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Ultrasound technologies in support of ballast water treatment on board ships

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Abstract. This paper examines the challenges of ballast water treatment on board ships. While international maritime trade provides major economic benefits, it also facilitates the uncontrolled transfer of invasive aquatic species through ballast water, causing ecological imbalances that impact biodiversity, human health, and the economy. In response, the International Maritime Organization introduced the Ballast Water Management (BWM) Convention, requiring ships to install certified treatment systems. The study analyzes general treatment principles and a case study on the Mary Maersk, focusing on system performance in difficult conditions such as turbid waters. It also proposes integrating ultrasound technology to improve efficiency. By generating acoustic cavitation, ultrasound can disrupt microorganisms and prevent biofilm formation, maintaining effective disinfection with minimal additional energy consumption, while supporting environmental protection.

Keywords: ballast water treatment, marine environmental protection, Ballast Water Management (BWM) Convention, ultrasound technology

1. Introduction

In the early stages of modern commercial navigation, ballast water was used almost exclusively for technical reasons to ensure vessel stability (Rawson & Tupper, 2001). Ballasting operations were conducted without ecological assessments or controls, set against a backdrop of non-existent legislation. This empirical practice led to the massive, involuntary transfer of aquatic organisms between different ecosystems, increasing the risk of significant biological imbalances. As maritime trade accelerated in the second half of the 20th century, the volume of biological transfers reached unprecedented levels. The first signs of a major ecological crisis appeared in the 1980s, a notable example being the introduction of the comb jelly Mnemiopsis leidyi into the Black Sea in 1982 (Shiganova et al., 2001). A definitive turning point in scientific perception was the 1993 study by Carlton and Geller, "Ecological

Roulette," which revealed that over 3,000 species were being transported annually within 3 billion tons of discharged ballast water, likening the process to a dangerous gamble with global biodiversity (Carlton & Geller, 1993).

This awareness spurred the creation of an international legislative framework. The decisive moment came in 2004 with the adoption of the BWM Convention (Ballast Water Management) (IMO, 2004). This treaty mandates that vessels implement certified management plans, maintain detailed record books, and utilize approved treatment systems. Furthermore, it establishes rigorous port inspections to prevent biological invasions.

Having entered into force globally in September 2017, the BWM Convention transformed ballast water management from a purely operational task into a strict international legal obligation (MEPC, 2016). This regulatory evolution culminates on September 8, 2024, when the D-2 standard (regarding water treatment performance) becomes mandatory for all commercial vessels, marking a final transition toward environmentally responsible navigation.

This study analysed both the general principles of existing ballast water treatment systems and a specific case applied aboard MV Mary Maersk, a large-capacity container vessel. The work aimed not only at analysing the ballast water treatment method, but also at identifying possible improvements to the current system, particularly in challenging operational scenarios such as ports with high-turbidity waters.

2. General aspects regarding ballast water management for container ships

Maritime transport is a key driver of international trade, ensuring the continuity of global cargo flows. To guarantee stability and safety during voyages, vessels utilize ballast tanks, arranged according to ship type, where seawater is pumped in or discharged to compensate for the vessel's cargo load (Rawson & Tupper, 2001).

Technically, ballast water is used to adjust a vessel's center of gravity and ensure stability through an integrated system of pumps and tanks (Rawson & Tupper, 2001). This is especially vital for container ships, which can carry up to 24,346 TEU (such as the MSC Irina). Due to the high vertical stacking of containers both above and below deck, these ships face a naturally high center of gravity and inherent instability, making precise ballast management essential for safe operation.

While essential for maritime safety, ballast water poses a significant risk through the involuntary transfer of marine species across ecosystems. Lacking natural predators, these organisms, ranging from microorganisms to larvae, can become invasive and disrupt local biological balances. Annually, over 10 billion tons of ballast water are transported globally, moving roughly 7,000 species daily. Research highlights that shipping is responsible for 90% of marine invasive species, with the risk of biological invasions projected to increase between 3 and 20 times by 2050 due to rising maritime traffic (Sardain et al., 2019) represented in Figure 1.

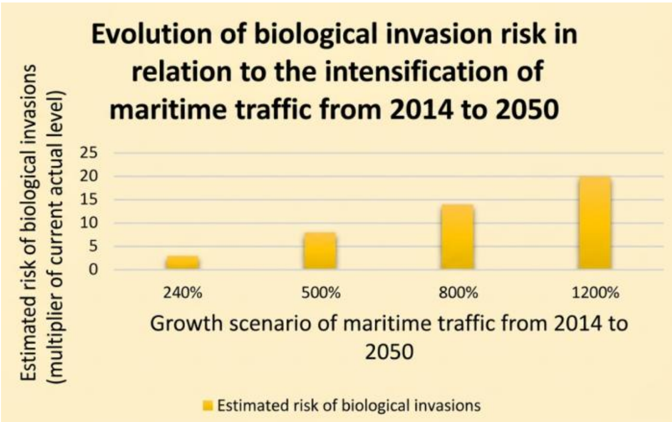

Figure 1 Chart regarding the evolution of biological invasion risk in relation to the intensity of maritime traffic from 2014 to 2050 (Sardain et al., 2019)

The analysis highlights a direct correlation between the expansion of maritime trade and the increase in ecological risk. Based on projections for the year 2050, four scenarios of maritime traffic growth are evaluated (ranging from 240% to 1200% compared to 2014 levels). The results indicate that the risk of introducing invasive species increases exponentially, potentially becoming up to 20 times higher in the maximum development scenario. This evolution demonstrates that the intensification of naval transport proportionally amplifies the danger to vulnerable ecosystems.

