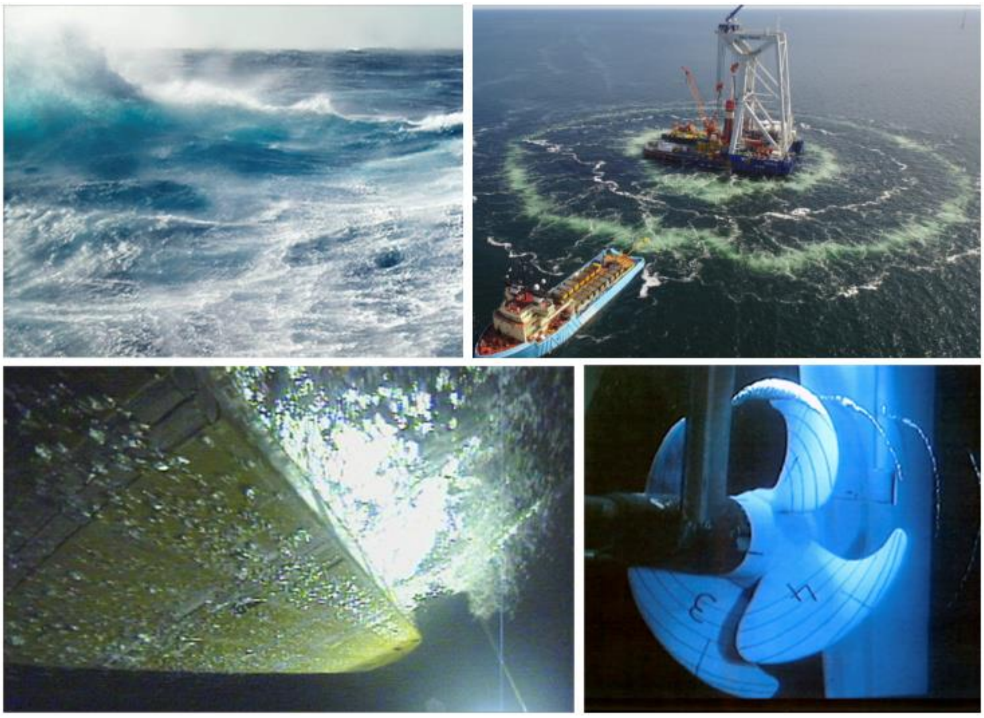
Toegepaste en
Technische Wetenschappen

AQUA Program Summary
An NWO (Dutch Research Council) sponsored program

"AQUA" – Water Quality in Maritime Hydrodynamics

P17-07



On the effect of aerated water quality (top left picture) on noise mitigation (top right picture – Arkona offshore wind project, www.vanoord.com), on ship drag reduction by air-lubrication (bottom left picture) and cavitation hindrance (bottom right)

Contents

1. Overview

Program leader	Prof. dr. D. Lohse – University of Twente, Physics of Fluids Dept.
Representative from user group	Dr H. Prins - MARIN
Participating organisations	1. University of Twente – Physics of Fluids 2. Delft University of Technology – Maritime and Transport Technology / Process and Energy 3. NIOZ – Dept of Ocean Systems
Participating Industries / Institutes:	AkzoNobel Damen Shipyards Group IHC MARIN Royal Netherlands Navy – Dept of Maritime Systems Wärtsilä STX-France A.P. Møller - Maersk TNO Maritiem Kennis Centrum
Program budget	3.22 M€
Total no of research positions	6 PhDs (Univ. of Twente and TU Delft) 1 Postdoc (NIOZ)
Keywords	Maritime hydrodynamics, drag reduction, bubble curtains, cavitation inception, underwater noise, bubbles, air-layer stability, sound generation, surfactants

2. Summary

2.1 Summary

This program aims to develop the knowledge and technology to significantly improve predictions of the effect of water quality on (a) ship resistance and (b) underwater radiated noise of cavitating ship propellers and pile driving for offshore wind turbines. We want to achieve a breakthrough on the following three long-standing problems in the Maritime Industry:

1. A lacking understanding of the efficacy of transitional air layers and air bubble injection on friction drag reduction and lacking procedures for reliable model tests or computational simulations.
2. A lacking understanding of the effect of water quality on propeller cavitation inception.
3. An incomplete understanding of the effect of water quality on the radiated underwater noise by a cavitating propeller and by pile driving for wind turbines.

