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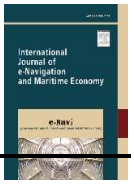

Original article

Review on Research and Application of Current Ship Drag Reduction Technologies

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Abstract

In response to the escalating demands of global trade and the pressing imperative for environmental preservation, the shipping industry is confronted with the dual challenges of augmenting energy efficiency and significantly curtailing carbon emissions. Ship drag reduction technology emerges as a promising solution to address these critical issues. Over the recent years, a spectrum of diverse drag reduction technologies has been developed, each precisely targeting distinct components of ship resistance and influenced by a multitude of factors. We provide a comprehensive synthesis and critical evaluation of the existing literature on ship drag reduction technologies. It categorizes these technologies into four primary domains: body-attached drag reduction, surface drag reduction, air lubrication drag reduction, and other specialized drag reduction techniques. By presenting detailed and extensive experimental data, coupled with real-world application cases, we underscore the practical implementation and proven efficacy of these technologies in reducing ship drag. We delve into the current limitations and challenges encountered by these technologies. We also offer strategic recommendations for future research endeavors and practical applications, aiming to overcome these limitations and enhance the overall performance of drag reduction technologies. The insights provided in this paper aim to serve as a guide for ongoing efforts in developing innovative and effective utilization of ship drag reduction technologies, ultimately contributing to the sustainability and efficiency of the shipping industry.

Keywords: Ship Resistance, Body-Attached Drag Reductio, Air Lubrication Drag Reduction, Energy Saving and Emission Reduction

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1. Introduction

The shipping industry is a significant contributor to greenhouse gas emissions, exerting a substantial impact on climate change. According to *the International Maritime Organization's (IMO) Fourth Greenhouse Gas Study 2020*, the global shipping sector emitted 1.076 billion tons of greenhouse gases in 2018, accounting for 2.89% of total global emissions (Joung, 2020). This alarming statistic underscores the critical need for reducing carbon emissions within the maritime sector.

In response, international frameworks such as *the MARPOL Convention and the 2023 IMO Strategy on Reduction of GHG Emissions from Ships* have been implemented, positioning energy efficiency and environmental sustainability as top priorities for the industry.

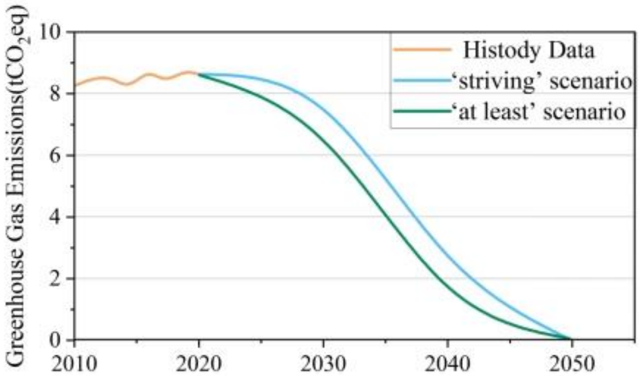


Figure 1. Emission reduction scenarios based on *IMO's 2023 Strategy*

Drag reduction technology has emerged as one of the most effective strategies to lower energy consumption and improve the energy efficiency of ships. Since water resistance constitutes the largest component of ship resistance, optimizing the hull form remains a fundamental approach to drag reduction. For instance, Islam et al. (2019) analyzed the effects of speed, draft, and trim angle on ship resistance, while Le et al. (2023) employed unsteady simulation methods to study the influence of length-to-beam ratios on resistance components. Their findings demonstrated that total resistance decreases as the length-to-beam ratio increases, with pressure resistance showing particularly notable changes. Similarly, Qian (2012) developed a hull form optimization system based on CFD using the iSight platform, achieving reductions in wave-making resistance by 5.97% and total resistance by 9.42%. Other studies, such as Liu et al.'s (2020) development of the OPT Ship-SJTU optimization software for cruise ships, further illustrate advancements in this area, achieving a 0.98% resistance reduction in optimized designs.

In recent years, the rapid development of new materials and technologies has driven novel drag reduction techniques, ranging from altering hull surface structures to employing innovative materials. Wang et al. (2023) highlighted key advancements in air lubrication drag reduction, bionic superhydrophobic surfaces, and step-reduction technologies, among others. Similarly, Guo (2022) reviewed the microscopic mechanisms of surface drag reduction technologies, noting that their effectiveness ranges from 15% to 30%. For air lubrication methods, studies such as those by Chillemi et al. (2024) and Qin et al. (2024) demonstrated drag reduction rates as high as 50% to 90% under optimal conditions.

