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Past, present and future

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Air Lubrication Technology – Past, Present and Future

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Abstract

This paper presents the span from the historical roots and background of air lubrication to actual research project results derived from full-scale demonstrators or as expected from the EcoLiner currently being under construction. Three techniques are discussed: Air Cavity Ships, Air-film and (micro-)bubble drag reduction.

1. Introduction

Strategies to reduce the frictional resistance of a ship has traceable been discussed even by one of the founding fathers of maritime research, Sir William Froude. The most intuitive approach to reduce ship resistance is to replace parts of a ship's flat bottom by actively ventilated recesses such that these areas insulate the ship's hull from the surrounding water. As friction in air is about just 2% of friction in water, the achievable drag reduction theoretically scales with 49/50 and the area fraction that is exploited by such a cavity. However, additional free surfaces can, if not designed properly, cause a new wave-making or wave-breaking resistance once waves are generated inside these cavities. In the worst case, disturbances imposed by edges of the recesses are even spoiling the radiated waves of the ship. Samples of that are shown and discussed in the following.

Techniques to separate the hull from water by air could also be based on water repellent surfaces, so called air-film techniques. Contrary to constructive recesses, these techniques can do almost without hull-shape modifications, however, generating a sustainable (super-) water repellent surface effect to real ship hulls is challenging in many ways: toxic or luxuriant ingredients are practically not applicable and aging of the effect by unavoidable seawater pollutants or bio fouling are just a few problems faced. In theory, drag is reduced as high as in the air cavity case, however, practically the ineluctable instability of air films is restricting the achievable circumference of the air patches and this way causing a suboptimal crop of insulation.

The third technique discussed in the following is the control of turbulence by means of e.g. (micro-) air bubbles. Here the presence of the bubbles of dedicated size, and in particular regions of the boundary layer, is seen accountable for a reduced turbulent drag production. However, clustering of bubbles (coalescence) and washing out of bubbles into regions of less turbulence production activity is a yet unresolved problem causing relaxation of the drag reduction effect. Furthermore, the theoretical achievable drag reduction is limited to the laminar drag as still a Stokes-condition is valid at the hull and nevertheless a boundary layer is formed.

2. The past of air lubrication (up to 1999)

Since science discovered the composition of ship's drag, the idea arose to affect or minimise the frictional resistance, *Thill (2010)*. In 1875, Sir William Froude wrote to Bruno Joannes Tideman on the subject of air lubrication. In other words, as soon as scientists understood that a ship's drag can roughly be split into frictional and a residual resistance they not only brainstormed ideas to reduce the residual resistance, e.g. by streamlining the ship to reduce wave height and to avoid flow separation, but also ideas how to directly affect the frictional resistance.

2.1. Air based drag reduction techniques of the past

In the years till 1999 air lubricated vessels were not massively applied but still there are some examples worth being mentioned in the following.

Wing in Ground effect (WIG) - The wing in ground effect is a phenomenon increasing the lift of a moved forward profile by a favourable interaction of ground and pressure side of the profile. To be honest, a WIG is much more an aeroplane rather than a ship. However, until hovering the vessel is really sailing and the problems in the transition from sailing to hovering is a highly challenging research field yielding some innovative combinations of ship- air cushion- and WIG techniques, *Fischer (1998)*. Furthermore, in most countries a captains license is sufficient to “sail” such a vessel and not a pilot diploma. This makes WIGs an ultimate example of an air lubricated vessel, whereas “ship” here is purely seen from a legal perspective and the moment till hovering.

Hovercraft - A hovercraft is an air lubricated vessel. It is one of the few maritime applications that insulates by 100% the ship’s surface from the water and this way expose the whole usually wetted surface to gaseous friction. The company Hoverspeed successfully operated the English Canal from Dover to Calais in the years from 1981 onwards, with 6 SRN4-Hovercrafts at the beginning of service. Though with respect to time this formed the fastest link from continental Europe to England, the fleet was reduced to 2 vessels in 1990 and taken out of service in October 2000. Despite sailing without water contact, hovercrafts are not competitive with “traditional” vessels as they require an enormous amount of energy just to “float” and replace the air escaping between the flexible seals and the water surface, they do have a wave resistance as the moving pressure field is generating a wave pattern and the energy dissipating with the radiated waves origins from the propelling engines of the craft. Just two SRN4 Mk III vessels escaped from dismantling and are displayed in the Hovercraft Museum Lee-on-Solent. Any other application is mainly restricted to spare-time or military purposes.

Surface Effect Ships (SES) - The total insulation of the hull from the water is not fully avoiding a wave resistance, but, at the other hand, goes hand in hand with tremendous air losses and the inherently required power to compensate for that. So what if the sideward flexible seals of a hovercraft are replaced by –of course– streamlined bodies, preferably slender hulls from which a low resistance is known. This, in rough lines, is the philosophy of surface effect ships (SES), looking like a catamaran with very slender hulls and hovercraft-alike flexible seal creating a pressure tight compartment between the bridge deck and the hulls. This pressure tight compartment is actively filled with air. This pressurised air raises the vessel more out of the water than a traditional catamaran would sail. SES are used for fast transportation purposes, *Ozawa (1997)*, or military and patrol purposes, respectively, *Steen (2001)*. Even if often claimed to be the benefit of a SES, it is not a reduced displacement that is potentially improving the vessel’s performance. Resistance-wise it doesn’t matter whether air or steel is displacing the water. It is the net reduced wetted surface that reduces the drag of a SES when the vessel is carefully designed. Thus, even a SES is a successful representative of an air-lubricated vessel. However, for drag and friction reduction, respectively, a pressurised compartment between two catamaran’s hulls is not required, a much thinner layer of air is accomplishing the same job.