For each of these three issues, "Water quality" refers to the dissolved and free gas content (bubbles), the chemical and particulate content of water. The economical and societal impact is that air-lubrication promises net power reductions of up to 15% of the current standard. Another impact of the proposed research is that hull vibration levels can be predicted with higher accuracy, resulting in optimization of propeller efficiency, recently shown to reduce power requirements by 10-15% [1].

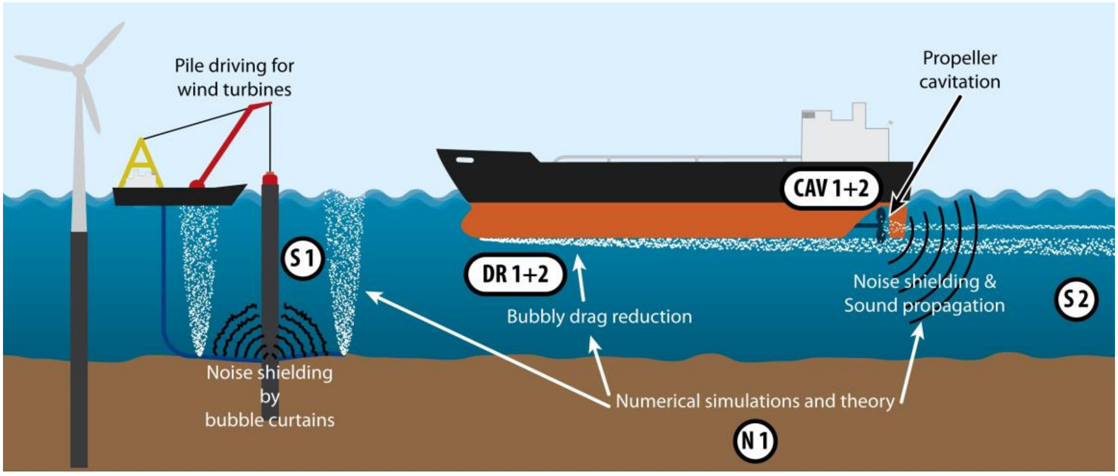


Figure 1 Graphical summary of the issues to be addressed: Air lubrication and bubbly drag reduction can reduce the hull friction considerably, reducing fuel consumption. Bubbles are also generated by cavitation at the ship propeller and are injected to mitigate noise from pile driving during offshore installations.

2.2 Unique selling point(s)

The unique selling point is that our consortium brings together fundamental physics of fluids, applied fluid dynamics, seawater chemistry and marine technology, all on a world-class level. The facilities comprise the unique high-precision Twente Turbulent Taylor-Couette facility, a complementary and new Multiphase Flow Tunnel in Delft, and our accurate bubble spectra measurement technique. The new Multiphase Flow Tunnel in Delft is likely the first laboratory in the world for systematic variation of Water Quality Gas and Water Quality Chemical.

3. Program description

3.1 Scientific challenges

Bubbles are omnipresent in the ocean, originating from air entrainment of breaking wind waves [2], [3] or falling rain drops [4], from natural gas release under the ocean, or from animals or plants [5]. In the last decades, however, the injection of man-made bubbles in the ocean has dramatically increased, for good economic and environmental reasons: (i) Bubbles are generated by breaking bow waves and cavitation on ship propellers. Satellite pictures of the wakes behind ships show that these bubbles are long-living as they are stabilized by surfactants [6], [7]. (ii) Bubbles and bubble-shedding air-lubrication layers are injected under the ship hull to reduce the drag of the ship and thereby reduce fuel consumption [8], [9]. (iii) Bubbles scatter and attenuate sound and therefore they are injected to mitigate noise from pile driving during the installation of offshore structures or other man-made sources of noise [10], [11].