While hull form optimization provides clear benefits, its potential is limited by the constraints of overall hull design and arrangement. In contrast, emerging drag reduction technologies offer significant potential, enabling resistance reduction without compromising operational efficiency. This paper aims to explore the intrinsic principles, experimental data, and practical applications of drag reduction technologies across four key domains: body-attached drag reduction, surface drag reduction, air lubrication, and other specialized techniques. By addressing current challenges and limitations, we propose strategic recommendations to further enhance the application of these technologies, contributing to the development of sustainable and energy-efficient shipping practices.

2. Component of Resistance

Ships experience both air resistance and water resistance during navigation, with water resistance constituting the majority. The primary components of water resistance include frictional resistance, viscous pressure resistance, and wave-making resistance.

2.1 Air Resistance

The parts of the ship above the waterline, including superstructures and appendages, are subject to air resistance. The primary strategies to reduce air resistance include minimizing the wind-exposed area and designing streamlined superstructures.

2.2 Frictional Resistance

When the hull moves, the water's viscosity creates a boundary layer near the hull surface, where the velocity gradient is significant, generating frictional shear stress on the hull surface. The resultant force in the direction of movement is the frictional resistance. Biofouling can also significantly increase frictional resistance. Demirel et al (2019) designed a computer program to predict the increase in frictional resistance due to biofouling for various ship types, including DTMB5415, KCS, JBC, and KVLCC2, with increases of up to 200% in severe cases.

Frictional resistance is a major component of hull resistance, and its proportion varies with speed. For low-speed ships, frictional resistance accounts for approximately 70% to 80%, while for medium- and high-speed ships, it accounts for around 50%.

Reducing frictional resistance typically involves three approaches: reducing the wetted surface area, minimizing surface roughness, and controlling turbulence generation.

2.3 Eddy-Making Resistance

Also known as eddy-making drag, this resistance arises from the pressure difference between the fore and aft parts of the hull during navigation.

The most critical factor affecting the resistance is the shape of the hull, particularly the stern, which is closely related to the hull form. During design, excessive curvature changes should be avoided, especially towards the aft, which should taper smoothly.

2.4 Wave-Making Resistance

When a ship navigates on the water surface, it disturbs the free surface, causing water particles to move up and down due to gravity and inertia, creating waves. The resistance caused by these waves is known as wave-making resistance.

Speed is the most significant factor affecting wave-making resistance. For low-speed ships, wave-making resistance accounts for only about 10%, while for high-speed ships, it can exceed 50%. Reducing wave-making resistance focuses on reducing or favorably combining navigation waves, achieved through methods such as improved hull design, use of specially shaped bows, speed control, and changes in navigation methods.

3. Appendage Drag Reduction Technologies

In addition to hull shape optimization, drag reduction can also be achieved through various appendages, each targeting specific resistance components. These appendages are often used in combination to amplify their overall effect. Li et al (2022) discussed the effects of long splash guards, long splash guards combined with wave-breaking plates, and flow-disruption plates on hull resistance and navigation attitude, finding that the combination of appendages can offset each other's shortcomings, with a drag reduction efficiency higher than the sum of individual effects, achieving more than 20%. Deng et al (2020) studied the drag reduction and roll reduction effects of installing bulbous bows and T-shaped foils on trimarans. The following sections briefly introduce the research and application of various appendage drag reduction technologies.

3.1 Bow Windbreak Wall

A bow windbreak wall, also known as a fairing, is a wind-blocking device added to the superstructure. This structure reduces the direct impact of airflow on the hull, directs the airflow along the fairing, effectively mitigates airflow separation in both upward and downward directions, and reduces vortex formation. Grlj and coworkers (2023) studied the air resistance of a container ship, considering factors such as the arrangement of containers, ship speed, and trim angle, and their effects on air resistance.