Air Cavity Ships (ACS) - When successively reducing the height of the cavity of a SES and displacing a higher percentage of the ships weight again by rigid steel rather than a dynamic cushion of air, the design principle of an air-cavity-ship is reached. By coincidence it is exactly the principle Sir Froude was discussing in the letter with Mr. Tideman. Even the subject of the discussion, the formation of an additional free surface at the ship’s bottom, is still an issue of concern and scientific research. Furthermore, air volumes within a fluid are seeking the way towards the upmost possible position; spirit-levels are based on this principle. As a consequence, any motion of a ship furnished with an air cavity in its flat bottom bares the risk that air from the cavity is escaping. This way, ACS are extremely sensitive to roll- and pitch-motions that they should – as much as technical feasible – avoid. Consequently, inland navigating ships are the lowest hanging fruits. ACS have a long record in the former Soviet Union for fast and slow sailing ships, *Sverchkov (2010), Gorbachev (1993)* with good success. Unfortunately, the positive experience did scarcely (except for e.g. *Matveev (1999)*) penetrate through the iron curtain such that in Europe, despite the potential and plausible benefit of the ACS principle just a few and sometimes even inept attempts were made for an application. One typical example for the latter is the case of the inland navigating vessel TMS Myriam, now TMS Echternach. A feasibility study on this vessel at MARIN showed that there is a drag reduction potential of up to 40%. This figure is roughly in line with the fraction of the flat bottom that could be used for hosting air cavities and the reduction of fluid friction to gaseous friction. Despite this promising potential, dockyard and owner opted for a traditional ship hull with add-on cavities as such cavities can be removed when not functioning. Trials indicated a much smaller but still positive drag reduction of just one third of the expected value. Since the principle failed the expectations by a factor of three, the cavities have been removed and the principle was for decades seen as not truly functioning. When estimating the additional resistance of an added-on cavity, however, the discrepancy of the imposed expectations can easily be explained. The necessity of severe structural modifications of the hull is seen as motivation of yet another air-lubrication technique.

Micro Bubble Drag Reduction (MB) - Tiny little bubbles in shear layers of fluid can –when having the right size and are kept at optimal distance to the surface– reduce the drag onto this surface by up to 80%, *Guin et al. (1998)*, yielding achievable net energy reductions for ships of up to 60%, *Merkle and Deutsch (1992)*. The principle is promising in many ways, as air is not seen as possible pollutant to water, as the technique can do almost without changing the ship's lines and structure, and as in theory it should be applicable to perpendicular walls as well. The latter could meanwhile be refuted in the EU project SMOOTH, Thill (2010). Contrary to the previous techniques, MB drag reduction is not insulating the hull from the surrounding water, it is affecting the flow itself beneficially. As the flow cannot be released from a Stokes-boundary condition, the achievable drag reduction is more limited than the previous techniques. One thinkable restriction is seen in the laminar flow condition. In other words, MB drag can at the utmost reach the lower resistance of laminar flows.

2.2. Alternatives to air for reducing drag

For the sake of completeness, the pros and cons of alternative techniques will briefly be discussed as they yielded to the focusing to air lubrication as subject for vanguard maritime research.

Surfactants (polymers) - Adding polymers with certain features into a turbulent boundary layer (TBL) has shown severe drag reductions in lab-conditions, *Lumley (1973)*, *Virk (1975)*. It was discovered unexpectedly by Toms in 1946, *Schrauwers (1996)*. Irrespective of questionable environment implications, this technique requires a continuous seeding and the related infrastructure and procurement aboard. Polymer additives or other surfactants are, therefore, not seen as an applicable technique in naval architecture. However, the deeper and ever-growing understanding of the physics of polymer drag reduction, *Virk (1971,1975)*, *Warholic et al. (1999)*, *Brasseur et al. (2005)*, is relevant and helpful for the understanding of MB drag reduction.

Grooved surfaces (shark skin) – These are copied from nature and were investigated e.g. by Tang and Clark (1993). The orientation and shape of the grooves generate small vortices that interact with burst events in a turbulent boundary layer favourably. However, the vulnerable small structure plus the threat that they could lose their beneficial effect when overgrown by bio-fouling led to the decision to not focus on such techniques for naval applications.

LEBU and OLD - Large Eddy Break Up devices and Outer-Layer Devices firstly generate a penalty on drag as they are emerged structures onto a flat surface. Nevertheless they can be net efficient when beneficial affecting the momentum exchange in a TBL. Seen the fragile size and biofouling implications, these techniques were seen not suitable in naval applications.

Compliant coating – As the grooved surfaces, perpendicular to the flow direction deforming and vibrating surfaces, for instance being enabled by compliant coatings, can beneficially interact with the TBL yielding a net drag reduction as firstly been reported by, *Kramer (1957)*. As the response of the surface should meet the actual flow (speed-) requirements, the technique works either well at just one (ship's) speed, or an active adaptation of the skin is required. Nature could solve this by actively affecting the features of the skin, *Kramer (1960)*, for naval application this was seen far beyond technical possibilities. Furthermore, aging and fouling matter could spoil the benefit by shifting the beneficial frequencies, such that this technique is mentioned just for the sake of completeness.

2.3. Management summary of drag reduction techniques

The technologies as described in section 2 have been summarised in Table 1, *Thill (2002)*. Based on this information it was decided to concentrate further to air cavities and –films and to micro bubble drag reduction.

Table 1: Overview and implications of drag reduction techniques

Technique	Possible drag reduction in [%]	Problems in naval application
Aeronautical techniques	<20	Different Reynolds number
Air cavity	**80**	Air control and stability
Air film in combination with HWR coating	**90**	Control at vertical side walls
Bionics	!	Lack of rotating propulsors
Boundary layer suction	20	Is applied to some extent (e.g. by the efficiency increase caused by a working propeller)
Compliant coating	<7	Maintenance, earnings and aging
Magneto Hydrodynamics	?	Efficiency and complexity
Micro bubbles	**80**	Control and relaxation
OLD / LEBU	7-40	Bio fouling and slamming
Oscillating hull surface	<45	Mechanical complexity
Polymer additive	<80	Environment
Riblets	7-10	Bio Fouling
Slipping skin	9	Mechanical complexity
Transition delay	0	Too high Reynolds number of ships
Vortex generation	0	Effect not measurable

3. The present of air lubrication (2000-2016)

3.1. Sailing ships

A rather comprehensive overview of the impressive fleet of air lubricated vessels operating in Russia is given by *Sverchkov (2010)*. A full scale demonstrator was built within the research project PELS 2, Fig.1. At the left of Fig.1 the free surface underneath the ship is clearly visible. The painted chessboard pattern was used to determine the wave length and amplitude optically.