The impact of bubbles on ship frictional drag, cavitation and sound propagation depends on their detailed dynamical properties. These, in turn, are crucially determined by the dissolved gas, chemical and particulate content of water. This holds for both the short-term dynamical behaviour of these bubbles and thus their performance in their respective tasks and - due to the long lifetime of the bubbles - also for the long-term acoustic properties of the ocean.

Water quality, is the overarching term, which includes:

- dissolved and free gas such as (micro-)bubbles (designated as water quality gas),
- chemical components such as dissolved salt and surfactants (designated as water quality chemical), and
- particulates such as dust, plankton and polymers (designated as water quality particulates), see Figure 2.

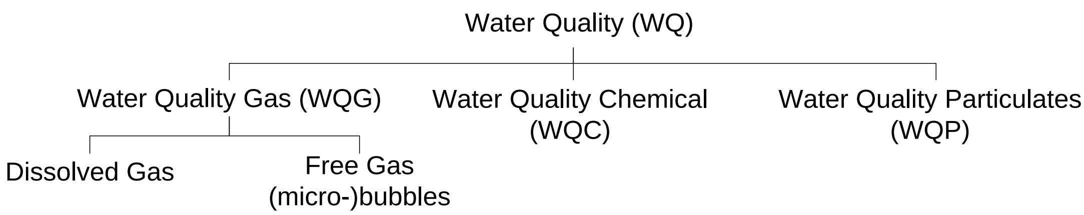


Figure 2 Definition of water quality

Past research on the applications of bubbles to frictional drag, cavitation and sound propagation has mainly focused on the behaviour of bubbles in fresh water. ***The objective of this programme is to better understand how these three applications related to bubbles and their dynamics are affected by the water quality*** (in particular the dissolved salt and gas concentration and the bubble size vs. concentration spectrum).

The dependency of bubbles on dissolved gas and Water Quality Chemical is illustrated by Figure 3b-c. In Figure 3b, we compare snapshots of bubbles rising against some flow under the very same water and gas flow conditions, but in one case without (left) and in the other case with 1.3% dissolved salt (right) added. The overall behaviour is dramatically different, as in the latter case the average bubble size is much smaller and the bubbles are correspondingly less deformed. The reason for this difference is that salt can suppress bubble coalescence, leading to much smaller bubbles in salty water. The impact of this for the applications of bubbles is tremendous. For example, Figure 3c shows the attenuation spectrum of monodisperse bubbles, revealing a very strong frequency dependence, and thus effectiveness for sound attenuation.

Bubble size also has a tremendous effect on bubbly drag reduction, as shown in Figure 3d. Until now however the majority of experiments were performed with fresh water, and including the water quality in the numerical and computational models has hardly been addressed. Incidental studies refer to the relevance of surface tension on the stability of the air layer [14]. Other studies refer to the mismatch in performance between model tests and full scale trials [15].

On the effect of water quality on cavitation inception, radiated pressures and noise production, only anecdotal accounts are available from full-scale practice [16], [17]. The importance of water quality on cavitation inception became clear after the classical study of ITTC 1966 where inception tests on the same headform in a wide range of facilities showed a dramatic variation [18]. The aforementioned accounts can only be understood by relating them to water quality. The resulting hypotheses are supported by a incidental studies that have been made on the relation between water quality and cavitation (e.g. [19]–[21]). A better understanding is urgently needed to enhance radiated pressure and noise predictions for full-scale situations.