Lu and coworkers (2015) modeled a multipurpose vessel and designed three types of bow fairings: multi-edged wedge, circular streamlining, and platform streamlining. Numerical calculations and wind tunnel tests showed that the circular streamlining fairing achieved the best performance, reducing drag by approximately 20%. Du (2019) designed and optimized various fairings, proposing eight different fairing schemes and comparing their drag reduction effects under various operating conditions. The innovation lies in adding vortex generators on both sides of the fairing to further enhance drag reduction, achieving up to a 32.47% reduction in air resistance with the optimal design. An et al (2021) designed three different bow protective structures to block air and waves. Simulation tests indicated that designs with a certain number of openings performed better. Deng and coworkers (2022) designed various fairings for container ships, with the optimal design achieving a drag reduction effect of 20.85%.

The "eFuture 13000C," a container ship designed by Japan's Ishikawajima-Harima Heavy Industries, was equipped with a bow fairing on its accommodation area, reducing greenhouse gas emissions by 21% when combined with optimized propulsion systems (Qin Q, 2011). In 2015, Mitsui O.S.K. Lines developed a windbreak wall and installed it on the medium-sized container ship "MOL Marvel," resulting in a reduction of approximately 2% in CO2 emissions under actual operating conditions.

Figure 2. The "MOL Marvel" with an installed windbreak wall

3.2 Bulbous Bow

A bulbous bow is primarily used to reduce wave-making resistance. Its special shape allows the waves generated by the bow to overlap and cancel out the waves generated by the bulbous bow, thereby reducing wave-making resistance. Different ship speeds and loads require different shapes of bulbous bows; for instance, teardrop-shaped bulbous bows are suitable for medium- to high-speed ships, while extended and sharp-nosed bulbous bows are suitable for low-speed, fuller vessels such as tankers and bulk carriers.

The determination of the bulbous bow shape is often conducted using a combination of intelligent algorithms and Computational Fluid Dynamics (CFD) methods. Chrismianto et al (2018) used CFD technology to explore the impact of bulbous bow shapes on the resistance of catamarans, focusing on cross-sectional and lateral parameters. The study concluded that the optimal parameter combination could achieve a significant drag reduction effect of 11% to 13%. Feng (2019) conducted an optimization analysis of the bulbous bow for a container ocean liner and concluded that the bulbous bow is more effective at reducing drag at low speeds. Zhang (2020) optimized the bulbous bow design of a KCS ship and found that, at a Froude number (*Fr*) of 0.26, the optimized bulbous bow could reduce wave-making resistance by up to 10.26%. Zhang (2023) used a genetic algorithm to optimize the bulbous bow shape of an ocean-going training vessel, resulting in a 1.77% reduction in total resistance compared to the original vessel. Díaz-Ojeda et al (2023) designed a novel bulbous bow for small fishing vessels, which was validated through towing tank experiments to achieve a 10% drag reduction effect.

Japan's Shin Kurushima Dockyard Co., Ltd successfully developed the environmentally- friendly SK bow. Tank testing validated that this bow could reduce wave-making resistance by up to 30% (2023).

Figure 3. The SK Bow

However, improper design can adversely affect maneuverability and safety, underscoring the need for careful parameter selection.(2023).

3.3 Bow Wave-Suppression Appendages

Bow wave-suppression appendages, also known as strakes, typically refer to plate structures installed on the bow of ships. These structures alter the direction and speed of water flow, effectively suppressing the generation of bow waves.

Bow wave-suppressing appendages, such as strakes, alter water flow to minimize bow waves. Wang et al.

(2017) designed appendages for high-speed ships and achieved total resistance reductions of 6.67% during towing tank tests. Zhao et al. (2022) improved upon these designs with non-flat three-dimensional structures, achieving a resistance reduction of 10.6% in experiments..

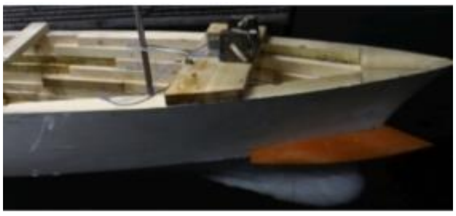


Figure 4. Sharp-Angled Bow Appendage

3.4 Wave-Suppressing Hydrofoils

Hydrofoils generate lift at high speeds, partially raising the hull to reduce frictional and wave-making resistance. Lu et al. (1998) studied near-surface hydrofoils and achieved a 25% reduction in residual resistance. Chen et al. (2022) combined bow and stern hydrofoil appendages, achieving reductions of 7.38% and 9.35%, respectively. Wang et al (2019) investigated the effects of attack angle, size, and other parameters of hydrofoils on the drag reduction performance of high-speed catamarans. Shukla et al (2023) used CFD software to study the flow field characteristics of hydrofoils, including the nature of the waves they generate and the thrust produced. Suastika et al designed a semi-enclosed hydrofoil installed at the stern, as shown in Figure 5 (2017). Towing tank tests demonstrated that it achieved a drag reduction effect of 10%.