Fig.1: MS *Kraichgau*, experimental air supply system (left) and view inside an air cavity (right and close up left), courtesy of Damen (PELS 2 project)

3.2. Recent Research Projects

3.2.1. PELS 1

The project energy-saving air-lubricated ships (PELS 1) started in 2001 and was funded by the Dutch research funding platform e.e.t. (Programme office Economy, Ecology, Technology of the Dutch ministry of economy affairs). Four dockyards, one engineering office and two branch organisation together with MARIN joined forces on fundamental research on the subject of applicable drag reduction techniques for ships. A sound literature review addressed three techniques as interesting candidates for practical maritime applications, being air-cavity-ships, micro-bubble drag reduction and air films on super water repellent (SWR) coatings, *Fukuda et al. (2000)*. The latter was seen most promising as it could likely do with least constructive changings and, therefore, is suitable for retro-fitting existing ships with drag reduction techniques. For the SWR tests an available painting was selected that is used to keep military antenna (domes) free from dust and dirt as rain cleans the treated surface from such impurities as the water droplets (including the pollutant particles) simply roll off. However, for maritime this painting is much too expensive with litre prices of several hundred dollars. Nevertheless, SWR coatings created large air carpets onto the treated surface that insulates the hull from water and this way generated the desired effect. They could do with the least air supply as the air verbatim stuck to the hull. The high degree of water repellence is expressed by a contact angle larger than 170^0 and is tried to visualise in the photographs in Fig.2.

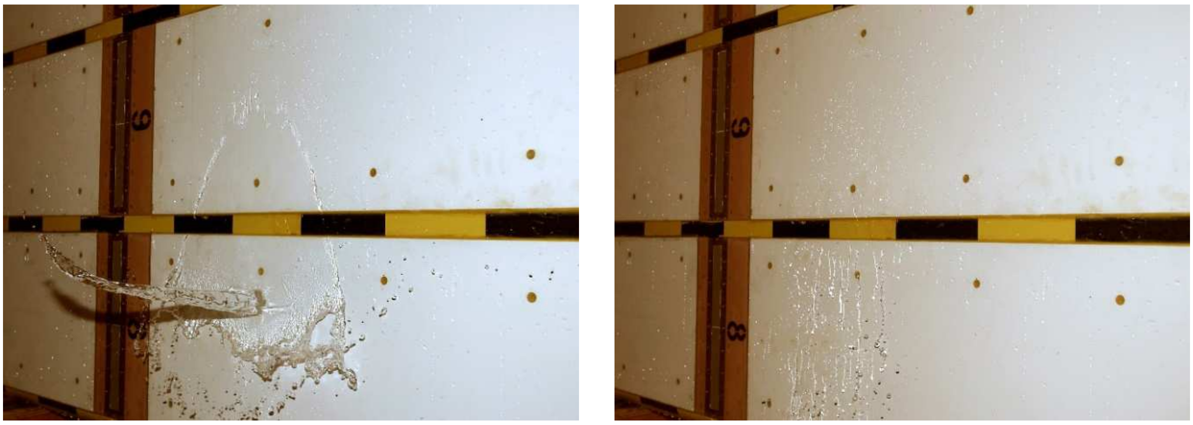


Fig.2: SWR coating (HYREC™)

The principle of MB drag reduction was studied in detail. Dedicated LDV techniques that can do with bubble-light-scattering were developed and applied. The local void-fraction of gas could be measured and optical tracking of the bubbles was realised in a master thesis within the project, *Leijnse (2003).*

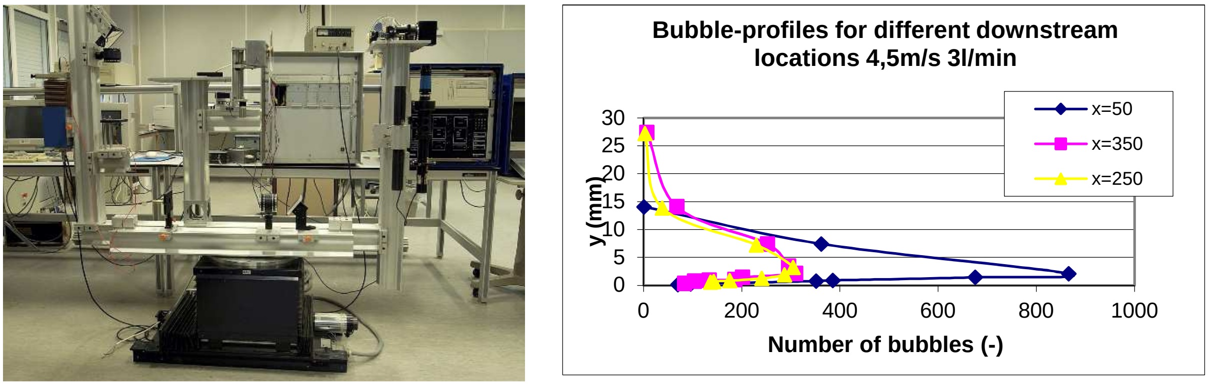


Fig.3: LDV set-up (left) and void fraction measurement result (right)

The analysis of the bubble deformations showed that the bubbles oscillate in position and slightly in size and shape. A Fourier-analysis showed a distinct peak at – in this case a frequency of about 500

Hz, Fig.4 (right). This frequency coincides perfectly with the frequencies of ejection events in a TBL of 5-6 times T^+ as found by *Bogard and Tiederman (1987)*. Fig.4 (left) shows a comprehensive summary of flow phenomena in a TBL, *Meng (1998)*. Here T^+ is about 100, thus the hypothesis was derived that the bubbles interact with burst- and ejection events in a beneficial way, for instance that the inhibit or spatially restrict the ejections and this way reduce the turbulent drag production mechanisms. This would explain a net drag reduction in the flow, *Thill (2004)*.