The accidental introduction of invasive species via ballast water poses a major challenge, generating immense economic and social costs. In Southeast Asia alone, the annual impact is estimated at $33.5 billion (Nghiem et al., 2013; Popa, 2025). Direct costs include massive losses in aquaculture (over $1 billion annually in shrimp farms) and a 25% increase in maintenance expenses for industrial infrastructure due to biofouling. Indirect costs, though difficult to quantify precisely, severely impact tourism by compromising recreational areas and endanger public health through the transport of pathogens (Nghiem et al., 2013). Given these long-term effects, implementing preventive ballast water treatment technologies is essential to reduce biological transfer and protect regional economies.

3. Ballast water treatment technologies commonly used on board ships

Ballast water treatment systems used on board commercial vessels have evolved significantly over the last two decades, becoming mandatory equipment for ecologically responsible operation (IMO, 2004; MEPC, 2016). The most common technical solutions currently implemented are categorized into three main strategic approaches. First, physical systems such as mechanical filtration are used to remove larger organisms and sediments. Second, chemical systems utilize oxidizing agents like chlorine or ozone to disinfect the water. Finally, photo-physical systems, most notably ultraviolet (UV) radiation treatment, are employed to neutralize microorganisms by disrupting their DNA, ensuring that the ballast water discharged meets international environmental safety standards (Zhang et al., 2024).

Ultraviolet (UV) radiation treatment of ballast water

Ultraviolet (UV) treatment is a widely used physical method for decontaminating ballast water, particularly effective within the UV-C spectrum (200-280 nm). The process works by destroying the genetic material of microorganisms at an optimal wavelength of 250-260 nm (Zhang et al., 2024). The onboard system consists of high-intensity lamps protected by quartz tubes; water is drawn from the sea chest, mechanically filtered to remove sediments, and then passed through the UV reactor for biological inactivation.

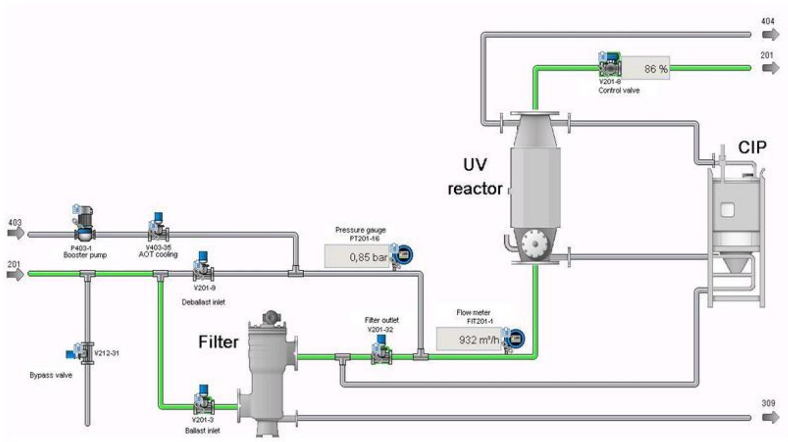

Figure 2 Operating diagram of the UV radiation treatment method (Mary Maersk Ballast Water Management Plan, 2013)

Chemical treatment of ballast water

Chemical treatment of ballast water uses oxidizing agents or biocides to destroy the cellular structure of microorganisms. The most common methods are:

- **Ozonation**
  - Ozone (O_3) is generated onboard via electrical discharges and injected into the ballast system.
  - It acts rapidly through irreversible oxidation and spontaneously decomposes back into oxygen, leaving no chemical residues.

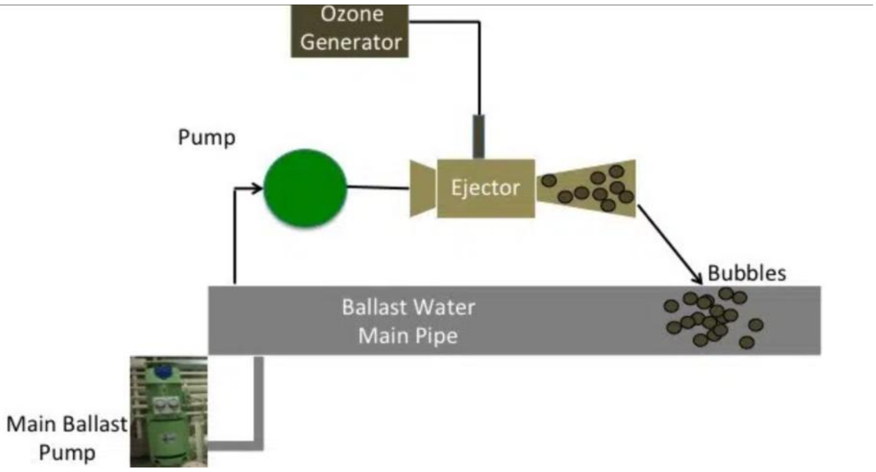

Figure 3 Operating diagram of an ozonation system (Marine Insight, 2023)

- **Chlorination and Electrochlorination**
  - These methods use sodium hypochlorite to inactivate the biological functions of organisms.
  - Electrochlorination is an autonomous variant that generates the biocide directly from the salt in seawater through electrolysis.
  - The process is influenced by salinity, temperature, and turbidity, and is often preceded by a mechanical filtration stage to ensure optimal exposure of organisms to the chemical agents.