Figure 5. Rear View of Experimental Ship with Installed Hydrofoil

The Swedish company Candela launched the C8 hydrofoil boat, which achieves 80% drag reduction by installing three torpedo-type hydrofoils to provide hull lift. In 2019, China's Hyundai Mobis Company mass-produced hydrofoil flying boats, designing and selling over 30 models of hydrofoil boats.

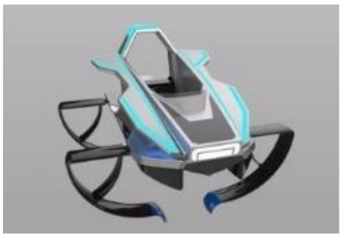


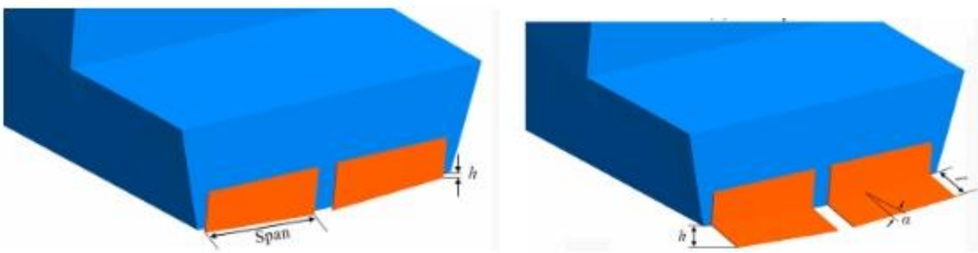
Figure 6. Concept of Curved Plate Hydrofoil Flying Boat by Mobis

Specially shaped hydrofoils often reduce the stability of the vessel, particularly during the process of lifting out of the water, making accidents more likely. Therefore, hydrofoil boats require a higher level of operator skill.

3.5Wave-Suppressing Plates

Generally referred to as stern wave-suppressing plates or stern flaps, these are plate-like structures installed at the stern of the ship. Their primary function is to reduce resistance by counteracting the forces and moments exerted by waves on the hull.

Karafiath et al (2011) noted that wave- suppressing plates primarily improve the trim of small yachts, thereby reducing frictional resistance, while for larger vessels, they mainly improve the wake flow field, reduce wave-making resistance, and decrease vortex formation to lower viscous pressure resistance. Jadmiko et al (2018) studied the drag reduction effects of stern flaps and wedge-shaped plates, finding that installing stern flaps reduced total resistance by 3.5% at a speed of 28 knots, representing the optimal solution. Song et al (2024) conducted simulations to calculate the effects of installing transom flaps and stern flaps on the stern, as shown in Figure 7. The results indicated that these devices reduced heave and pitch motions by 7.2% and 3.9%, and 4.4% and 2.1%, respectively.



(a) transom flaps (b) stern flaps

Figure 7. Two types of stern plate

In the early 21st century, the Canadian Navy signed an agreement with the U.S. Department of Defense to design stern wave-suppressing plates, which can reduce fuel costs by 5-10% (Heo J, 2004). Dong's team studied the drag reduction effect of wave-suppressing plates on deep-V ships, with experimental results showing a drag reduction rate of up to 6%. This technology has been applied to a certain type of frigate (Dong WC, 2011).

Figure 8. Wave-Suppressing Plates on a Frigate

Appendage drag reduction technologies typically achieve drag reduction rates of 5－15%, with certain configurations exceeding 25%. When combined with other drag reduction methods, these technologies can deliver significant performance improvements.

4. Hull Surface Drag Reduction Technologies

Hull surface drag reduction engineering involves modifying and coating the hull surface to reduce roughness and prevent marine biofouling, thereby decreasing the resistance encountered during navigation. Common technologies include polymer coatings (antifouling coatings), superhydrophobic materials, micro-grooves, fish scale biomimicry, and flexible walls.

4.1 Polymer Coatings

Long-chain polymer molecules are used, which undergo stretching deformation under the influence of water flow, forming a microstructure that can absorb kinetic energy from turbulence and reduce resistance.