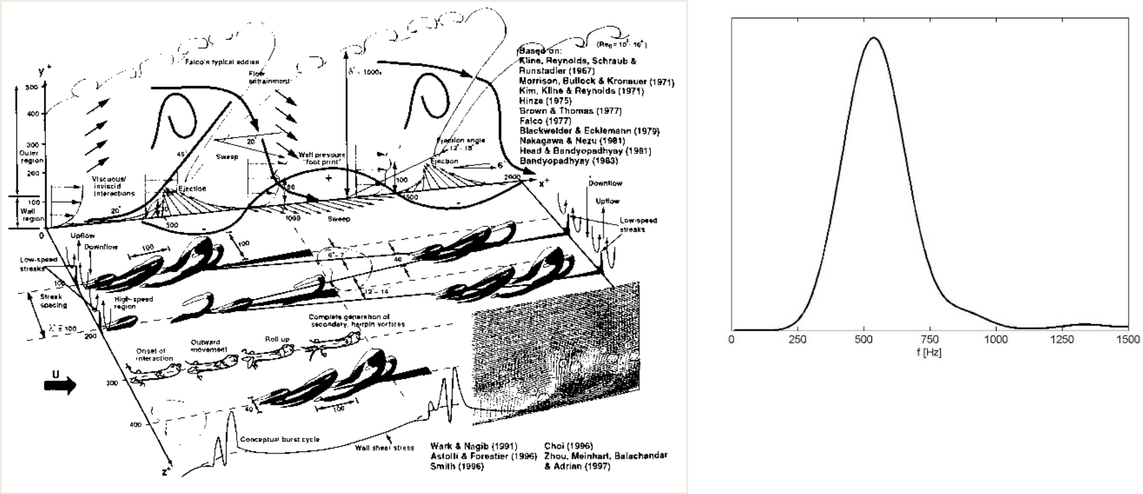


Fig.4: Flow phenomena in a TBL (left) and analysed MB dynamics (right)

Besides this fundamental investigation practical developments were required to accurately use and measure gas flow quantities in maritime model tests. As if dealing and measuring two types of fluids wasn't demanding enough, all these techniques were designed to work even in vacuum, as the resistance and propulsion tests at MARIN were conducted in the depressurised towing tank or in the large cavitation tunnel of TU Berlin. The latter as Reynolds effects were suspected to play a role in particular for MB drag reduction. As the highest achievable Reynolds number in a towing tank is restricted and full scale measurements of drag are challenging in many ways, a section of a ship's bottom have been built in the large cavitation tunnel of Berlin and tested at flow speeds up to 11 m/s. This way a Reynolds number of about 8E7 was realised. Drag reductions of about 40% have been validated and a slight dependency on the ambient pressure was observed.

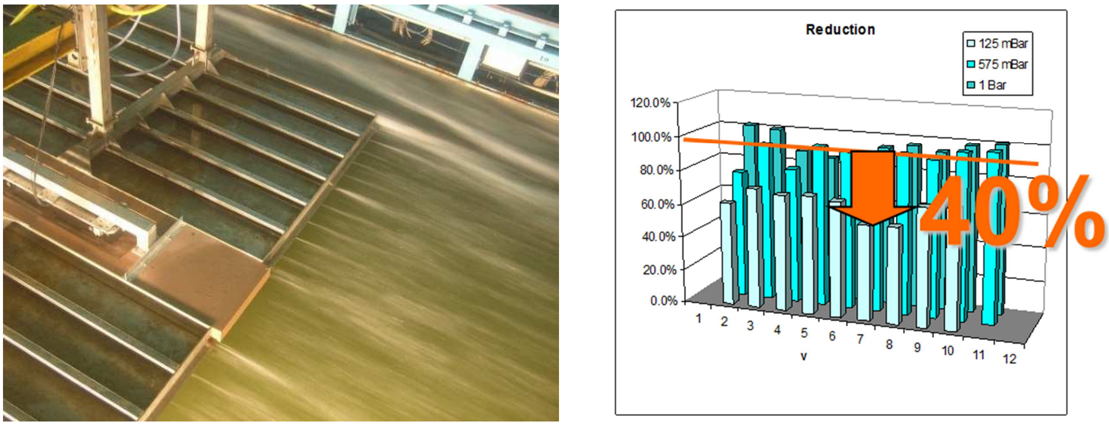


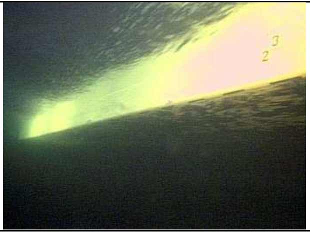
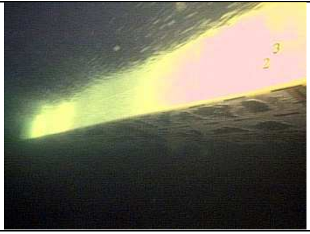
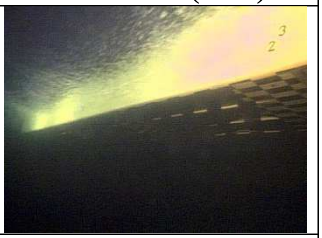
Fig.5: High Reynolds number set-up (left) and results (right)

Besides MB and SWR, air cavities have been tests in PELS 1 as well, see Fig.6. All tests were conducted at two different scales, from which the small model was built in 10 segments and used for comprehensive seakeeping and manoeuvring tests as well, *Walree (2002)*.

