission as well as fuel consumption. Due to the aforementioned limitation at higher speed and lower depths this paper will assess the potential of a passive air lubrication technology being applied on ships and boats with low draughts. Here a focus will be laid on ocean-going ships, which are partially coated with AIRCOAT in the upper hull area. Furthermore, ocean-going boats with a draught below 5 meter that can be coated entirely will be considered. The resulting reduction of fuel consumption and the therefore accompanied economic and environmental benefit will be approximated.

2. Designing AIRCOAT

In order to achieve the AIRCOAT prototype within a short project duration, a multi-step incremental innovation process enabling the route from laboratory to market (Fig. 3) is targeted It involves the development of an initial small-scale testing prototype 1 (S1) in the laboratory, which will be designed, tested and scaled in the first project year. Results will be used to develop and demonstrate an initial large-scale application pilot 1 (L1) at industrial production scales. The obtained insights will then be evaluated by the consortium at mid-project to revise the AIRCOAT concept. This will result in a successive repetition of the process by developing an optimised small-scale testing prototype (S*). This acts as the base for the optimised large-scale application pilot (L*) that will generate conclusive results required for the full-scale validation (F*).

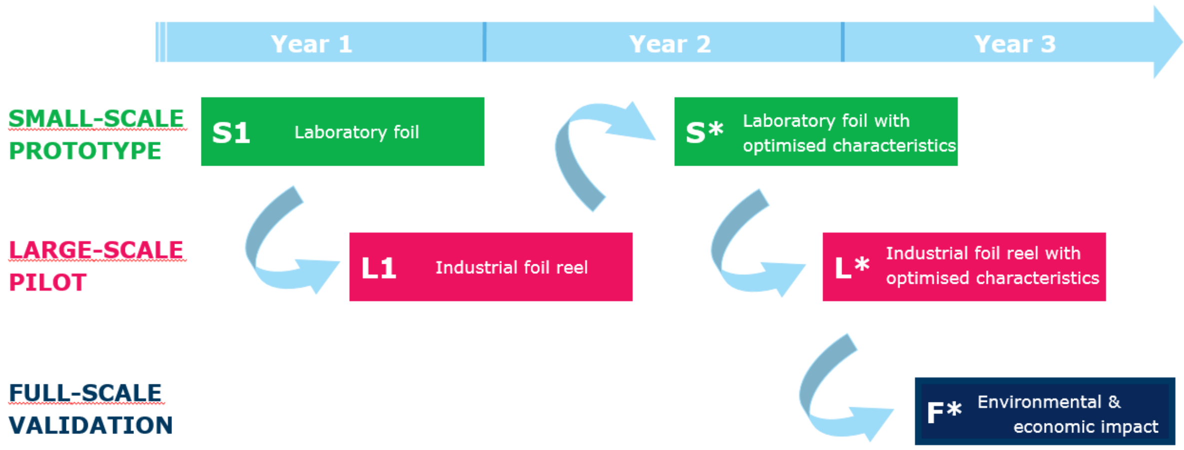

Fig. 3: AIRCOATs multi-step incremental innovation process

During the development of the AIRCOAT prototypes lithographically produced polymer structures are moulded. This happens several times as positive or negative structures until a flat and thin foil with a self-adhesive backside is available, which consists of a material, which is hydrophobic and at the same time fouling resistant under water.