Ma (2017) developed pentene/α-olefin binary and ternary copolymer drag reducers, achieving a drag reduction rate of up to 59.79% with this coating. Rowin et al (2021) studied a novel coating, which is a bilayer of polyacrylamide and polydopamine, achieving a drag reduction rate of 19% in experiments. Tian et al (2021) prepared mixed PEO and CTAC/NaSal aqueous solution, achieving a drag reduction effect of 24% under optimal mixing ratios and temperatures. Ying et al (2022) investigated the synergistic drag reduction effects of cationic surfactants and polymer composite systems, achieving a drag reduction rate of 69%, which is significantly higher than that of single-component drag reduction. Gu and coworkers (2024) experimentally explored the drag reduction performance of a binary solution of polyacrylamide and xanthan gum, finding that this solution has good durability in terms of drag reduction.

These studies indicate that polymer drag reduction is typically achieved by blending multiple components into a mixture, and it shows excellent performance in experiments. However, these materials are prone to mechanical degradation and agglomeration during storage. The use of polymer drag reduction can pose environmental hazards to marine life, and maintaining effectiveness requires continuous polymer release, which is costly. Moreover, the longevity of the coating effect is suboptimal, failing to remain effective throughout the designated docking intervals.

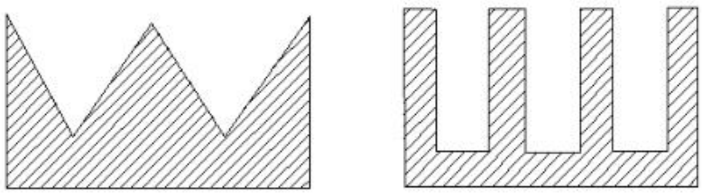
4.2 Superhydrophobic Coatings

Superhydrophobic materials typically have a contact angle with liquids of 150° or more, reducing the wetted surface area and thereby forming a stable gas-liquid interface on the material surface, which reduces frictional resistance.

Methods for constructing superhydrophobic surfaces include layer-by-layer hot pressing, electrochemical deposition, spraying, sol-gel methods, electrospinning, phase separation, plasma treatment, and chemical etching. Peng et al (2019) used hydrochloric acid etching to perform chemical reactions on aluminum alloy surfaces, achieving a superhydrophobic surface with a contact angle of 156° after modification with stearic acid solution. Zhao et al (2023) modified SiO_2 with $C_{14}H_{19}F_{13}O_3Si$ to obtain hydrophobic SiO_2, which was then mixed with fluorosilicone resin in a certain ratio to prepare a hydrophobic coating with a contact angle of 163° and a maximum drag reduction rate of 23.4%. Liu et al (2022) used 3D printing to prepare a superhydrophobic coating with the petal-like surface, and experiments measured a drag reduction rate exceeding 50% at low speeds. Many scholars have conducted research and innovation on superhydrophobic coatings. Reviews and analyses by Khan (2022) and Yang (2022) highlighted the current state of development and applications in this field, pointing out its broad development prospects.

4.3 Micro-Groove Drag Reduction

Inspired by the V-shaped grooves on the surface of sharks, which can reduce drag, such structures have been applied to fluid drag reduction, with straight-angled grooves typically referred to as riblets. Zhang (2020) analyzed the distribution of local friction resistance and vorticity fields near riblets through experiments and numerical simulations. The study found that friction near the base of the riblets was lower, while friction at the riblet tips increased sharply, weakening the intensity of vortex motion and thereby reducing drag. Martin et al (2016) used modeling and calculations to analyze the effects of groove depth, thickness, and spacing on drag reduction performance.



(a) V-Shaped Grooves (b) Riblet Grooves

Figure 9. Two Shapes of Micro-Grooves

Yu (2020) conducted numerical simulations of drag reduction on biomimetic sharkskin surfaces with three different parameters using Fluent software, and fabricated biomimetic sharkskin structures on titanium alloy surfaces using wire-cutting techniques, achieving a drag reduction rate of approximately 14% under optimal conditions. Wu et al (2020) designed five different shapes of microstructures, and experiments found that riblet-shaped micro-grooves were the most effective, achieving a drag reduction rate of up to 27.7%. Li (2019) prepared different types of microstructure surfaces using chemical etching, anodizing, and sandblasting methods, finding that embedded microstructures had better drag reduction effects, with a maximum drag reduction rate of 40%. Zheng et al (2023) fabricated a transverse micro-groove structure, where the riblet direction is perpendicular to the water flow direction, resulting in a 26.91% reduction in frictional resistance and a 9.63% reduction in total resistance.

