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A State-of-the-Art Review on the Drag Reduction Techniques of Underwater Vehicles for Reduced Fuel Consumption and Enhanced Maneuverability

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Abstract

In a range of domains, including commerce, defense, and ocean inquiry, underwater vehicles are crucial. These vehicles' hydrodynamic drag, with a direct effect on their performance, use of energy, and mobility, remains a significant challenge. A thorough analysis of the most recent methods employed for reducing drag in underwater vehicles is offered in this article. The review puts drag methods into three main categories such as active method (include systems and technologies), passive method (design features and materials), and biomimetic (derived in nature). This review covers facts on the basic principles, advantages, and limitations of each drag reduction method as well as how well they work given different operational conditions and mission requirements. In picking the best drag reduction method, an underwater vehicle's design, operational environment, speed, energy limits, design constraints, and its goals may be considered for consideration. The best approach to lower drag on an underwater vehicle could be a combination of passive, active, and biomimetic techniques, given the particular requirements and limitations of the vehicle. A comparative analysis reveals that microbubble flow technology is the most effective conventional method for drag reduction in axisymmetric underwater bodies, achieving 50% reduction. Among biomimetic techniques, lotus leaf-inspired surfaces stand out, achieving a remarkable 77.2% drag reduction.

Keywords: Underwater vehicles, drag, fuel consumption, sustainability.

1. Introduction

Nowadays, the rising demand for energy is becoming a global challenge. Energy conservation and reducing consumption are crucial areas of research. Drag reduction technology is essential for achieving energy savings in the transportation and military sectors. Studies show that when a ship sails underwater, 70-80% [1] of its total resistance is due to surface friction. Even at high speeds, friction can still account for approximately 40% of the resistance. It has been calculated that for a given power and energy level, a 10% reduction in resistance can lead to a 3.57% increase in both ship speed and distance [1]. In the United States, ground vehicles consume a significant amount of petroleum, making up approximately 77% of all domestic and imported supplies. Automobiles account for 34%, light trucks for 25%, and large heavy-duty trucks and trailers for 18%. Even a small 1% increase in fuel efficiency for ground vehicles can lead to substantial annual savings of 245 million gallons of fuel. Ground vehicle fuel consumption also contributes more than 30% of CO_2 and other greenhouse gas emissions [2]. By slightly reducing drag, significant energy can be saved annually. As fuel prices continue to rise, economic considerations will become more important, driving the development of drag-reduction technologies for commercial vehicles. This is also crucial for addressing the current energy shortage and easing the energy crisis [3]. The principles of drag reduction in underwater vehicles share a clear connection with those in road vehicles, as both face similar challenges in minimizing resistive forces to enhance energy efficiency, performance, and operational range. Xin et al. (2018) used shark skin as the bio-replication template and found an 8.25% drag reduction [4]. KRAMER et al. (1961) used 4-feet-long slender models coated in ducted rubber to imitate dolphins with compliant skin and found a 40% drag reduction [5]. Hu et al. (2017) designed a jointed superhydrophobic and hydrophilic surface

using the lotus effect and found a 77.2% drag reduction [6]. Bideaux et al. (2011) used active control in a strip of pulse jets and found 20% drag reduction. Bellman et al. (2010) performed active control and found 20% in a synthetic jet [2]. For road vehicles Nath et al. (2021) performed CFD for spoiler and diffuser with a maximum reduction of 16.53% [7]. Verzicco et al. (2002) found a drag coefficient (C_d) of 0.223 using computed numerical methods on a road vehicle [8]. Present-day underwater vehicles are valuable tools for unmanned surveys. They carry sensors and follow pre-programmed paths to collect data for various purposes. Most underwater vehicles operate in a horizontal plane, covering as much area as possible. However, some applications require significant vertical navigation, such as data gathering in shallow or deep water. Advanced technologies can enhance underwater vehicle operations. These include treating video data like other data, using models to plan and automate complex tasks, and providing more data to experts for remote troubleshooting. These technologies are borrowed from other industries that have benefited from automation. By applying advanced hardware and software, underwater vehicle operations can become more productive and valuable [9], [10]. Literature review reveals that although several research were carried out on drag reduction of aerial, road and underwater vehicles, an up-to-date review on the drag reduction methods of underwater vehicles and their systematic comparison is absent in the literature. Hence, the objective of this research is to explore different drag reduction techniques of underwater vehicles for reduced fuel consumption and provide a comparative analysis among them.
In section 2, types of drag in underwater water vehicles, in section 3, classification of UVs, in section 4, Trends in drag reduction conventional techniques of underwater vehicles, in section 5, Trends in drag reduction bio-inspired techniques for underwater vehicles, in section 6, Recommendations and challenges are discussed.