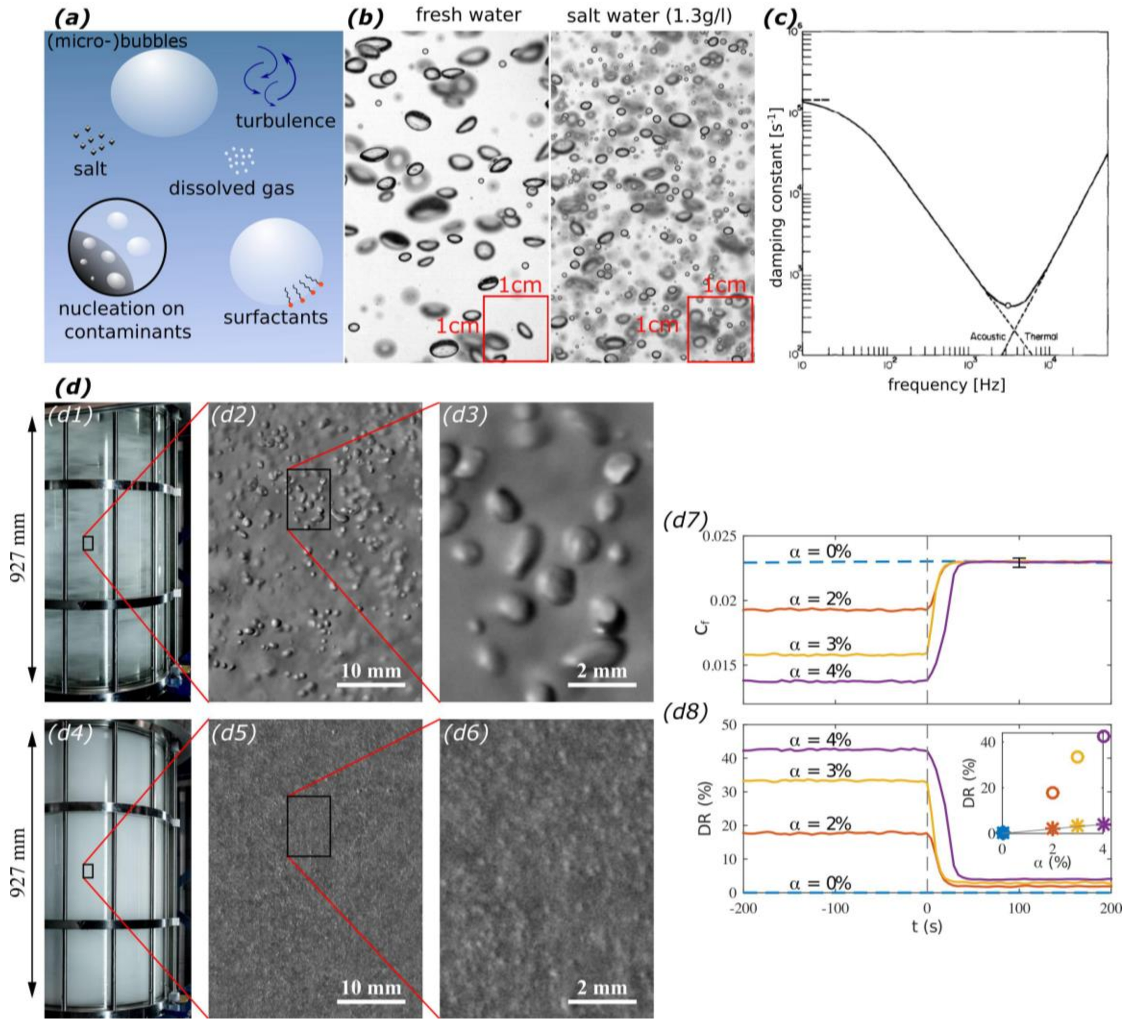


Figure 3 ***a)*** *Overview of water quality and flow properties influencing the bubble (size vs. concentration) spectrum in seawater.* ***b)*** *Bubble images for the same water and gas flow rates without (left) and with 1.3% dissolved salt (right). Images taken in the Twente Physics of Fluids group.* ***c)*** *Acoustic damping constant as a function of the driving sound frequency for air bubbles with a radius of 1 mm in water* [12]. ***d)*** *Comparison of results on bubbly drag reduction in turbulent flow* [13]*: (d1-6) Snapshots of the bubbly turbulence (Re=$2\cdot10^6$) with increasing magnification (from left to right). In the upper row no surfactants are present resulting in large deformed bubbles, whereas the lower row shows the addition of Triton X-100 results in a larger number of smaller bubbles. (d7) The skin friction coefficient (C_f) as function of time for strongly turbulent flow for different gas volume fractions (α). At t=0 s a surfactant is injected (dashed vertical line), after which we observe a large increase in the measured torque and after 20 s all curves overlap. (d8) Drag reduction (DR) as function of time. After injection of the surfactant nearly all DR is lost. Inset: The averaged DR before (circles) and after (asterisks) addition of the surfactant, as a function of α. The thin line equals DR=α, showing that after addition of the surfactant the small residual DR is caused by the reduced density of the fluid mixture.*