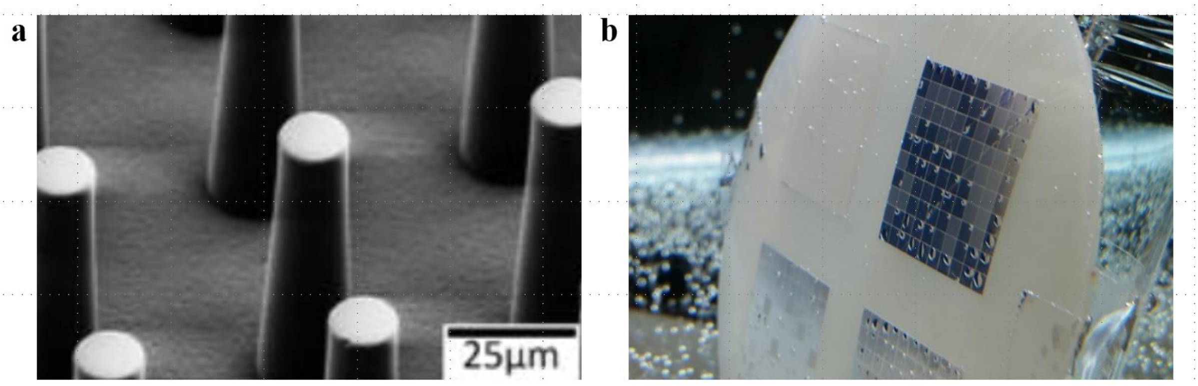

Fig. 4 (a) Electron microscopy image of one of the small-scale AIRCOAT prototypes showing its geometry; (b) Image of a submerged AIRCOAT sample. The square silvery areas are coated with the AIRCOAT technology and clearly showing a silvery air layer that keeps the surface dry whereas uncoated white areas are wet.

After the iterative optimisation and testing of structures and moulding techniques for small samples, results led to the development of a roll-to-roll process for AIRCOAT foils and to a first large-scale application pilot. The first self-adhesive AIRCOAT foil can now be applied on test bodies and small boats up to the few-m^2-range, as shown in Fig. 5 (a). Future hydrodynamic measurements will validate the friction reduction and the air layer stability at higher speeds and at near operational Reynolds numbers.

Partially coated vessels will be tested at sea within the project. A first coated small vessel is shown in Fig. 5 (b-c). In next steps, the coating will be applied to the entire hull of a small research vessel (11 m length) and a Cargo vessel will be coated partially with AIRCOAT.

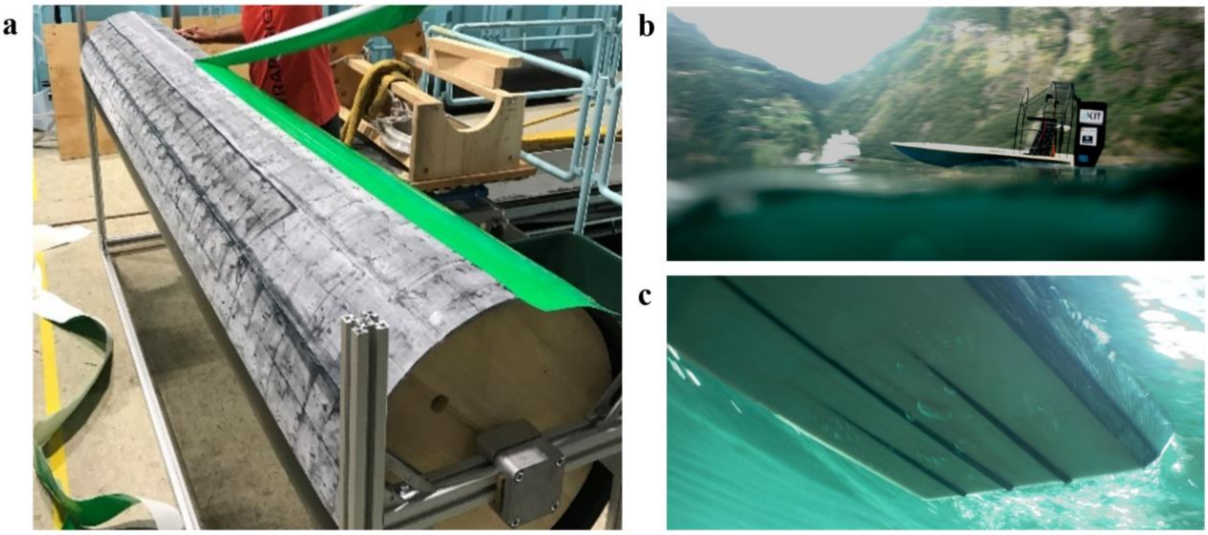

Fig. 5: AIRCOAT applied: a) Manual application of the first large scale self-adhesive AIRCOAT foils on testing body at HSVA (Hamburg). b) KITs AIRCOAT model boat on a test tour in Geiranger Fjord (Norway) (c) Underwater sight of the AIRCOAT prototype in sea water. The bright air layer is more clearly visible on the dark blue sidewall of the boat.