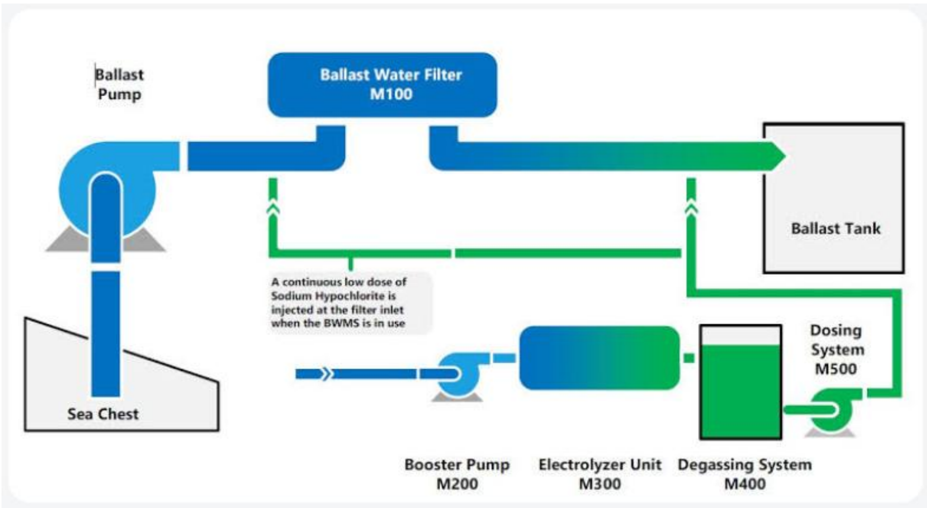

Figure 4 Schematic diagram of an electrochlorination system (Drydock Magazine, 2023)

Mechanical filtration

Mechanical filtration is an essential pre-treatment method, typically used in combination with technologies such as UV or chlorination (Zhang et al., 2024). It retains particles between 40-100 microns using stainless steel or synthetic filter elements. Modern equipment includes self-cleaning functions to maintain a constant flow rate in high-turbidity waters. While they can capture up to 95% of particles over 50 microns, filters are not effective against organisms smaller than 10 microns, which is why mechanical filtration is rarely used as a standalone method.

Analysis of the ballast water treatment technologies

The comparative analysis, shown in Tabel 1, highlights UV radiation treatment as the most balanced solution (18 points), offering an instantaneous reaction time and minimal ecological impact, although its efficiency may decrease in turbid waters (Zhang et al., 2024). Mechanical filtration (16 points) stands out for its minimal energy consumption but is limited to retaining large organisms. While ozonation (15 points) is the most effective at eliminating pathogens, it involves toxicity risks and high energy consumption. Chlorination and electrochlorination (13 points) received the lowest score, primarily due to their negative environmental impact through the formation of hazardous by-products. In conclusion, the UV system represents the optimal balance between performance and sustainability.

Table 1. Comparative analysis between ballast water treatment technologies

Treatment Method	Efficiency in organism removal	Reaction time	Energy consumption	Environmental impact	TOTAL SCORE
UV Radiation	**4**	**5**	**4**	**5**	**18**
Ozonation	**5**	**4**	**3**	**3**	**15**
Chlorination/ Electrochlorination	**4**	**4**	**3**	**2**	**13**
Mechanical Filtration	**3**	**3**	**5**	**5**	**16**

4. The Alfa Laval PureBallast 3.0 treatment system implemented on board the vessel Mary Maersk and its limitations

The Alfa Laval PureBallast 3.0 system utilizes a combination of mechanical filtration and UV radiation with Advanced Oxidation Technology (AOT) to eliminate microorganisms (Alfa Laval, 2020). The AOT process generates hydroxyl radicals that destroy biological structures during both ballasting (filtration + UV) and de-ballasting (UV only). The system is fully automated via a PLC controller and real-time monitoring sensors. Its core components, the filter, UV reactor, and Cleaning-In-Place (CIP) unit, are compactly installed in the engine room (as seen on the Mary Maersk), ensuring compliance with international environmental standards (Mary Maersk Ballast Water Management Plan, 2013).

To ensure maximum efficiency in the ballast water treatment process, the Alfa Laval PureBallast 3.0 system is built around three fundamental components: the mechanical filter - a self-cleaning (back-flush) unit that removes particles larger than 40 µm without interrupting the water flow, the UV reactor with Advanced Oxidation Technology (AOT), and the automatic Cleaning-In-Place (CIP) system. These modules form the backbone of the biological and physical water purification process, guaranteeing compliance with the requirements imposed by international regulations.