The final findings of the PELS 1 project including visualising photographs are summarised in Table 2.

Fig.6: Large model (left) and small model (right)

Table 2: PELS 1 results

	Micro bubbles (MB)	Air film (SWR)	Air cavities (ACS)
Photograph:			
C_F Reduction (bottom area)	>40 %	>30 %	Dry bottom area measured and C_F of air used
Net power reduction	±5 %	>5 %	>7 %

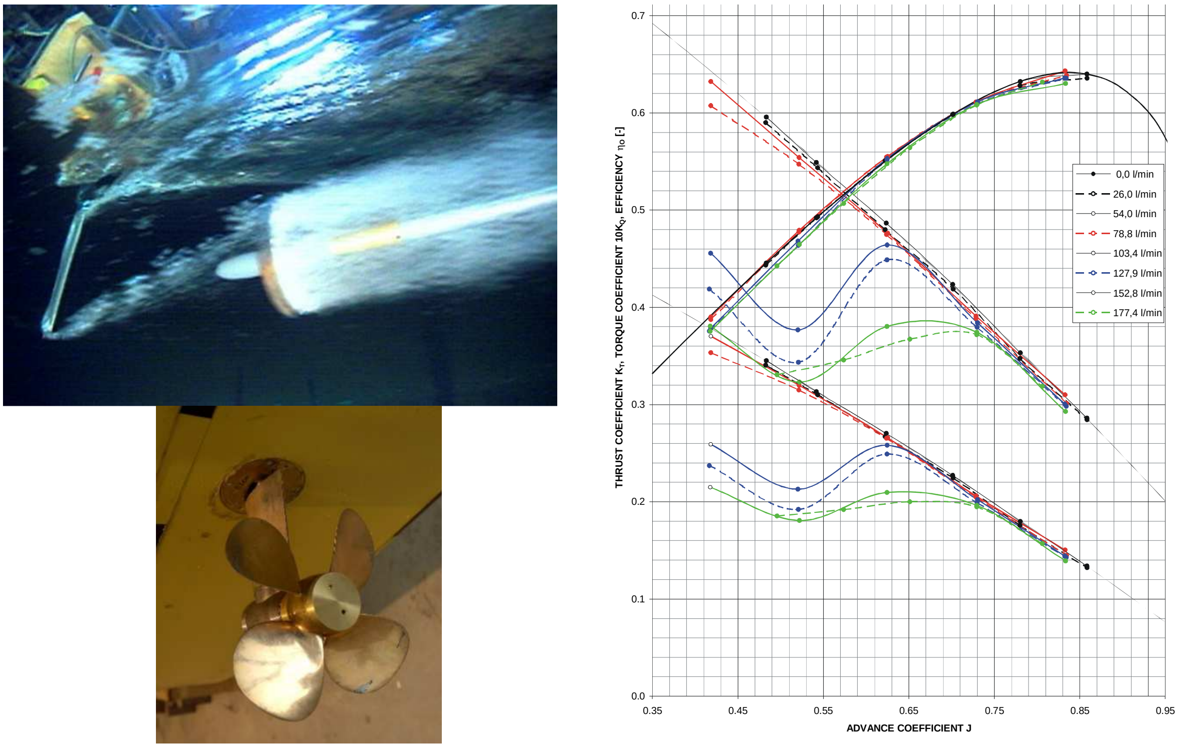


Fig.7: Ventilated propeller open water tests (left top), details of the propulsor (left below) and results (right)

All three techniques have been tested in waves, manoeuvres and calm water. The latter in terms of resistance and propulsion tests. Though ventilation of the propellers was as far as possible avoided by constructive means (rudder propellers with slender struts to let the air pass above the propeller and not leak along the low pressure domain along a traditional shaft, see Fig.7 left below), the behaviour of ventilated propellers was investigated in terms of enforced ventilated propellers, Fig.7 left top and related open water tests, Fig.7 right), *Thill (2005)*.

It was found that conventional propeller can cope with a rather huge amount of air before starting racing and that even when racing the total efficiency is not decreasing. However, when racing the advance coefficient changes unfavourably such that either constant ventilation should be enforced or CPP propellers should be used to compensate the virtual pitch reduction of a racing propeller. Either way, even this aspect is solvable, such that the next step consequently was the application of this technique, preferably within another research project.

3.2.2. PELS 2

PELS 1 was dedicated to fundamental research. Seen the encouraging results of Table 1 and Fig.7, a new consortium teamed up and successfully applied for research funding, this time within the Dutch Senter Novem. Target of this project was to apply the gained results of PELS 1, to close possible knowledge gaps and building the first full-scale demonstrator, Fig.1. In this consortium also issues such as the engineering of the air supply system end the development of dedicated bridge control systems were picked up. As lowest hanging fruits inland navigating vessels were addressed as here excited severe motions by external waves that could hamper the application due to increased air losses and resulting higher power demand of the blowers are of minor importance. Shallow water aspects were investigated within the largely parallel conducted SMOOTH project. Within PELS 2 air cavity ships were envisaged to be surveyed applied to inland pusher barges. These barges were “on stock” at one of the project’s partners and are regularly maintained. Within one of such a maintenance period one barge could have been converted and tested parallel to the original barge as plenty of them are available. However, after thorough CFD testing it needed to be concluded that the barges’ fullness and blunt bow is imposing severe 3D pressure fields over the whole length of the barge making it impossible to achieve a stable wave pattern inside the cavities. It was, therefore, decided to test the technique on a self-propelled inland navigating ship, the MV Kraichgau. A model was built at a scale of 1:7.7 and tested for reference purposes with a flat bottom and with several air cavity configurations within inbuilt recesses inside the flat bottom, Fig.8.