Finally, this project aims at understanding the effect of injected bubbles and those originating from air-lubrication on sound propagation and sound shielding in seawater (i.e., with a water quality different from fresh water), both in the context of the naval industry and for environmental protection. The latter is particularly relevant for pile-driving in the ocean (e.g. for offshore wind turbines, see Figure 1), causing a tremendous amount of underwater noise, thus affecting ocean life. Legislation is fortunately enforcing to minimize underwater sound emission, and the most promising technology to achieve this are so-called bubble curtains (Figure 1), absorbing and reflecting the underwater sound. However, it is not yet understood at all what bubble sizes and densities are optimal and how water quality affects the properties of such bubble curtains (see Figure 3b,c,d).

3.2 Research lines

The proposed research will bring together the fields of physical and engineering fluid dynamics, acoustics, and chemical oceanography to investigate the effect of bubbles and seawater quality on bubble drag reduction, cavitation, and sound propagation. The consortium contains groups with as diverse backgrounds as physics, engineering and chemistry.

The program integrates three lines of research:

1. Drag reduction and water quality[1]: There is a variety of ways that aim at a reduction of the friction drag of ships through air-lubrication. Some of them have claimed successes, such as air-lubrication by air chambers or cavities and (transitional) air layer techniques. Other techniques that aimed at air-lubrication by bubbles in the boundary layer have often been demonstrated to have little or no effect. We have demonstrated that the addition of surfactants (i.e., changing the chemical water quality) can dramatically affect drag reduction [13] and it has also been demonstrated that model tests in fresh water showed significantly better results than full scale tests in sea water [15]. It is unknown to what extent the difference in surface tension contributes to this difference, or whether it is mainly due to dissolved salt resulting in suppression of bubble coalescence [22]. This program aims to quantify the effect of water quality on the frictional drag reduction, combining experiments, modelling, and numerical simulations.
2. Cavitation-induced vibrations, radiated noise and water quality: Cavitation-induced vibrations and noise by the ship propeller can be classified after their frequency and their character: tonal or broadband (see e.g. [23], [24]). We make a distinction here between pressure pulses at frequencies below 100 Hz, where compressibility of the fluid hardly plays a role in the propagation of the pressure signal, and radiated sound at frequencies well above this limit. Furthermore, we distinguish between tonal frequencies, such as the blade passing frequency and multiples thereof, and broadband frequencies, such as caused by a cloud of oscillating bubbles or a cavitating vortex. Furthermore, we aim to quantify the effects of the flow and the water quality on vortex cavitation inception, with a focus on scaling issues, and the effect of water quality on developed cavitation and its radiated pressures.
3. Noise-shielding by bubble clouds and curtains and water quality: Injected bubbles dramatically change the propagation of underwater sound and can even shield it. The sound reflection and absorption as a function of the sound frequency is strongly related to the size of the bubbles [25], which in their turn are strongly affected by salt and surfactants, see Figure 3.

In all three lines of research we will use four types of water:

- Clean water for comparison
- Water with 3.5% (weight) NaCl, representing the average salt concentration in the open ocean (including the North Sea).
- Artificial seawater with major and minor element concentrations resembling those of natural seawater (i.e. with dissolved Mg, Ca, K, SO_4, B, Br, etc. in addition to NaCl).
- Natural sea water, which differs from the artificial seawater by containing dissolved organic compounds and particulate matter.

In addition, we will control the gas content of the water, by injecting air and/or CO_2, or by degassing.

[1] Water quality refers to dissolved and free gas, dissolved chemical components and particulates in the water, see also the definition in Section 3.1.