2. Types of drag in underwater vehicles

Drag, or fluid resistance, has numerous forms, and the most vital are pressure drag and friction drag. When something traverses a fluid, pressure drag force, also called the form drag, occurs. It requires energy to push the fluid aside in front of the object and to fill the space left behind it. As moving forward required movement of the fluid ahead of time, this form of drag is especially relevant when moving in water. On contrary, friction drag, also referred to as viscous drag, stems from the fluid's interaction with a surface parallel to its flow as well as the molecules' attraction between each other [11]. The texture of a surface influences the amount of drag it encounters due to friction. Fluids with higher viscosity, or thickness, create more drag because their layers are more attracted to each other, which results in increased friction along the surface [12]. For streamlined shapes, skin friction drag constitutes the most significant portion of total drag, often exceeding 60% or 80% [13] in air or underwater environments. Fig. 1. and Fig. 2. presents the phenomena of friction drag and pressure drag, respectively.



Fig. 1. Skin friction drag

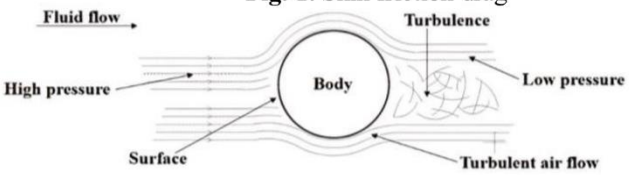


Fig. 2. Pressure drag

3. Classification of UVs

Underwater vehicles (UVs) are classified into various groups depending on their goal, design, functionality, and types of operation. Manned underwater vehicles (MUVs), which are also called human-occupied vehicles (HOVs), are used to study deep-sea life and explore the ocean's resources [14]. Submarines are specially used by the military for controlling emergencies like underwater warfare and coastal defense where the depth varies from 200 to 600 m and speed varies from 8 to 20 m/s [15]. The deepest diving manned submersible called Shinkai 6500 carried a crew of 3 people (2 pilots,1 researcher) to the maximum depth of 6500m [16]. Unmanned underwater vehicles (UUVs) are used for collecting information about ocean water, performing risky military operations, environmental monitoring, and even exploring oil and gas. Autonomous underwater vehicles (AUVs) dominate the UV sector due to their large capacity of battery and breakthroughs in hydrogen fuel cells They can cover a wider area as a result. AUVs can be used to collect physical properties of water under the ocean such as density, depth, and conductivity, and map out hydrothermal vents, and tsunamis. Torpedo-shaped hull forms, Length varies from

1.42 to 10m, Speed 0.5 to 2m/s, and Depth of work is about 200 to 600m [15], [17]. In Remotely operated vehicle (ROV) system, the pilot controls the vehicle using the Surface Control Unit (SCU) where the decision is made online. ROVs are primarily employed for tasks like location tracking, dynamic positioning, auto steering, and auto depth control. Marine Academy uses them for deep water missions, and oil and gas extraction [18]. Autonomous underwater gliders (AUGs) are the robots used to glide through the water against the current or waves. These types of robots can use the energy of the ocean to run themselves by converting heat energy to mechanical energy. AUVs, AUGs are very economical due to their small size, long long-term use. But they have a depth limit in operation of about 200m, with a standard speed of 0.1 to 0.5 m/s [15].