(a) Protruding grooves (b) Embedded grooves

Figure 10. Two Types of Micro-Grooves

The above studies indicate that various micro-groove shapes, such as V-shaped and riblet-shaped grooves, can achieve drag reduction effects. However, there is a lack of comparative studies on the drag reduction effects of all micro-groove forms, and techniques like laser engraving are currently too costly for mass production.

4.4 Biomimetic Fish Scale Surface

Biomimetic fish scale surface technology optimizes the hull surface by mimicking the arrangement and structure of fish scales. The unique arrangement of fish scales results in lower surface roughness along the scale alignment direction. This structural design reduces the velocity gradient of liquid flowing over the hull surface, thereby reducing frictional resistance. The overlapping arrangement of fish scales also effectively guides water flow, reducing turbulence generation.

Muthukumar et al (2020) demonstrated in simulations that biomimetic fish scale arrays provide effective drag reduction, detailing specific mechanisms, and showed that resistance could be reduced by approximately 27% in simulations. Zhang et al (2021) used numerical analysis methods to study the flow field characteristics of fish scale surfaces, conducting orthogonal tests on four factors: angle, depth, spacing, and water flow speed. The optimal combination achieved a drag reduction rate of 7.8%, with actual experimental measurements showing a maximum drag reduction rate of 8.3%. Zhang et al (2020) used laser etching to prepare biomimetic fish scale surfaces on aluminum alloy materials. These surfaces also exhibited superhydrophobic properties, with a maximum contact angle of 158° and a maximum drag reduction rate of 40%. Mosghani et al (2023) fabricated a ctenoid-shape microstructure and verified through experiments that this structure achieved a 20% drag reduction effect under turbulent conditions.

4.5 Flexible Walls

Flexible walls or coatings use the elastic properties of their materials to influence the interaction between the hull surface and water flow, a biomimetic application inspired by dolphin skin. Flexible walls can elastically deform under the pressure of water flow, absorbing turbulent kinetic energy, helping to delay the transition from laminar to turbulent boundary layers, and reducing the additional friction and energy loss caused by turbulence.

Kulik et al (1996) demonstrated through experiments that flexible walls play a significant role in reducing surface friction resistance and lowering noise generated by flow. Huang (2007) used spray polyurea elastomer technology to prepare polyurea composite flexible drag reduction coatings. Water tank tests showed that the optimal drag reduction rate of this bilayer composite flexible coating was between 12% and 15%. The team of Zhao and Liu (Guo HT, 2022; Song YJ, 2021; Wang P, 2021; Zhang ZK, 2021) combined the principles of flexible wall drag reduction and floating vibration reduction, constructing a micro-floating raft array porous flexible skin structure, achieving a maximum drag reduction effect of 15%.

The above introduces several surface drag reduction technologies and their respective research and application situations. These technologies typically achieve drag reduction effects of 10% to 30% when used alone, which is not particularly ideal. Therefore, many scholars have conducted studies on the combined application of these technologies. The biomimetic fish scale material prepared by Zhang also exhibits superhydrophobic properties. Zhang et al (2012) prepared flexible surface materials using polyurethane as the matrix, achieving a maximum drag reduction rate of 17.0%. When micro-groove structures were created on this material, the maximum drag reduction rate increased to 24.9%. Of course, many researchers have developed other different materials and surface microstructures in surface drag reduction technologies, leading to a certain degree of application in the maritime field. However, the drag reduction effect of surface drag reduction materials is often far lower than experimental values in actual complex liquid flow fields and under fatigue conditions. Ensuring the effectiveness and durability of drag reduction remains a problem to be solved.

5. Air Lubrication Drag Reduction Technologies

The essence of air lubrication drag reduction technology is that air has significantly different density and viscosity compared to water. By injecting an appropriate amount of gas into the bottom of the hull, forming and maintaining an air layer or gas-liquid mixture layer at the bottom, the actual wetted area of the ship is reduced, thereby reducing the frictional resistance of the ship.