3.3 Description and coherence of the projects

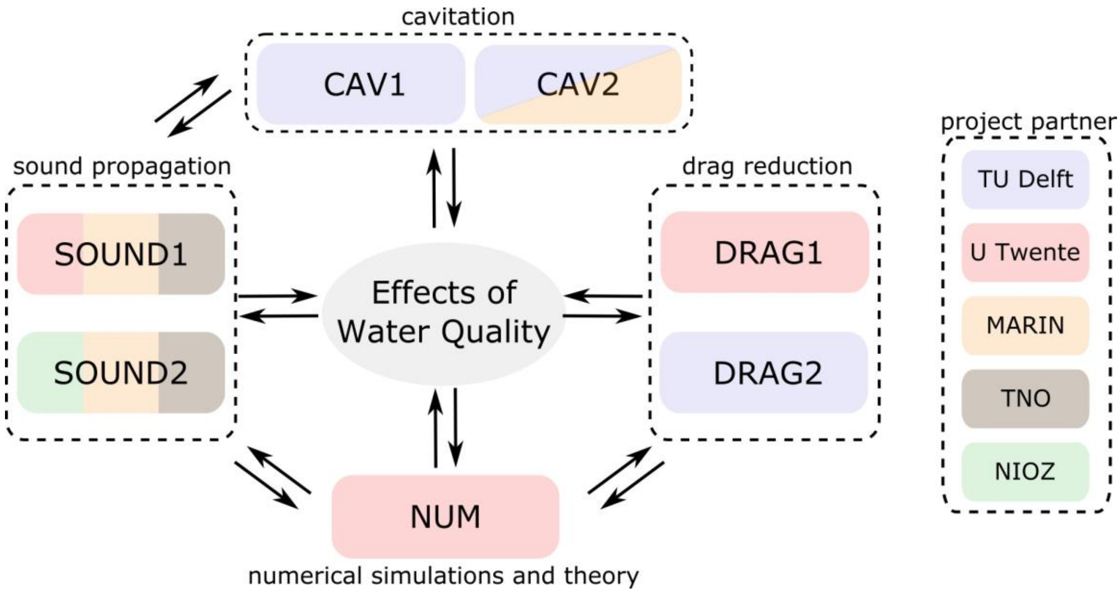


Figure 4 Structure of the program and the cooperation between partners

Three different interrelated themes are addressed in this program as shown in Figure 4: Drag reduction by air lubrication, cavitation and sound generation and propagation. All are sensitive to water quality effects. Each of these themes will be worked out in two experimental projects.

Projects DRAG-1 and DRAG-2
These projects focus on the effects of water quality on drag reduction by air lubrication, including the interaction between the water quality and the plate surface properties (e.g. hydrophobic or hydrophylic). The DRAG-1 project focuses detailed measurements in the Twente Taylor Couette Set-up, building further on earlier STW projects (Ship Drag Reduction by Air Lubrication (STW project 07781) and SHIPDRAC (STW project 13265). A focus is thereby placed on water quality, surface physical properties and surface roughness. This project runs parallel with the DRAG-2 project, which will largely be carried out in the newly built Multiphase Flow Tunnel at Delft University of Technology (TUD). Here the effect of water quality on a transitional air layer over a flat plate will be studied. In-kind contributions will be given by AkzoNobel and MARIN. AkzoNobel will provide a flat plate configuration with different coatings. MARIN will provide support for the experimental set-up and experiments. MARIN will also do exploratory RANS and PANS computations using a mixed flow approach and ensure that the new results can be linked to the previous drag reduction projects in Delft (as mentioned above plus the STW AIRSHIP project 13277).