Fig.8: Model of MV Kraichgau (left) and a sample of tested bottom configuration (right)

Barges could have been tested parallel as the standard design would be available in large numbers for reference testing. The self-propelled vessel, however, needs to be tested as reference, thereafter being retro fitted with air cavities to eventually be tested as air cavity ship again. This complicated the field tests as weather conditions needed to be comparable. Too much trials measurement corrections were seen as not helpful as the applicability of air cavities should result from a direct comparison and not from comparing two sets of corrected trials measurements. In the end, depending on speed and loading conditions an impressive power reduction of ±15% was determined by means of model tests and full scale trials, Fig.9.

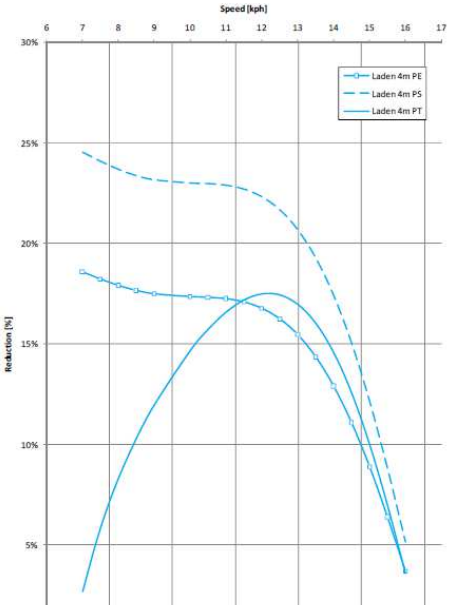


Fig.9: Trials of MV Kraichgau (left) and results (right)

3.2.3. SMOOTH

The 7th framework EU project Sustainable Methods for Optimal design and safe Operation of ships with air-lubricaTed Hulls (SMOOTH) brought drag reduction techniques for maritime applications to international EU level. MARIN initiated and coordinated this project with 11 European partners plus a supervisory board consisting of leading European end-users. Once it became apparent that both applied for projects were granted, the workscope of both projects (PELS 2 and SMOOTH) was mutually with the both financiers adjusted to avoid overlapping work and double funding. This allowed for an even more thorough approach and measurement campaign. The always constructive cooperation of the EU officer in this regard is gratefully acknowledged here. As identical models were shipped between 4 different test facilities, even possible facility effects could have been addressed. The answer beforehand: within the state of the art measurement accuracy no facility effects were observed.

Another topic was the full-scale survey of microbubbles enabled by the MB equipped inland ship Till Deymann provided by the SMOOTH partner New-Logistics. As this vessel is equipped with 4 rudder propellers for propulsion with poor accessibility of the shafts for placing the torque sensors, new equipment was developed at MARIN for the envisaged measurement campaign, Fig.10. Ship model and full-scale hull of Till Deymann were equipped with single ventilation strips at the bow made from dedicated porous media. Little – if any – drag reduction that was found at model scale could not be confirmed at full-scale. Seen the length of the full-scale ship (110 m) and the scale factor of λ=9.286 this was seen as evidence for relaxation phenomena as shown e.g by *Merkle and Deutsch (1992)*. In the light of these adverse findings on MB drag reduction it was decided to cancel further tests on Till Deymann and to “borough” the ACS ship Kraichgau from the PELS 2 consortium. This way interesting additional tests could have been conducted, for instance addressing the effect of different types of water (salt and fresh water). One remarkable work-package of SMOOTH was WP2 devoted to the development of SWR coatings for maritime application. The experimental one of PELS 1 is simply too expensive and the application rules are also not doable in the rather robust environment of a dockyard. Field tests on SWR were no part of the SMOOTH project. Model tests were performed at Istanbul Technical University and MARIN. One practical implication was found when handling the SWR coated ship models. Hydrophobic surfaces usually are lipophilic, in other words as the reject water they attract oil. Finger prints of staff handling the ship model already reduced the water repellent effect. One can easily imagine what remnants of oil will do to a SWR coated ship. Even if the painting was cheap, putting the vessel out of service for regularly repainting jobs would simply not be affordable. The segmented model of the PELS 1 project could have been tested at the large circulating tunnel of SSPA. The strong dependency of the cavity length with the drag reduction could be investigated in more depth as in a tunnel there is no free surface at the ship's waterline that is affecting the wave pattern inside the cavity, too. In Fig.11 the setup in the tunnel is shown and one exemplary result of the local resistance measurements, *Thill (2010)*. If the design of the cavity is not appropriately selected, the expected drag reduction can, thus, even revert to a drag increase.

Fig.10: Till Deymann (left) and new torque sensors (right)

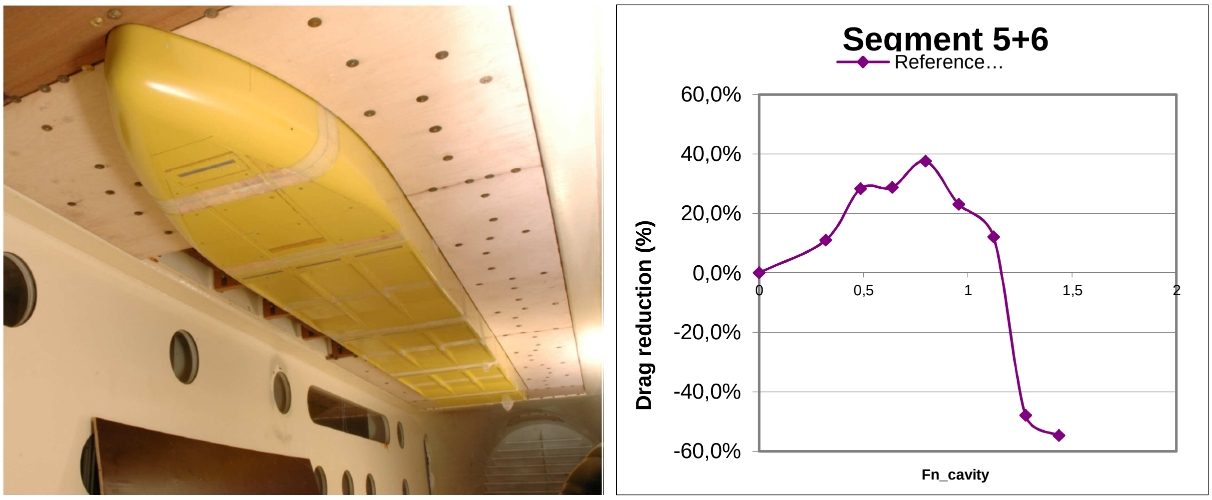


Fig.11: Local drag force measurements at the SSPA tunnel (left) and results (right)