5.1 Microbubble Drag Reduction (MDR)

Injecting micron-sized microbubbles into the bottom of the hull forms a two-phase gas-liquid mixture flow, which can effectively reduce the density and viscosity of water. Sanders et al (2006) found in large-scale flat-plate bubble drag reduction experiments that the drag reduction effect significantly decreased from a few meters downstream of the bubble injection point until drag reduction completely failed. Zhan et al (2023) analyzed the effects of three factors-jet flow rate, number and location of air holes, and ship speed-on drag reduction.

Gamal et al (2021) used numerical simulations to analyze the effects of bubble size, distribution, and injection rate on drag reduction. The study found that under optimal conditions, the drag reduction rate could reach 27.6%. Ye and coworkers (2023) conducted numerical simulations using Fluent to calculate microbubble drag reduction for a large ship, analyzing the variation in drag reduction effects at different scale ratios. The maximum drag reduction rate reached 20%, with some reduction in drag reduction effectiveness as the scale ratio increased. Xia et al (2023) developed a population balance model to simulate the effects of microbubbles on the drag and lift of underwater vehicles. The data showed that a drag reduction rate of approximately 26% could be achieved, with a lift coefficient of 0.4. Zhao et al (2024) conducted a numerical study of microbubble drag reduction for low-speed bulk carriers, finding that larger jet quantities resulted in higher drag reduction rates. Smaller bubble volumes produced more uniform distributions, and the turbulent viscosity was lower, leading to more effective drag reduction.

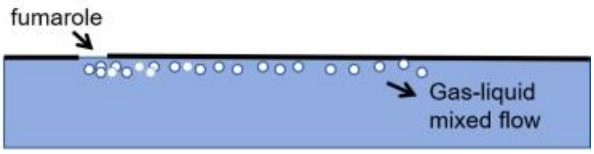


Figure 11. Microbubble Drag Reduction

Some companies, such as the UK's Silverstream and South Korea's Samsung Heavy Industries, were early adopters of microbubble drag reduction in actual ship applications. In 2022, China applied a microbubble drag reduction system for the first time on a 24,116 TEU container ship, reducing carbon emissions by 3% to 4%. In 2023, Professor Wu's team at Zhejiang University developed a "Ship Bubble Drag Reduction System," receiving the Approval in Principle (AIP) certificate from the China Classification Society, marking significant progress in promoting the application of bubble drag reduction technology in China.

5.2 Air Layer Drag Reduction (ALDR)

By forming a stable layer of gas at the bottom of the hull, the contact area between the liquid and the surface is reduced, thereby reducing water resistance.

Figure 12. Air Layer Drag Reduction

Huang et al (2018) conducted jet drag reduction experiments, confirming a transition phase from microbubbles to a stable air layer after gas injection. Once a stable air layer was formed, the maximum drag reduction rate reached over 80%. Zheng et al (2022) used the VOF model in Fluent software to study the air cavity layer model, analyzing the effects of four parameters-flow speed, ventilation step height, ventilation rate, and groove length-on air layer formation. They found that when $Fr < 2.0$, the air layer remained stable with a significant drag reduction effect, but when $Fr > 2.0$, the air layer became unstable, and localized bubbles did not merge into the air layer, resulting in a poorer drag reduction effect. Ye et al (2024) studied the effect of water depth on air layer drag reduction and found that under optimal experimental conditions, a drag reduction rate of up to 50% could be achieved.

Gao et al (2017) studied key influencing factors of air layer drag reduction technology, including jet method, nozzle shape, and airflow rate. They found that drag reduction rates varied between 15% and 65% depending on the jet method, with the single continuous slot method achieving the highest drag reduction rate. A ship model based on this method achieved a drag reduction rate of 47%, and the method was applied on the "Yangshan 2", a 10,000-ton open container ship, achieving net energy savings of over 7%. In January 2023, Dalian Shipbuilding delivered the " NEW SPLENDOR" VLCC, equipped with a Chinese independently developed air layer drag reduction system (2024).

5.3 Air Cavity Drag Reduction (ACDR)

Air cavity drag reduction is a special form of air layer drag reduction. It involves designing one or more cavities at the bottom of the ship and forming stable air cavities within these grooves. The air in these cavities can reduce the direct contact area between the hull and water, thereby reducing water friction on the hull.

Figure 13. Air Cavity Drag Reduction

Wu et al (Wu H, 2017; Wu H, 2019) studied the effects of cavity depth and configuration on ship resistance and air layer stability. Experimental results showed that without air injection, bottom grooves increased total resistance; with air injection, increased depth enhanced air layer stability, and the absolute drag reduction rate of flat plates could exceed 40% with suitable configuration and depth. Matveev, through simulations, found that the presence of air cavities could effectively reduce the heave motion of ships (Matveev KI, 2022).