Projects CAV-1 and CAV-2
These projects focus on the effects of water quality on cavitation inception and nuisance such as cavitation-induced vibrations through pressure pulses as well as noise generation. The CAV-1 project has a focus on water quality effects on developed sheet and vortex cavitation, such as occur at the leading edge of the propeller blade, the tip region and from the propeller hub (see **Error! Reference source not found.**). The CAV-2 project has a focus on tip vortex cavitation inception and its sensitivity to water quality and scale. These experimental projects will be linked to full-scale measurements through the in-kind contribution of the Royal Netherlands Navy on one of their Diving Support Vessels, as well as to an existing complete data set for the Damen Combi Freighter. MARIN will provide propeller models representative for the Diving Support Vessel and the Damen Combi Freighter for testing in the Delft Multiphase Flow tunnel. Wärtsilä will support the analysis by URANS computations. Damen Shipyards will support the full-scale Diving Support Vessel trials with sound measurements and CFD computations to determine the radiated noise source strength.

Projects SOUND-1 and SOUND-2
These projects focus on the effect of water quality on the underwater sound propagation. The SOUND-1 project aims to quantify the influence of environmental factors such as water quality (surfactants, salt and dissolved gas concentrations) and background turbulence on bubble generation and development. Second, we aim to clearly identify which physical mechanisms are most relevant to effective noise reduction by bubble curtains. TNO will provide access to their anechoic basin including equipment for acoustic measurements. Furthermore, a joint industry

project, initiated by MARIN, aims to measure the characteristics of a full-scale bubble curtain. The SOUND-2 project aims to obtain a high-quality dataset in which all relevant water quality parameters affecting the generation and propagation of cavitation-induced noise are measured at sea. This dataset can be used to direct future laboratory research and theoretical modelling. NIOZ will provide the research vessel Pelagia. TNO will enable underwater radiated noise measurements with an acoustic buoy. MARIN will provide instrumentation and expertise to measure the micro-bubble spectrum near the propeller as well as cavitation observation equipment.

Project NUM
An overarching project on numerical and theoretical modelling completes the program. In modern hydrodynamics, a one-to-one connection and comparison between theory and numerics on the one hand and experiments on the other hand is essential, to be able to make predictions for parameter domains that are not or hardly experimentally accessible, and to gain the required understanding.