3. Application of AIRCOAT to the global ocean going fleet

The structure size of the AIRCOAT surface structure depends on the vessel draught. Half of the global fleet consists of vessels with draught of 6 meters or less. In Fig 1, the global fleet is divided into draught bins and vessels with 15 meters of draught or less represent over 90% of the cases. These vessels, almost 200 million square meters of wet steel surface, are good candidates for AIRCOAT application, because of the more coarse surface structure required to maintain a stable air layer. The total estimated wet surface of the global ship fleet is over 313 million square meters and one third of this can be found with the largest 10% of the ships (Fig. 6). These are usually the largest bulk cargo vessels and very large crude oil tankers (Fig. 7) which sail the intercontinental voyages. However, the predicted global fuel consumption of vessels (Jalkanen et al., 2009; Jalkanen et al., 2012; Johansson et al., 2013; Johansson et al., 2017) with 15 m draught or less indicate that over 75% of fuel is consumed by this group of ships.

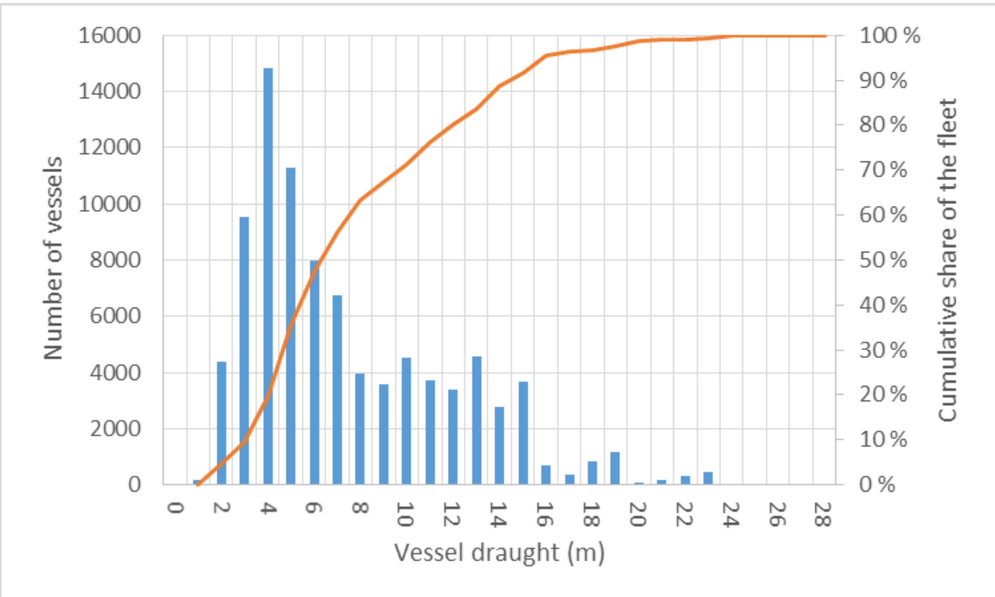

Fig. 6 Cumulative share of the world's fleet vessel by draught. Blue bars represent the Number of ships per draught bin and orange line represent the cumulative share of the fleet per draught bin.

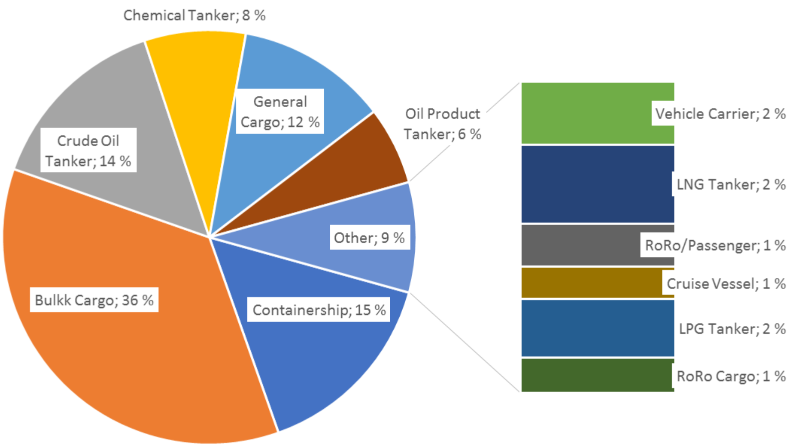

Fig. 7 Share of wet surface by ship type (data from FMI ship emission modelling using STEAM3 model)

Drag reduction with advanced hull coatings will help to reduce the GHG emissions from ships and is one of the available options for meeting the gradually tightening requirements for energy efficient designs. It should be noted that the fuel consumption and wet surface estimates given above represent the commercial ship fleet. There are significantly more small boats than large ships. Already at the Baltic Sea, boats outnumber ships by 30:1, which makes the wet surface area of boats a significant contributor to skin drag. The number of motorboats at global level is unknown, but it is likely measured in tens of millions.