3.2.4. STW (Stichting Techniche Wetenschappen = Foundation of Technical Sciences)

There are, in general three thinkable ways to locally insulate a ship's hull from the water, Fig.12, *Rotte et al. (2016)*. Within a STW research project, Zverkhovskyi (2014) concentrated on external air cavities,Fig.12 (b)), in particular the stability of yet another free surface underneath a ship's hull. He could validate that the maximum stable length of such an enforced cavity is about half the length of a gravity wave length of that speed. This, as such a cavity reaches the hull's surface at the position of the first node.

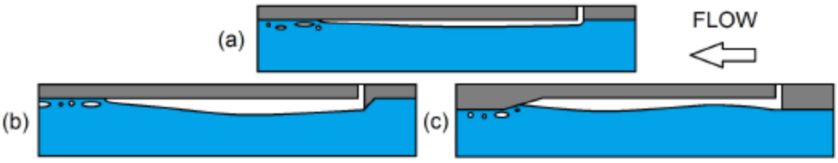


Fig.12: Air layer techniques: natural air layer (a), external cavity (b) and hull integrated (internal) cavity (c)

The internal cavity can afford more lengths as there is sufficient height to cover the forthcoming wave crest of a gravity wave length, which explains the optimum at about 80% of the length as found in Fig.11. Zverkhovskyi showed also that is does matter were an enforced cavity starts, i.e. the increasing local Reynolds number does affect the stability of the free surface, Fig.13. This imposes an uncertain scale effect even to air cavities as the Reynolds number of ships could not have been tested in laboratories. However, averaged over time these effects vanish, Fig.14, and the amplitude of the disturbance is small enough to play a secondary role for full scale ships with integrated cavities. Within the same project, *Harleman (2012)* investigated experimentally and numerically the effect of turbulence on bubbles in wall bounded flows for better understanding of MB drag reduction. Within his set-up, tests at high Reynolds numbers were not possible. At the Reynolds numbers of his survey, even a drag increase by (electrolytic generated) MB was observed. It is not clear when and whether this will change at higher Reynolds numbers and provides thus space for future research.

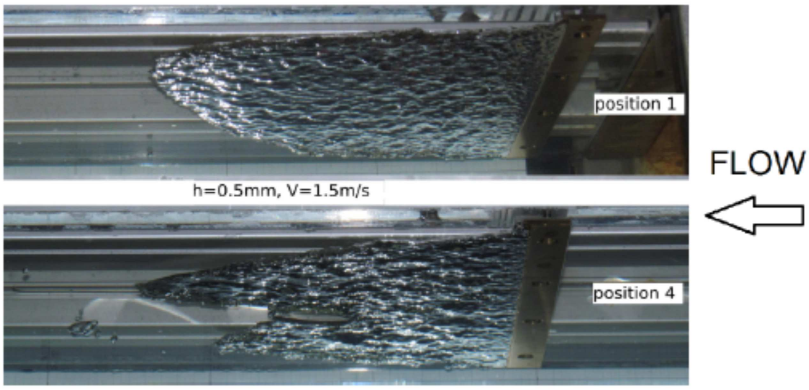


Fig.13: Cavity stability

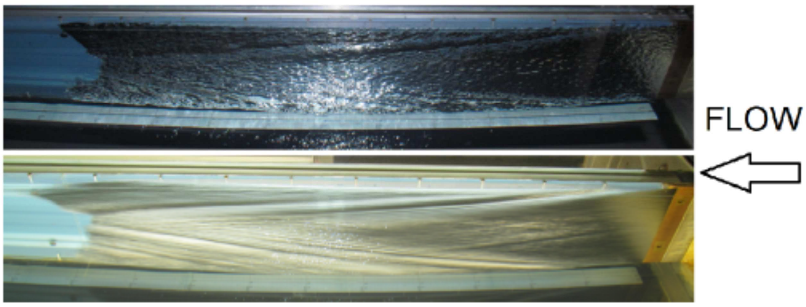


Fig.14: Different wave-systems on the external cavity surface, V=1.5 m/s. Top: instantaneous wave profile; Bottom: time averaged wave profile

4. The future of air lubrication (beyond 2016)

Drag reduction techniques are rightly in the focus of maritime (and fundamental) research. Admittedly at the start of the period used for section 3 the pressure due to high fuel prices was higher. Nevertheless, drag reduction is worth a closer look as it besides improving the profitability of the ship the technique can contribute to attain the climate targets as defined in Paris.

Even with the progress being made as described in this paper, there is still the desire, if not even the need, for future research as will be outlined in the following. Basic physics of micro bubble drag reduction are badly lacking at least for the high Reynolds numbers of sailing ships. Though remarkable progress is made in the field of **d**irect **n**umerical **s**imulation (DNS) of turbulent structures, Fig.15, a DNS simulation of a complete ship including full two way bubble interaction is still too far away. Phenomena like clustering of bubbles and local turbulence interaction, e.g. for a better understanding of relaxation of drag reduction are still an important issue that for the meantime needs to be addressed experimentally. Three surface instabilities are limiting the applicability of enforced air cavities and that they might play a secondary role for the reattachment features of the free surface for an internal air-cavity as well. Even if this is regarding the exploitable length of the cavity a second order effect, it might play a dominant role for estimating air losses at the trailing seal of a cavity and this way play a role for the overall energy balance of the ship. Air losses in calm water and seakeeping have been addressed by *Thill et al. (2005)*. The procedures developed for model tests are transferrable to full-scale air-supply control mechanisms, however, the control of air for an air-lubricated vessel can go much beyond than this; partly switching on and off parts of the lubricated ship's bottom can improve manoeuvring performance, safety (by reduced stopping distances) and comfort for passengers (noise and acceleration levels). Even after the two decades of applied research, there is still much work to be done.