This study evaluates the operational performance, energy consumption, and ecological footprint of the Alfa Laval PureBallast 3.0 ultraviolet (UV) ballast water treatment system installed aboard MV Mary Maersk, under real operating conditions in the Indian Ocean, where salinity, turbidity, and biological load vary considerably (Alfa Laval, 2020; Mary Maersk Ballast Water Management Plan, 2013).

Tabel 2. System parameters

Parameter	Value
Total water volume treated	20,000 m^3
Treatment capacity	1,000 m^3/h
Nominal UV reactor power	33 kW

Peak power during ramp-up	63 kW
Ramp-up duration	5 min

The total operating time required to treat 20,000 m^3 at the rated capacity of 1,000 m^3/h is calculated as follows in equation 1:

$$T_{total} = \frac{20.000\, m^3}{1.000 m^3/h} = 20\; hours \tag{1}$$

The hourly energy consumption is decomposed into two phases:

- Ramp-up phase (equation 8) - the UV reactor operates at peak power (63 kW) for 5 minutes to warm lamps and stabilize operating parameters:

$$E_{(ru)} = P_{(ru)} \times \frac{t_{ru}}{60} = 63kW \times \frac{5}{60} = 5{,}25\; kWh \tag{2}$$

- Steady-state phase equation 9 - the reactor runs at nominal power (33 kW) for the remainder of each operating hour:

$$E_f = P_n \times t_f = 33kW \times 1h = 33kWh \tag{3}$$

Combined hourly energy demand is shown in equation 4:

$$E_{total} = E_{(ru)} + E_f = 5{,}25kWh + 33kWh = 38{,}25kWh \tag{4}$$

Total energy consumed over the full 20-hour treatment cycle is shown in equation 5:

$$E_{20.000m^3} = E_{total/h} \times T_{total} = 38{,}25 \times 20 = 765\; kWh \tag{5}$$

Electrical power aboard MV Mary Maersk is generated by main generators running on Heavy Fuel Oil (HFO). Given the conversion efficiency of 0.3 kWh/l HFO, the fuel volume required to supply the system is illustrated in equation 6.

$$Consum_{HFO} = \frac{E_{20.000m^3}}{0{,}3} = \frac{765}{0{,}3} = 2.550l\; HFO \tag{6}$$

The total mass of combusted fuel using average HFO density of 1.01 kg/l per ISO 8217 (ISO, 2017) is shown in equation 7.

$$m_{HFO} = 2{,}550\; l \times 1.01\; kg/l = 2{,}575.5\; kg \tag{7}$$

Three key pollutants resulting from combustion of 2,575.5 kg of HFO were quantified using internationally recognised emission factors.

Carbon dioxide (CO_2), based on the IPCC (Intergovernmental Panel on Climate Change) (IPCC, 2006) emission factor of 3.114 kg CO_2/kg HFO, derived from the carbon-to-CO_2 molecular mass ratio (44/12 ≈ 3.67 for pure carbon; 3.114 for HFO blends) is calculated using equation 8.

$$E_{CO_2} = 2{,}575.5\; kg \times 3.114\; kg\; CO_2/kg\; HFO \approx 8{,}020\; kg\; CO_2 \tag{8}$$

Sulphur dioxide (SO_2) - HFO sulphur content up to 3.5%; the factor of 2 reflects the SO_2/S molecular mass ratio (64/32) (Van Loon & Duffy, 2011) shown in equation 9.

$$E_{SO_2} = mHFO \times S\% \times 2 = 2{,}575.5 \times 0.035 \times 2 \approx 180.3\; kg\; SO_2 \tag{9}$$

Nitrogen oxides (NO_x) - formed from atmospheric N_2 and O_2 at combustion temperatures; emission factor of 87 kg NO_x per tonne of fuel (vessel-specific) (IPCC, 2006).

$$E_{NO_x} = 2.5755\; t \times 87\; kg/t \approx 224\; kg\; NO_x \tag{10}$$

The Alfa Laval PureBallast 3.0 system demonstrates high operational efficiency, treating 20,000 m^3 of ballast water within 20 hours and meeting the requirements of Standard D-2 of the Ballast Water Management Convention (BWM Convention) (MEPC, 2016). However, this performance entails a measurable ecological cost: the combustion of 2,550 litres of HFO to power the system generates approximately 8,020 kg of CO_2, 180 kg of SO_2, and 224 kg of NO_x per treatment cycle (IPCC, 2006; ISO, 2017). Considered at the frequency of typical ballasting and deballasting operations throughout an annual calendar, these figures acquire significant relevance in the context of maritime sustainability. Additional operational constraints, including sensitivity to water turbidity, maintenance costs, and biofilm accumulation on UV lamps, are discussed in subsequent sections of this study.

While the the Alfa Laval PureBallast 3.0 system effectively meets international regulations for invasive species control through filtration and UV radiation, practical observations revealed significant limitations: susceptibility to water turbidity, biofilm accumulation on lamp surfaces, high maintenance requirements, and reliance on HFO generated electricity, which partially undermines the system's environmental purpose. To address these shortcomings, Chapter IV proposes ultrasonic technology as a complementary solution to optimise the UV treatment system's overall performance.