3.1. Partially coating the entire ocean-going fleet

Related to the aforementioned hurdles with air layer stability at high depth, it is an option to only partially coat a ship with AIRCOAT. If for example only the first top five meter were to be coated with AIRCOAT, such partial application still covers about one third of the total wet surface of the global IMO registered fleet. Application of AIRCOAT to this area would result to cover over 90 million square meters of wet surface area. Coating only the first three resp. one meter would cover 20% resp. 7 % of the entire global fleet (Fig. 8).

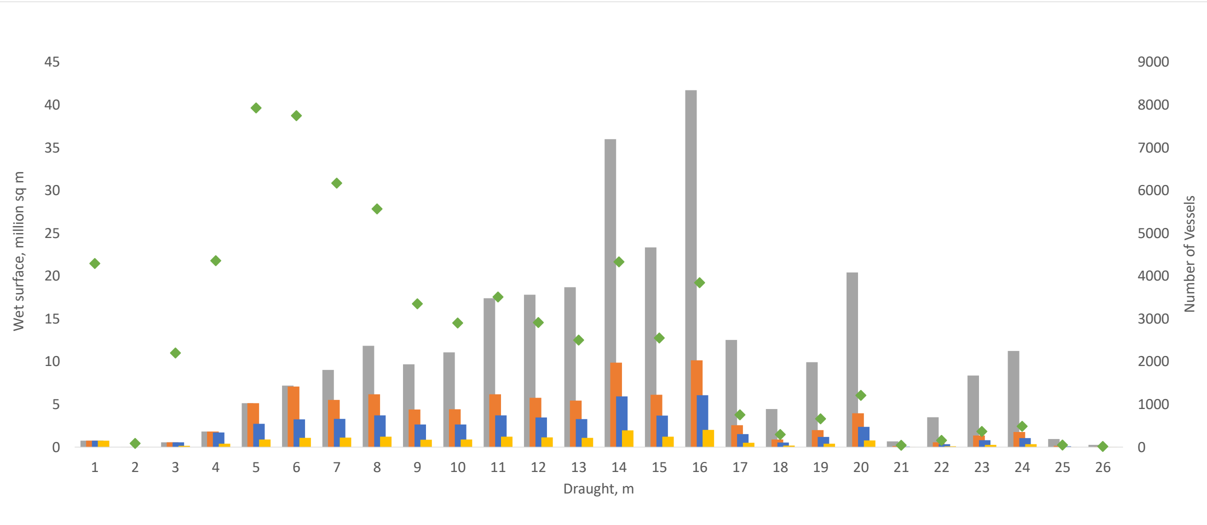

Fig. 8 Application of AIRCOAT to vessel hulls up to the depth of one (yellow bars), three (blue bars) and five (orange bars) meters per draught bin. Bars indicate the share of the wetted surface area of the entire (grey bars) IMO registered global fleet. The green diamonds shows the number of vessels per draught bin.

For these scenarios, the effect on the reduction of the skin frictional resistance coefficient (C_F) was calculated. Therefore, the average Reynolds number (Re) of all ships in a draught bin was calculated C_F was calculated according to the ITTC-1957 skin friction line (ITTC, 2002). As current results indicate a high dependence of achieved drag reduction with air layer stability, vessel speed, environmental conditions, local hull application area and more a value for average friction drag reduction of AIRCOAT cannot be named at this stage. In order to assess the economic potential calculations with five different drag reduction scenarios were made: Skin friction reduction drag reduction via AIRCOAT (C_{FA}) of 20%, 15%, 10%, 5% and 2 % were considered. A weighted average (by wetted surface coated without and with AIRCOAT) of C_F and C_{FA} was calculated to get the total partially coated skin frictional resistance coefficient (C_{FP}) for each draught bin (see the results for case C_{FA}=10% in Fig. 9).