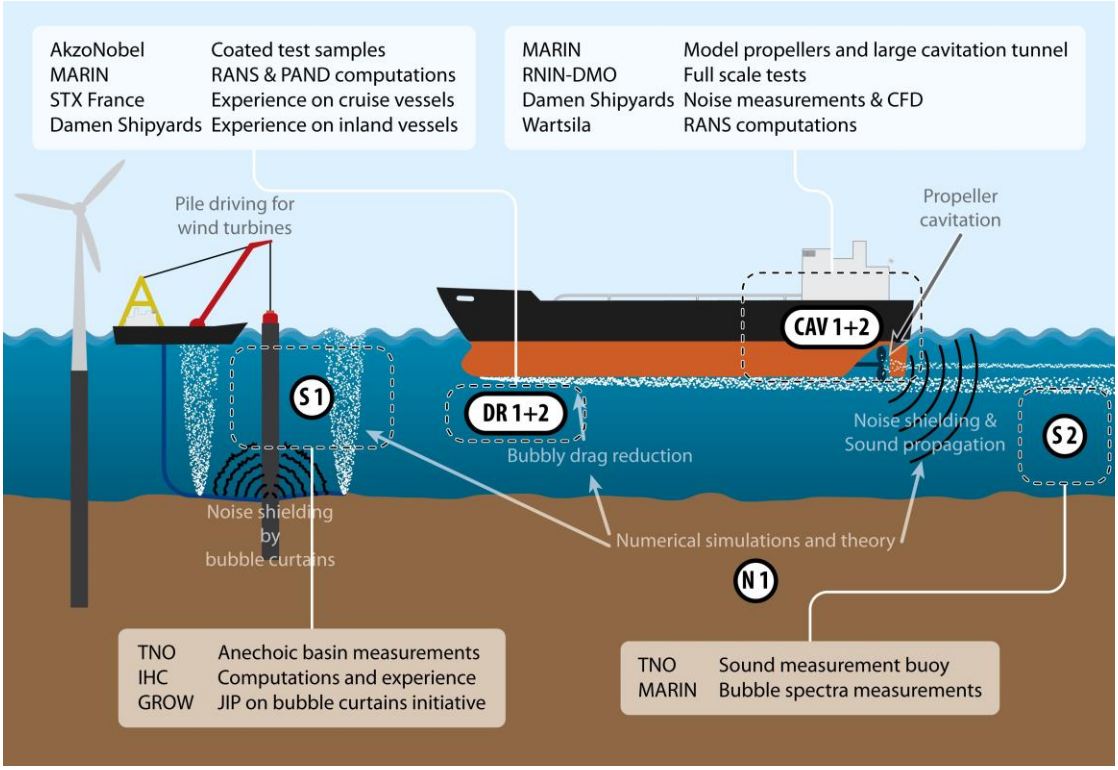


Figure 5 In-kind contributions of companies and knowledge institutes

New Multi-Phase Flow Tunnel
Because the new MultiPhase Flow tunnel requires the biggest investment (a total of 700 k€ from this program), a brief description of the unique features of this tunnel is given here (from [26]). The new tunnel has a total volume of approx. 25 cubic metre, which is low for a modern cavitation tunnel with water quality gas control but therefore allows for chemical water quality management. The volume can be so low because we have adopted a water quality gas philosophy where not all the microbubbles are filtered out, but only those above a threshold of approx. 50 µm. The advantage of this approach is that microbubbles are needed for cavitation inception conditions anyway, but that they just should not exceed a given threshold diameter. This relaxed requirement compared to other modern tunnels allows for the limited volume. The low volume also allows for a more practical management of solid particles in the water, which likely also affect cavitation inception. With a dual contraction design, the tunnel also facilitates two test section sizes: One for cavitation tests featuring dimensions of 0.3*0.3*2.13 m (width*height*length) as a maximum flow velocity of 12 m/s. The other section is for the remaining research themes that need maximum optical access and no low pressures. The large section features dimensions of 0.5*0.5*5 m and a maximum flow velocity of 4.3 m/s.

Research line and workpackage	Projects	Research groups applying	Potential users
1. Water Quality Effects on Drag Reduction	DRAG-1: Effect of roughness and water quality on drag reduction by air lubrication	University of Twente - Physics of Fluids: Dr. S. Huisman, Prof. Chao Sun, Prof. D. Lohse	AkzoNobel, MARIN, Damen, Maersk, DMO-RNIN
	DRAG-2: Dynamics of transitional air layers	Delft University of Technology - Mechanical Engineering: Prof. C. Poelma, Dr. W.P. Breugem - Maritime and Transport Technology: Prof. T. van Terwisga	AkzoNobel, MARIN, Damen, Maersk, DMO-RNIN
2. Water Quality effects on Cavitation	CAV-1: Water quality effects on cavitation and noise	Delft University of Technology - Maritime and Transport Technology: Prof. T. van Terwisga - Mechanical Engineering: Prof. J. Westerweel	Damen, Wärtsilä, IHC, DMO-RNIN, MARIN, TNO
	CAV-2: Cavitation inception in tip vortices	Delft University of Technology - Mechanical Engineering: Prof. J. Westerweel, Dr. G. Elsinga - Maritime and Transport Technology: Prof. T. van Terwisga	Damen, Wärtsilä, DMO-RNIN, MARIN, TNO
3. Water Quality effects on sound propagation	SOUND-1: Shielding noise by bubble curtains and the effect of water quality	University of Twente - Physics of Fluids: Dr. D. Krug, Prof. A. Prosperetti, Prof. D. Lohse	DMO-RNIN, MARIN, TNO, wind turbine installation industry
	SOUND-2: The effect of water quality on the acoustic footprint of ships	NIOZ - Prof. G.J. Reichart, Dr. L.J. de Nooijer, Dr. L Devriendt	DMO-RNIN, MARIN, TNO, Wind turbine installation industry
N: Numerical simulations	NUM: Numerical simulations on bubbly drag reduction in turbulent flow and on sound propagation in bubbly flow	University of Twente - Physics of Fluids: Prof. D. Lohse, Prof. A. Prosperetti, Prof. R. Verzicco	MARIN, AkzoNobel

Table 1 Schematic overview of the program

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