5. Integration of Ultrasonic Technology in Ballast Water Treatment Aboard MV Mary Maersk
Ultrasound consists of mechanical pressure waves propagating through a medium, such as water, air, or solid structures, at frequencies above the upper limit of human hearing (conventionally 16 kHz) (Ensminger & Bond, 2011). As these waves travel, they produce rapid alternating cycles of compression and rarefaction, generating local pressure fluctuations that can interact directly with suspended particles, gas bubbles, and the cellular structure of microorganisms.

The most significant effect of ultrasound propagation in liquids is acoustic cavitation (Ensminger & Bond, 2011; Huang et al., 2024). During rarefaction phases, pressure drops sufficiently for microscopic cavitation bubbles to form. These bubbles grow rapidly and collapse violently during the subsequent compression phase, a process known as implosion, generating shock waves and high-velocity liquid jets capable of destroying microbial cells and rupturing bacterial walls. To produce these effects in a controlled manner aboard a vessel, piezoelectric transducers are used, converting electrical energy into high-frequency mechanical vibrations (Ensminger & Bond, 2011).

According to Huang Xiao et al. (2024), cavitation bubble implosion generates local pressures exceeding 50 MPa, temperatures of approximately 5,000 K, and liquid microjets reaching speeds of up to 300 m/s, conditions sufficient to mechanically destroy microbial cell walls. Using the main treatment pipe diameter of DN250 (d = 0.25 m), the cross-sectional area through which the ultrasonic wave propagates is illustrated in equation 11.

$$A = \pi \times (\frac{d}{2})^2 = \pi \times (\frac{0,25}{2})^2 \approx 0,049\ m^2 \qquad (11)$$

For a 400 W ultrasonic transducer, the resulting acoustic intensity acting on the water column is shown in equation 12.

$$I = \frac{P}{A} = \frac{400}{0,049} \approx 8163 \frac{W}{m^2} \qquad (12)$$

This value significantly exceeds the cavitation initiation threshold in seawater (1,000–3,000 W/m²) (Huang et al., 2024), confirming the system's capability to generate effective cavitation even in highly turbid conditions.

This value significantly exceeds the cavitation initiation threshold in seawater (1,000–3,000 W/m², per Huang, Zhou & Liu, 2024), confirming the system’s capability to generate effective cavitation even in highly turbid conditions.

A localised ultrasonic field near the quartz tubes creates a mechanically unstable environment, preventing microorganism adhesion and biofilm formation (Huang et al., 2024). The analysis was performed using the following parameters from Tabel 3.

Table 3. Parameters used in the biofilm prevention analysis

No.	Physical Parameter	Value
1	Ultrasonic frequency applied	28 kHz
2	Speed of sound in water	1,500 m/s
3	Seawater density	1,015 kg/m³
4	Acoustic pressure generated by transducer	22 kPa

The ultrasonic wavelength, the physical distance between two successive pressure maxima, is represented in equation 13 (Ensminger & Bond, 2011).

$$\lambda = \frac{v}{f} = \frac{1.500}{28.000} = 0,05357\ m \approx 5,36\ cm \qquad (13)$$

The particle oscillation velocity, represented in equation 14, indicating how fast water particles move under the acoustic field.

$$\upsilon_p = \frac{p}{\rho \times c} = \frac{22.000}{1015 \times 1500} = 0{,}01445 \frac{m}{s} \approx 1{,}445 \frac{cm}{s} \quad (14)$$

The angular frequency of oscillation is calculated using equation 15.

$$\omega = 2 \times \pi \times 28.000 = 175.840 \frac{rad}{s} \quad (15)$$

The oscillation amplitude, which is the maximum displacement of water particles per cycle, is represented in equation 16:

$$A = \frac{0{,}01445\ m/s}{175.840\ rad/s} = 8{,}217 \times 10^{-8} m \approx 82{,}1\ \mu m \quad (16)$$

These rapid, high-frequency oscillations (28,000 cycles per second) continuously displace bacteria attempting to adhere to the quartz tube surfaces, preventing biofilm formation at the earliest stage (Huang et al., 2024).

A piezoelectric transducer operating at 28 kHz is proposed, mounted laterally on the DN250 ballast pipe via a retractable system through a 120 mm port, positioned upstream of the UV-AOT reactor (Alfa Laval, 2020). This pre-treatment arrangement disrupts suspended microorganisms before UV exposure, reducing lamp stress under high-turbidity conditions.

The transducer body (250–300 mm long, 110-115 mm diameter) houses a natural quartz crystal as the active piezoelectric element. Vibrations are transmitted through an acoustic coupling assembly, directing energy into the water column. The transducer requires approximately 300–350 V AC at 400 W to generate effective cavitation.

Power is sourced from the vessel’s shaft generator, which converts mechanical energy from the main propulsion shaft into electricity during navigation, avoiding additional fuel consumption or emissions. Since the shaft generator outputs 440 V at 60 Hz, incompatible with the transducer’s requirements, an electronic converter supplies the correct operating frequency (28,000 Hz) and voltage (300–350 V).