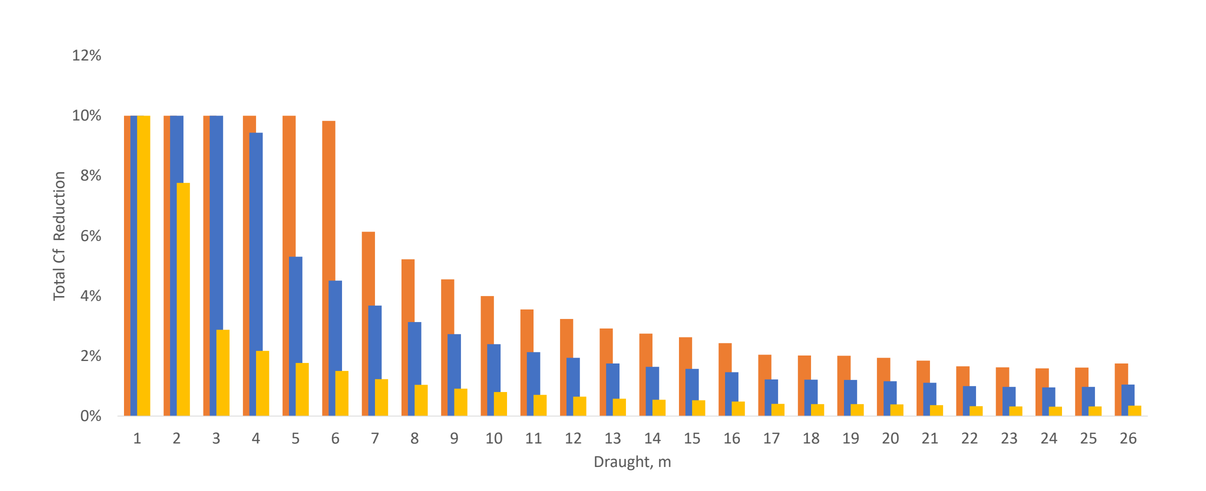

Fig. 9: Total partially coated skin frictional resistance coefficients C_{FP} for C_{FA} = 10 % (AIRCOAT reduced skin frictional resistance by **10%** on average) for partially coated vessel up to the depth of one (yellow bars), three (blue bars) and five (orange bars) meters per draught bin.

Ship drag consists of two predominant components: viscous and wave drag. At low speeds up to 15 knots (kn) it almost entirely consists of viscous drag. At speeds between 15 and 25 kn the viscous drag is dominating with wave drag increasing exponentially and being predominant at higher speeds. Skin friction is the major component of viscous drag (ABS, 2013). Mean design speed of all considered 68,405 vessel was 14.48 (±4.37) kn, hence a factor of 0.95 for the ratio of viscous to total resistance (R_v/R_T) was applied to C_F data according to mean per ship speed from ABS (2013). Estimates do not contain additional environmental factors (waves, sea currents and ice cover) which could increase the estimates by as much as 5 to 15 % (Johansson et al., 2017). A weighted average (by share of total global wetted surface area) of all C_{FP} resulted in an overall drag reduction coefficient (C_{DR}) per scenario (see Tab. 1).

Tab. 1: Drag reduction coefficients for all scenarios of all draught bins

C_F reduction / Depth applied	20%	15%	10%	5%	1%
5m	6.2%	4.7%	4.0%	2.0%	0.8%
3 m	3.7%	0.0%	1.9%	0.9%	0.4%
1m	1.3%	0.8%	0.6%	0.3%	0.1%

Considering the share of the wetted surface for the three different depth scenarios AIRCOAT shows a market potential of 9.3, 5.5, and 1.8 billion € for the 5, 3 and 1 meter case. Multiplying the total fuel consumption of 276 million tons of all IMO registered ships as modelled by STEAM3 (Johansson et al., 2017) with the average fuel price of 570 € per ton mixed fuel (HFO and MDO) with CDR resulted in an estimation of the economic impact per draught and CF reduction scenario (see Fig. 10). As AIRCOAT would replace the need for antifouling coating, the costs for antifouling of 4.2€ m^2 per year were deducted. The costs for applying AIRCOAT were assumed to be 100 € per m^2 per dry dock period. For example, coating the top 5 meters of all IMO registered ships with an AIRCOAT foil with an average CF reduction of 10% could save 3.5 billion Euros annually. Partly coating only the top two meters of all vessels hulls would in turn be negative, meaning cost would be larger than benefit. However, any reduction of ship drag and hence fuel consumption leads to reduced emissions. Considering a CO_2

emission of 831.3 billion kg of all IMO registered vessels (Johansson et al., 2017), for which the top one meter is coated with AIRCOAT (CF=10%) would then still lead to CO_2 savings of 5.2 billion kg.