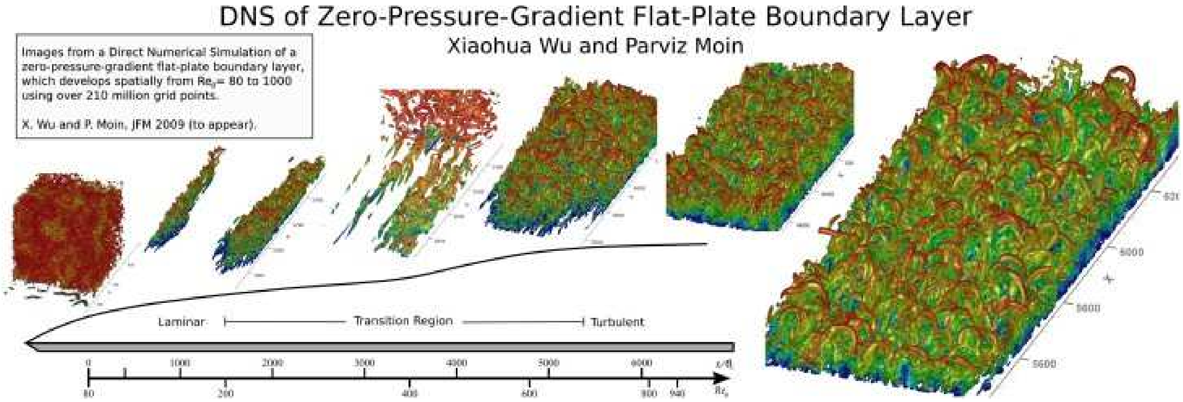


Fig.15: DNS results of turbulent boundary layers, Re=80…1000.

Following the promising results of model and full scale tests, Damen decided to develop a new inland waterway standard as a successor of the Damen Riverliner. With the Ecoliner concept of Damen, Fig.16, the realisation of the innovative combination of Air-Lubrication (Air cavities), Hull Optimisation (CFD), Propulsion System (Flex-Tunnel) and Power Generation (LNG) is integrated to maximize energy efficiency and minimize emissions.

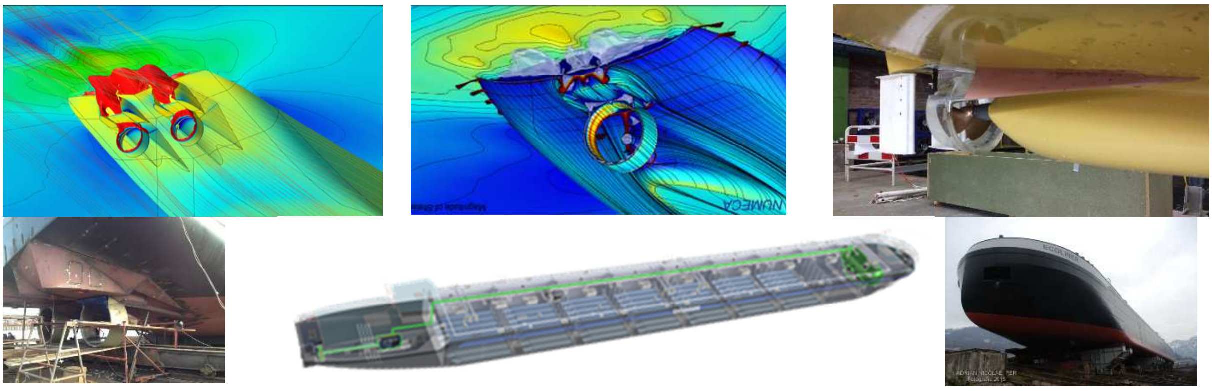


Fig.16: Damen Ecoliner concept (green above LNG system, blue air cavities, remaining figures CFD and hull details)

5. Conclusion

From the three surveyed techniques for air lubrication applied to ships air cavities are seen as the most promising. Consequently one prototype has been built on specs already. A potential of 15% net energy reduction was already confirmed, even for a 70m full scale demonstrator. Much research has been accomplished, much still has to be done, either for enabling practical applications for air-films or MB drag reduction, or for smart(er) control for improving the yet encouraging results of air cavity ships.

Acknowledgements

The author’s first involvement in air lubrication applied to ships was at MARIN. Firstly pure in industrial research projects that cannot be made public here. MARIN very early decided to spend own efforts in the development, design and purchasing of suitable equipment to handle air in maritime research for being prepared once the marked is requesting support. The far-sightedness of this vision and the freedom to actively shape this process is gratefully acknowledged. As a consequence, MARIN was well prepared applying for funded research projects on the subject, e.g. PELS 1&2 and SMOOTH. Without the funding by e.e.t., Senter Novem and the EU these projects could never be conducted, thus many thanks for the unique chance provided by these institutions. DST joint the SMOOTH project and provided the possibilities to continue the research in particular in the field of inland navigating vessels. Even after accomplishing the funded research projects, MARIN, DST and Damen continued dedicated research at own expenses to close some remaining knowledge gaps.
Last but not least thanks is owed to DUT, providing now the resources to consolidate the research and disseminating the achieved knowledge, either in terms of lectures and scientific exchange opportunities or writing papers like the presented one. Also DUT is actively pushing the knowledge further in terms of dedicated research projects. In this regard DUT is deeply beholden to STW, providing the means of funding that is essential for academic research in the Netherlands.

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