Ultrasonic technology emerges as a technically viable and ecologically advantageous complementary solution for ballast water treatment aboard MV Mary Maersk. With an acoustic intensity of 8,163 W/m^2, well above the cavitation threshold, and a particle oscillation amplitude of 82.1 μm at 28 kHz, the proposed system is capable of both inactivating microorganisms in high-turbidity conditions and preventing biofilm accumulation on UV lamp surfaces, directly addressing the key limitations of the existing PureBallast 3.0 system.

To generate the ultrasound required for the proposed treatment, a piezoelectric transducer is selected to convert onboard electrical energy into high-frequency mechanical vibrations capable of inducing cavitation. An operating frequency of 28 kHz is chosen as the optimal value for acoustic cavitation in seawater, at which ultrasonic waves generate cavitation microbubbles whose violent implosion mechanically destroys microorganisms in the water column. The transducer is proposed to be installed immediately upstream of the UV-AOT reactor within the existing PureBallast circuit, allowing acoustic cavitation to pre-treat the water flow by disrupting suspended microorganisms and particles, thereby enhancing the subsequent effectiveness of UV radiation and reducing lamp stress under high-turbidity conditions.

The proposed piezoelectric transducer is designed for lateral installation on the DN250 (250 mm) main ballast pipe, using a retractable mounting system through a 120 mm port to facilitate maintenance. The transducer body measures approximately 250–300 mm in length and 110–115 mm in diameter, housing a natural quartz crystal as the active piezoelectric element. Vibrations generated by the crystal when subjected to electrical current are transmitted through an acoustic coupling assembly directly into the water column. At an operating power of 400 W, the transducer requires approximately 300–350 V AC to produce the mechanical amplitude necessary for effective cavitation.

Power is supplied by the vessel's shaft generator, a generator mechanically driven by the main propulsion shaft, which produces electricity during navigation without additional fuel consumption or emissions. Since the shaft generator outputs 440 V at 60 Hz, which is incompatible with the transducer's requirements (28,000 Hz, 300–350 V), an electronic converter is used to transform the standard electrical output into the frequency and voltage needed to excite the quartz crystal and generate ultrasound (Mary Maersk Deck Manual, 2013).

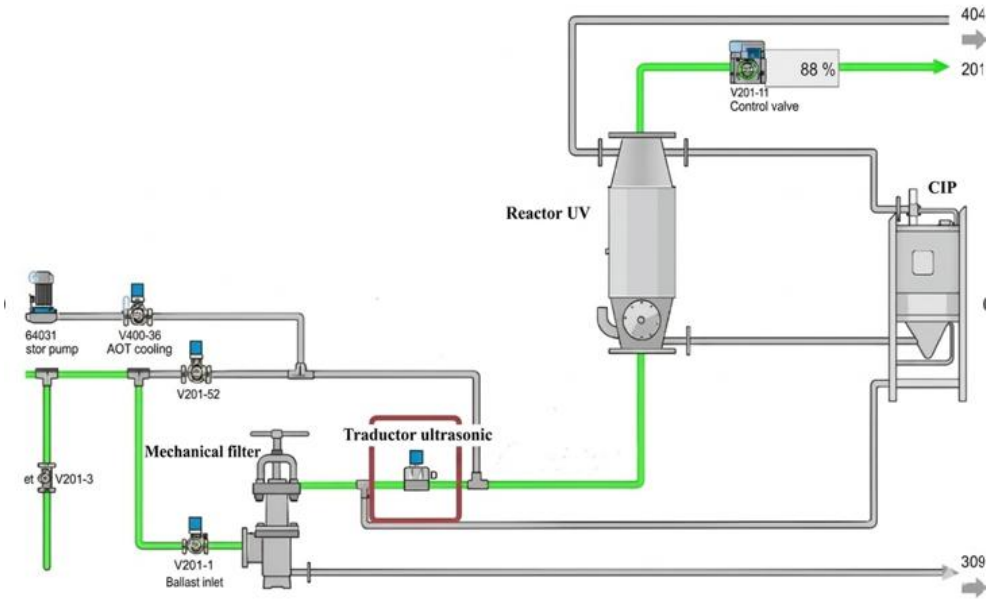

Figure 5 Placement of the Ultrasonic Transducer in the Existing Onboard Installation (personal study)

6. SWOT Analysis of the Complementary Ultrasonic Treatment Method Aboard MV Mary Maersk

Table 4. SWOT Analysis of the Complementary Ultrasonic Treatment Method

STRENGTHS	**WEAKNESSES**
- Complementary method; does not replace UV treatment - High biological efficiency in high-turbidity environments - Low energy consumption - Reduction of biofilm accumulation on UV lamps	- Limited applicability at very high flow rates - Sensitivity to transducer positioning - Complex technological integration into existing infrastructure
OPPORTUNITIES	**THREATS**
- Growing global demand for alternative ecological solutions - Long-term cost reduction through low maintenance requirements - Wide applicability across commercial vessels - Reduced risk of UV system damage caused by overloading in turbid waters	- Possible regulatory uncertainties regarding the approval of new complementary technologies - Possible adverse effects on adjacent components of the installation

The main weaknesses include reduced cavitation efficiency at very high flow rates due to insufficient exposure time, challenges in achieving uniform acoustic wave distribution across the water flow, and the additional complexity of integrating the system into the existing onboard installation.