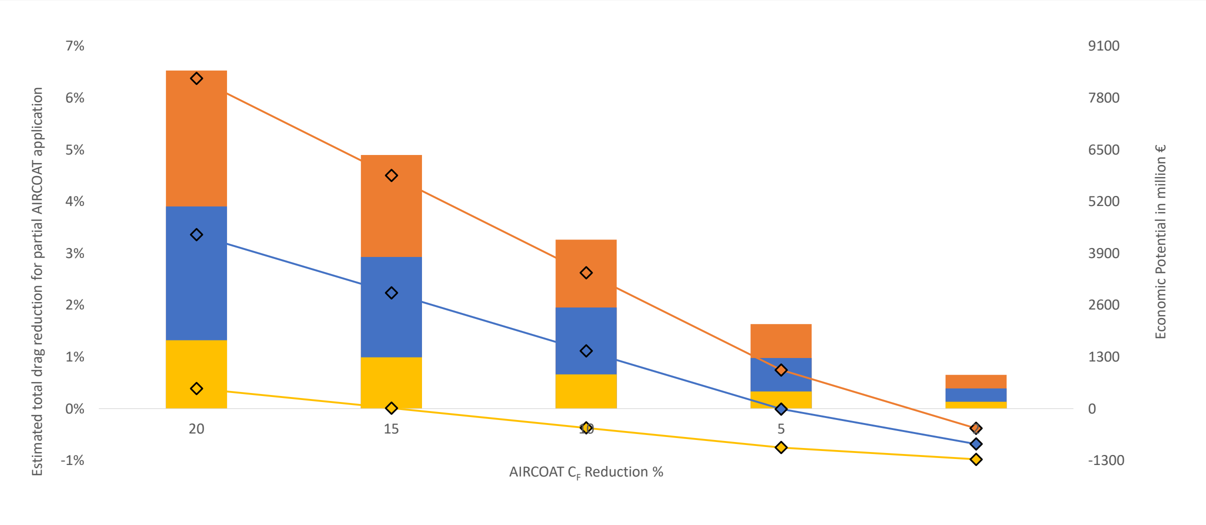

Fig. 10: Drag reduction coefficients (bars) and economic potential for partially coated vessel up to the depth of one (yellow), three (blue) and five (orange) meters for all scenarios of all draught.

3.2. Fully coating ocean-going vessels with low draught

More than 5 % of the entire (IMO registered) global fleet are boats of a draught below five meters, hence the potential for fully coating these vessels were assessed. Fuel savings for were calculated following the procedure described in chapter 3.1. As the entire vessel hull would be coated, the weighted average by wetted surface was not done, hence C_F equals C_{FA}. Three low-draught scenarios where considered: Fully-coating all IMO registered vessels with a draught below one, three and five meters. Again, five scenarios with skin friction reduction drag reduction via AIRCOAT (CFA) of 20%, 15%, 10%, 5% and 2 % were considered. Tab. 2 summarises the results.

Tab. 2: Wetted surface (WS) and fuel saving reduction of fully coated low-draught vessel

Draught bin [m]	WS [10^9 m^2]	WS of total [%]	Fuel cons. [10^9 ton]	AIRCOAT costs [10^9 €]	AIRCOAT fuel savings [10^9 €] for C_F reduction of:				
					20%	15%	10%	5%	2%
5	15.5	0.1	15.1	245.3	1630.1	1222.6	815.0	407.5	163.0
3	3.1	0.0	3.0	48.7	323.4	242.5	161.7	80.8	32.3
1	0.8	0.0	0.7	12.1	80.5	60.4	40.3	20.1	8.1

Fuel savings in the million € magnitude could be reached with all scenarios. Correcting these data for the relatively high investments costs showed that the economic potential is only positive if the average skin friction reduction of AIRCOAT were between 5% and 20%. Here, coating all vessels of a draught below 5 meters with AIRCOAT has the largest economic potential (see Fig. 11). Even if average skin friction reduction is only 5%, this application could save 162 million € annually.