Due to the recessed bottom structure of hovercraft, they are well-suited for air cavity drag reduction, making this technology more commonly used in hovercraft. In 2016, the 25-ton "BB Green" hovercraft was successfully launched, injecting compressed air into the bottom cavities, reducing resistance by 40% during high-speed navigation.

Air lubrication drag reduction has shown excellent effects, with simulation calculations and experiments indicating drag reduction rates of approximately 50% to 80%, and practical applications achieving 10% to 40%. It offers advantages such as easy installation and no special requirements for ship types, making it one of the drag reduction technologies with the most promising prospects. However, there are also some issues, such as the generation of large numbers of bubbles, which can exacerbate ship wake and cause secondary exposure. The position, direction, and size of bubble generation need to be specially calculated based on the ship type, making the implementation process complex. Despite this, the prospects for this technology remain very promising, with an increasing number of ships adopting air lubrication drag reduction systems. Achieving better drag reduction effects and mitigating the adverse impacts of gas on ship navigation will remain major research directions in the future.

6. CONCLUSION AND OUTLOOK

The development and application of ship drag reduction technologies are crucial for the sustainable evolution of the maritime industry. Reducing energy consumption is one of the most effective ways to conserve resources in this high-energy-demand sector. This paper has provided a detailed review of the current research and application status of various ship drag reduction technologies, summarizing their effects and practical applications (see Table 1).

Table 1 Summary of Various Drag Reduction Technologies

Category	Name	Drag Reduction Rate	Reduced Resistance Component	Practical Application Effect
Appendage Drag Reduction	Bow Windbreak Wall	20%~35%	Air Resistance	Mostly applied to large container ships
	Bulbous Bow	10%~30%	Wave-Making Resistance	Widely applied
	Bow Wave-Suppressing Appendages	2%~10%		Usually used in combination with other technologies
	Wave-Suppressing Plates	3%~10%		
	Wave-Suppressing Hydrofoils	10%~80%	Frictional Resistance	Great potential, applied to high-performance vessels
Surface Drag Reductio	Polymer Coatings	10%~30%	Frictional Resistance	Usually used in combination with other technologies; durability issues need to be addressed
	Superhydrophobic Coatings			
	Micro-Grooves			
	Fish Scale Biomimicry			
	Flexible Walls			
Air	MDR	20%~50%	Frictional	Excellent effect; a primary

Lubrication Drag Reduction	ALDR ACDR	Resistance	research direction for the future

Each category of drag reduction technology offers unique advantages and can complement others effectively:

(1) Impact on Performance: Certain technologies, while reducing drag, may affect stability, maneuverability, or even increase resistance under specific conditions.

(2) Durability of Effects: Technologies like superhydrophobic coatings may degrade over time due to wear and biofouling, necessitating regular maintenance.

(3) Environmental Concerns: Some coatings and materials may pose risks to marine ecosystems, emphasizing the need for environmentally friendly alternatives.

Despite these challenges, drag reduction technologies offer substantial benefits. When selecting or combining technologies, factors such as vessel type, operating conditions, and desired outcomes should be carefully considered to achieve optimal efficiency and cost-effectiveness. For instance, high-speed vessels may benefit more from appendage drag reduction and air lubrication, while low-speed ships could prioritize surface drag reduction methods.

Looking ahead, ship drag reduction technologies are expected to evolve in several key directions:

(1) Integration of Multiple Technologies: Combining drag reduction methods to maximize performance and economic viability.

(2) Intelligent Design: Leveraging artificial intelligence, big data, and related technologies to design and optimize drag reduction systems, enhancing their efficiency and adaptability.

(3) Development of Advanced Materials: Exploring innovative materials, such as superhydrophobic and microstructured surfaces, that offer superior performance, environmental sustainability, and durability.

(4) Focus on Environmental Sustainability: Prioritizing eco-friendly drag reduction technologies to support long-term sustainable growth in the maritime sector.

In summary, ship drag reduction technologies hold immense potential as a cornerstone of green shipping initiatives. By significantly reducing energy consumption and carbon emissions, these technologies will play a pivotal role in promoting the sustainable development of the global shipping industry..

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