In terms of opportunities, the system aligns with the maritime industry's ongoing decarbonisation efforts, offers potential for wider adoption across commercial vessels operating in turbid waters, and presents prospects for long-term cost reduction through lower maintenance requirements (Huang et al., 2024; Mary Maersk Deck Manual, 2013).

The primary threats relate to the absence of a standardised IMO approval framework for ultrasonic ballast water treatment technology. Additionally, prolonged acoustic vibrations may produce adverse effects on adjacent installation components, including seals, pipe walls, and flow sensors, necessitating careful monitoring during the testing phase (Ensminger & Bond, 2011).

7. Economic implications of ultrasonic integration

The integration of ultrasonic technology into the PureBallast 3.0 system also generates a significant economic advantage. The system's UV lamps lose 30-50% of their initial intensity after 8,000-12,000 operating hours, and biofilm deposits on the quartz tubes accelerate this degradation by forcing the lamps to operate at higher power output, thereby reducing their service life. By preventing biofilm formation, ultrasonics maintain optimal UV transmittance, extending the lamp replacement cycle by at least 20–25%. Combined with the reduced frequency of CIP cycles and the fact that the ultrasonic transducer draws power exclusively from the shaft generator, incurring no additional fuel consumption, the cost-benefit profile of the proposed solution is strongly favourable from an operational economics perspective.

In the absence of a complementary treatment solution, the PureBallast 3.0 system is subject to a repetitive degradation cycle driven by the operating conditions specific to the Indian Ocean. High-turbidity ballast water promotes the accumulation of biofilm on the quartz surfaces of the UV lamps, progressively reducing UV transmittance. To compensate for the loss of disinfection efficiency, the system automatically increases lamp output power, accelerating thermal stress and shortening the replacement interval. This cycle repeats with each maintenance operation, generating recurring costs and periods of reduced system performance.

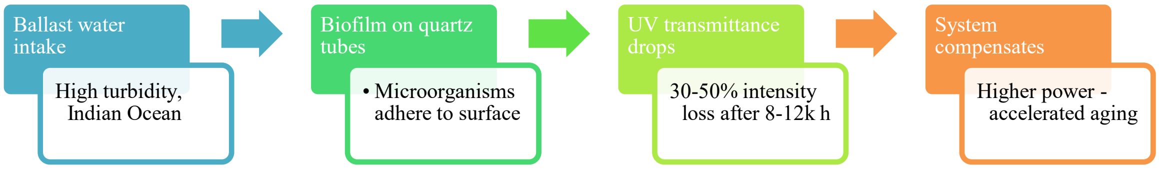

Figure 6 Degradation cycle without ultrasonics

The integration of a piezoelectric ultrasonic transducer operating at 28 kHz, positioned immediately upstream of the UV-AOT reactor, introduces a pre-treatment stage that fundamentally alters the degradation dynamic described above. By generating acoustic cavitation at an intensity of 8,163 W/m², well above the seawater cavitation threshold, the transducer continuously disrupts microorganism adhesion on the quartz tube surfaces, preventing biofilm formation at the earliest stage. As a result, UV transmittance is maintained at optimal levels without requiring power compensation, directly extending lamp service life by an estimated 20-25% beyond the standard 8,000-12,000 hour interval. The system draws power exclusively from the vessel's shaft generator, incurring no additional fuel consumption or emissions.