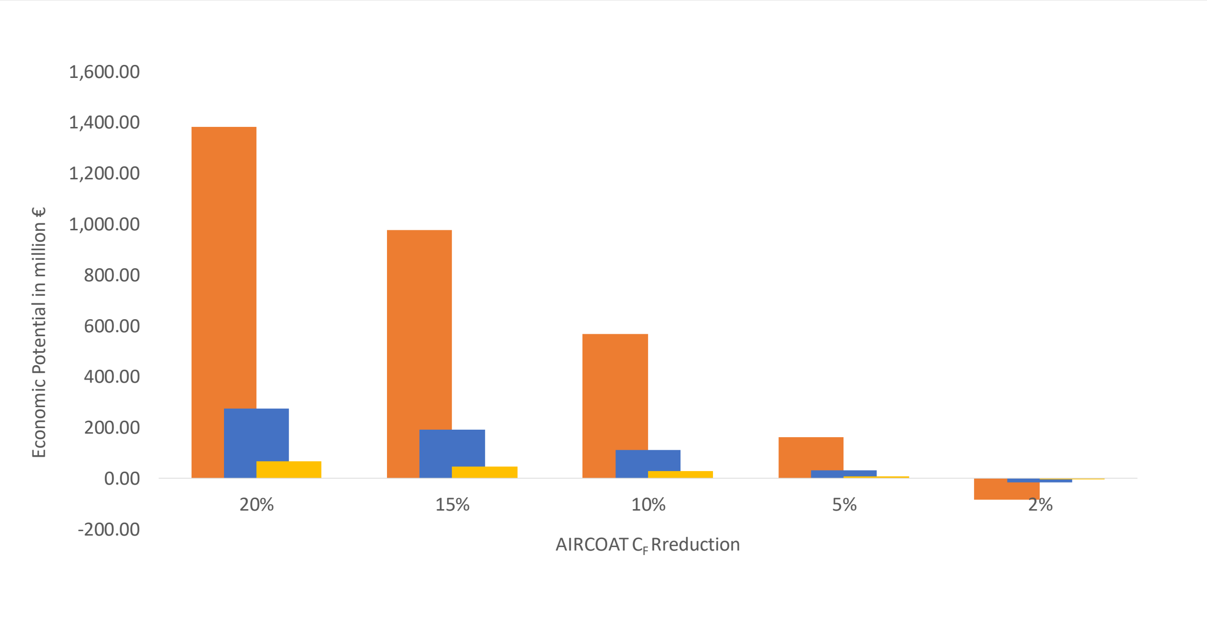

Fig. 11: Economic potential of fully-coating all IMO registered vessels with AIRCOAT, that have a draught of maximal one (yellow), three (blue) and five (orange) meters.

4. Conclusions

The work conducted within the AIRCOAT project will enable the determination of the stability of the air layer as a function of several key parameters and provides valuable insight for the application of AIRCOAT to full-scale trials. As the project and hence the development and testing is still ongoing this paper classified the economic and environmental potential by means of applying friction coefficient reduction scenarios of 2-20%. In order to investigate the potential for applying AIRCOAT at low depth only, the application of AIRCOAT to low-draught boats and partially coated ships was analysed with scenarios ranging from 1-5m depth. Calculation showed that partially coating high-draught and fully coating low-draught boats can lead to extensive cost savings if AIRCOAT reduces the skin friction coefficient for the vessels on average by at least 5%. Calculation only included the ~68 thousand IMO registered vessels bit did not include leasure boats and inland ships which both have a large share of the total global wetted surface area. Based on the fuel consumption modelling work, the potential for Green House Gas (GHG) reduction is significant provided that ship owners sail their ships with the same speed. Different shipping segments may have diverging views on the importance of reducing biofouling or hull friction as a primary application of AIRCOAT, which need to be considered. Close cooperation with ship owners is necessary to understand the practical challenges of AIRCOAT applications and development work.

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References

ABS, 2013, Ship Energy Efficiency Measures. American Bureau of Shipping.

Barthlott, W., Mail, M., Bhushan, B., Koch, K., 2017, Plant surfaces: structures and functions for biomimetic innovations. Nano-Micro Letters 9, 23.

Barthlott, W., Schimmel, T., Wiersch, S., Koch, K., Brede, M., Barczewski, M., Walheim, S., Weis, A., Kaltenmaier, A., Leder, A., 2010, The Salvinia paradox: superhydrophobic surfaces with hydrophilic pins for air retention under water. Advanced Materials 22, 2325-2328.

Bottaro, A., 2014, Superhydrophobic surfaces for drag reduction. Istituto Lombardo-Accademia di Scienze e Lettere-Rendiconti di Scienze 148.

Brede, M., Zielke, R., Wolter, A., Böhnlein, B., Fischer, M., Medebach, I., Barthlott, W., Schimmel, T., Leder, A., 2017, Stabilität und Reibungseigenschaften biomimetischer, Luft haltenden Beschichtungen für die Serienfertigung/ stability and friction of biomimetic, air retaining coatings for industrial applications. German Association for Laser Anemometry GALA e.V.

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, 2-10.

Butuzov, A., 1966, Limiting parameters of an artificial cavity formed on the lower surface of a horizontal wall. Fluid Dynamics 1, 116-118.

Dong, H., Cheng, M., Zhang, Y., Wei, H., Shi, F., 2013, Extraordinary drag-reducing effect of a superhydrophobic coating on a macroscopic model ship at high speed. Journal of Materials Chemistry A 1, 5886-5891.

Du, P., Wen, J., Zhang, Z., Song, D., Ouahsine, A., Hu, H., 2017, Maintenance of air layer and drag reduction on superhydrophobic surface. Ocean Engineering 130, 328-335.

Effectships, 2019, SES Europe AS - Air Supported Vessels (ASV).

Gad-El-Hak, M., Blackwelder, R.F., Riley, J.J., 1984, On the interaction of compliant coatings with boundary-layer flows. Journal of Fluid Mechanics 140, 257-280.

ITTC, 2002, Guidelines: Testing and Extrapolation Methods: Resistance-Uncertainty Analysis, 792 Example for Resistance Test. ITTC Recommended Procedures and Guidelines, Procedure.

Jalkanen, J.-P., Brink, A., Kalli, J., Pettersson, H., Kukkonen, J., Stipa, T., 2009, A modelling system for the exhaust emissions of marine traffic and its application in the Baltic Sea area. Atmospheric Chemistry and Physics 9, 9209-9223.

Jalkanen, J.-P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., Stipa, T., 2012, Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. Atmospheric Chemistry and Physics 12, 2641-2659.

Johansson, L., Jalkanen, J.-P., Kalli, J., Kukkonen, J., 2013, The evolution of shipping emissions and the costs of regulation changes in the northern EU area. Atmospheric Chemistry and Physics 13, 11375-11389.

Johansson, L., Jalkanen, J.-P., Kukkonen, J., 2017, Global assessment of shipping emissions in 2015 on a high spatial and temporal resolution. Atmospheric Environment 167, 403-415.

Lauga, E., Brenner, M., Stone, H., 2007, Microfluidics: the no-slip boundary condition. Springer handbook of experimental fluid mechanics. Springer, pp. 1219-1240.

MALS, 2019, Mitsubishi Air Lubrication System.

Matveev, K., 2003, On the limiting parameters of artificial cavitation. Ocean Engineering 30, 1179-1190.

Melskotte, J., Brede, M., Wolter, A., Barthlott, W., Leder, A., 2013, Schleppversuche an künstlichen, Luft haltenden Oberflächen zur Reibungsreduktion am Schiff. 21. GALA-Fachtagung" Lasermethoden in der Strömungsmeßtechnik.

Silverstream, 2015, Silverstream air lubrication technology proven to deliver significant lenergy savings.

Silverstream, 2016, Silverstream air lubrication technology proven to deliver significant long term energy savings.

Sofiev, M., Winebrake, J.J., Johansson, L., Carr, E.W., Prank, M., Soares, J., Vira, J., Kouznetsov, R., Jalkanen, J.-P., Corbett, J.J., 2018, Cleaner fuels for ships provide public health benefits with climate tradeoffs. Nature communications 9, 406.

Taghvaei, E., Moosavi, A., Nouri-Borujerdi, A., Daeian, M., Vafaeinejad, S., 2017, Superhydrophobic surfaces with a dual-layer micro-and nanoparticle coating for drag reduction. Energy 125, 1-10.