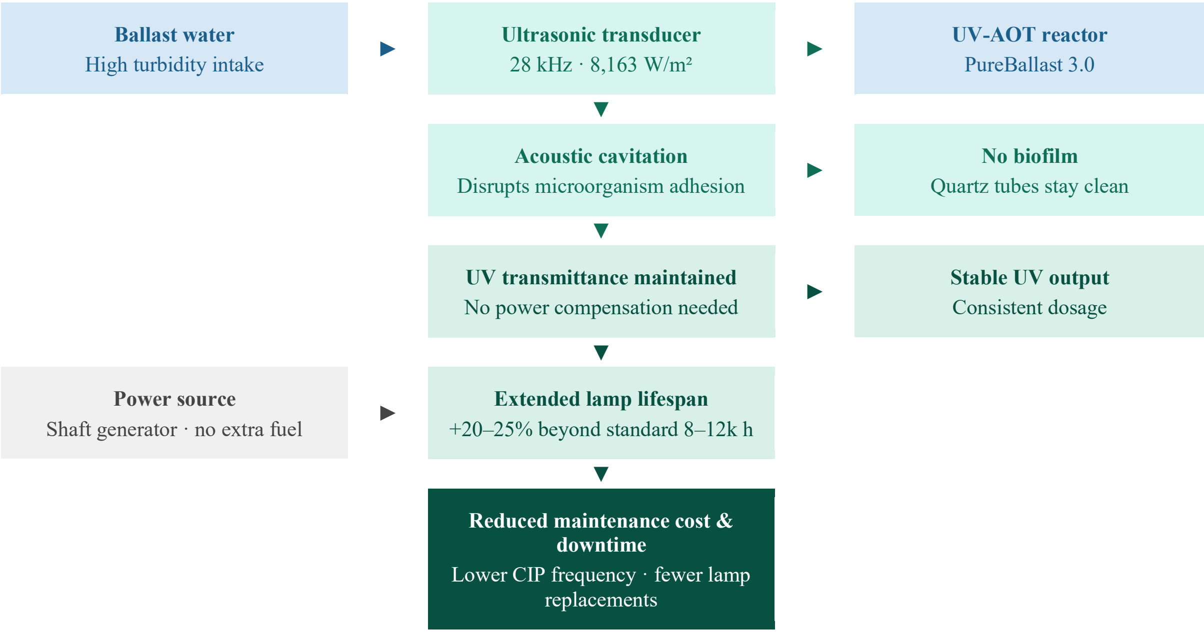

Figure 7 Degradation cycle with ultrasonics

The economic impact of ultrasonic integration is quantified across three key maintenance cost categories: annual lamp replacement, CIP chemical consumption, and maintenance downtime. In all three categories, the proposed solution produces a measurable reduction in expenditure. Lamp replacement costs decrease as a direct consequence of the extended service life enabled by biofilm prevention. CIP cycle frequency and associated chemical costs are reduced as the quartz surfaces remain cleaner for longer periods. Maintenance downtime decreases accordingly. Combined with the zero additional fuel cost of the shaft generator power supply, the overall cost-benefit profile of the ultrasonic integration is strongly favourable over the vessel's annual operating calendar.

Standard lamp lifespan	Lifespan extension	Lamp set cost (3rd party)	Added fuel cost
8-12k hours	**+20-25%**	**~$160-200**	**$0**

Figure 8 Cost comparison: with vs. without ultrasonics

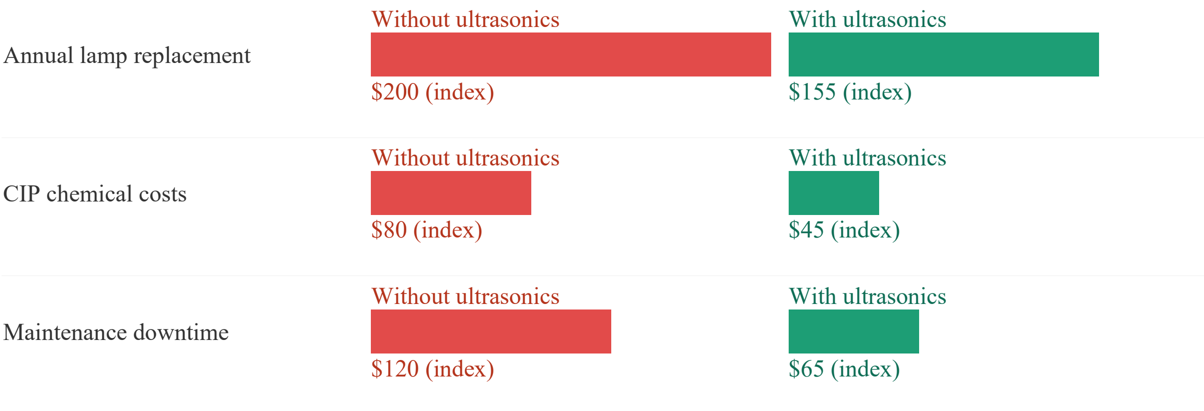

Figure 9 Relative annual cost index (indicative values)

8. Conclusions

This study examined the issue of ballast water treatment aboard vessels, a practice which, despite its operational necessity, facilitates the uncontrolled transfer of invasive aquatic species (Carlton & Geller, 1993), causing ecological imbalances, threats to biodiversity, human health, and local economies (Nghiem et al., 2013). In response, the IMO established the BWM Convention, requiring all vessels to be equipped with certified ballast water treatment systems (IMO, 2004; MEPC, 2016).

The study analysed both the general principles of existing treatment systems (Zhang et al., 2024) and a specific case aboard MV Mary Maersk (Alfa Laval, 2020; Mary Maersk Ballast Water Management Plan, 2013), a large container vessel, with a focus on identifying potential improvements for challenging operational scenarios such as high-turbidity ports. As a complementary solution, ultrasonic technology is proposed: through acoustic cavitation, it destabilises microorganisms and prevents biofilm formation on UV lamp surfaces, maintaining disinfection efficiency. Powered by the vessel's shaft generator, the system requires no additional fuel consumption or emissions. (Ensminger & Bond, 2011; Huang et al., 2024)

The integration of ultrasonic technology into the PureBallast 3.0 ballast water treatment system aboard MV Mary Maersk represents a technically viable and economically advantageous complementary solution. By generating acoustic cavitation at 28 kHz, the proposed system addresses the key operational limitations of UV treatment, particularly in high-turbidity conditions, while simultaneously extending lamp service life and reducing maintenance costs. Powered exclusively by the shaft generator, the solution introduces no additional fuel consumption or emissions, aligning with the broader decarbonisation objectives of the maritime industry. The findings of this study suggest that complementary ultrasonic treatment merits further investigation as a standard practice in ballast water management.

The study concludes that the integration of complementary technologies such as ultrasonics could represent a viable development pathway for ballast water treatment, contributing to the protection of the marine environment (Sardain et al., 2019).

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