4. Conventional drag reduction techniques of underwater vehicles

Surface drag reduction techniques have advanced quickly in recent years and are divided into two main categories: active and passive. Active drag reduction involves using external devices to deliver substances or energy to the vehicle's surface and its turbulent boundary layer, thereby controlling the flow field structure to reduce drag. Examples of active methods include polymer addition, wall suction/ejection, and wall vibration. Conversely, passive drag reduction requires no energy input; instead, it reduces drag by modifying or optimizing the surface structure of the object to alter the flow field structure [19]. Gases have much lower viscosity than water, so superhydrophobic surfaces (a passive drag technique) are promising for reducing drag in water. These surfaces have tiny structures that trap air bubbles. These bubbles create a layer between the water and the surface, which reduces friction and helps the object move through the water more easily, as the air-water interface has less friction than the water-surface interface [13]. Zhang et al. (2015) achieved a drag reduction of 15% by superhydrophobic coatings on a submarine model by experimental trials [27]. Among the various passive methods, riblets have emerged as the most extensively studied drag reduction technique. It works by incorporating longitudinal microgrooves on a surface, specifically designed to minimize skin friction in a fully turbulent boundary layer. Initially, it was thought in flow control that a smoother surface would delay the transition from laminar to turbulent flow. However, by the mid- 1960s, it was recognized that rough surfaces could actually reduce skin friction in turbulent flow near the wall [20]. An approach to active drag reduction is the use of micro-vibrations. This is done by using mechanical, electromagnetic, or piezoelectric devices to create tiny vibrations on the surface of an object. These vibrations can change the characteristics of the turbulent boundary layer, which can reduce drag. Piezoelectric actuators are particularly effective at creating these vibrations. By applying pulsed voltages to them, they can control the fluid flow and reduce drag. These actuators can be embedded in the wall to control the turbulent structures and achieve drag reduction [21]. Another method to reduce the friction on ship hulls is to create an air layer around them. This air layer can also improve other aspects of the ship's performance, such as noise reduction, shock resistance, and stability in rough seas. By covering parts of the hull with air, the amount of the hull that comes into contact with the water is reduced, which leads to less friction [22]. The addition of polymer additives (an active method) serves 3 main purposes in drag reduction. Firstly, it increases the thickness of the viscous sublayer, which acts as a buffer against the wall. Secondly, and most importantly, it reduces the velocity gradient at the solid-fluid boundary due to a slipping effect, thereby lowering viscous drag. Lastly, the long nano-chains formed by the polymers have a calming effect, reducing turbulence and promoting steady flow conditions within the boundary layer. These nano- chains also help reduce drag by reorienting themselves to align parallel to the flow, minimizing speed differences caused by turbulence as they rotate to balance the varying speeds at their ends [23]. For reducing skin drag friction, the wall deformation method involves moving parts of the wall to disrupt the turbulent flow near the surface, which can decrease friction. This method can be categorized into two main types. Spanwise traveling wave, the wall moves in a wave-like pattern from side to side, affecting the flow in that direction; streamwise traveling wave, the wall moves in a wave-like pattern from front to back, influencing the flow in the direction of movement. The volume force control method for drag reduction is a technique that directly modifies the properties of the fluid near the wall, thereby disrupting the streak structure and reducing drag. This approach utilizes electromagnetic actuators to generate Lorentz forces within the conductive fluid near the wall or plasma actuators to produce plasma forces. By controlling these forces, the motion of the near-wall fluid can be manipulated, resulting in a reduction of skin friction drag. The oscillation waves of the volume force can be propagated either perpendicular or parallel to the direction of flow to achieve the desired drag reduction effect [21]. A significant reduction in drag can be achieved by applying a spanwise oscillating volume force to the fluid near the wall [24]. While several methods have been investigated for reducing friction drag, a practical solution remains elusive. External flows, like boundary layers, have received less attention compared to internal flows. Buoyancy is a potential method for generating a body force to reduce skin friction drag [25]. Kametani et al. (2002) conducted direct numerical simulations of turbulent channel flow under both stable and unstable density stratification. Under stable stratification, turbulence was suppressed, reducing skin friction drag due to internal gravity waves, and the flow could become laminar at high Richardson numbers. In weakly unstable stratification, skin friction drag decreased due to reduced streamwise vortices near the wall, but at higher Richardson numbers, thermal plumes formed, increasing turbulence and skin friction drag [26]. Dong et al. (2013) obtained a drag reduction of 38.5%

on a macroscopic model ship by experiment. Wu et al. (2006) achieved an outstanding drag reduction rate of 50% by numerical simulation of microbubble flow around an axisymmetric body [29]. Table 1 represents the phenomena of trends in drag reduction conventional techniques of underwater vehicles.

Table 1: Trends in drag reduction conventional techniques of underwater vehicles

Investigator	Experiment / Simulation model	Drag reduction technology	Research method	Drag reduction rate	Conditions	Advantages/ Disadvantages	References
Zhang et al. (2015)	Submarine		Experiment	15%	φ = 4 cm × 33 cm T= 20min		[27]
Dong et al. (2013)	Macroscopic model ship	Superhydrophobic coating	Experiment	38.5%	Contact angle=159.7°	Extraordinary drag reduction technique.	[28]
Wu et al. (2006)	Axisymmetric body	Microbubble flow	Simulation	50%	$v^{\rightarrow} = {}^{\rightarrow}V^{\rightarrow}1$, $\gamma b = 1$	High reduction efficiency	[29]
Zhang et al. (2023)	Micro underwater vehicle	Piezoelectric drag reducer	Simulation	45.3%	Angle= 60° (between the PDR & incoming flow)		[30]
Zhang et al. (2024)	Unnamed UV		Simulation	18% (surge direction) 32% (heave direction)	Mesh Element size= .99m		[31]
Jeung et al. (2020)	Fluid transport system	Electrochemical water splitting	Experiment	26.5%	Contact angle 155°	Easily polluted by oil due to its high lipophilicity.	[32]

5. Bio-inspired techniques for drag reduction of underwater vehicles

Since the beginning of the 21st century, humans have been thinking about how to reduce energy wastage due to the global energy crisis. At the beginning of human civilization, to solve any problem man has taken knowledge from nature. To survive, natural organisms have evolved themselves with elegant morphologies, structures, patterns, or surface wettability with unique functionalities. Shark skin-inspired drag reduction, the shortfin mako shark (Isurus oxyrinchus) can obtain high speed and agility by reducing drag because of their placoid scales. Shark skin is covered with placoid scales embedded in a deeper collagenous layer ranging from 0.2 mm to 0.5 mm. The scales have very fine longitudinal grooves running along their scales. Longitudinal grooves are like small riblets which are aligned in the flow direction. These microgrooves helped streamline water flow, reduce turbulence, and minimize drag. The application of shark-skin inspired surface with scales aligned at a 90° angle resulted in a maximum viscosity reduction of 9% in 2019. Lotus leaves have self-cleaning and superhydrophobic properties. Due to the microscale papillose epidermal cells and an additional layer of epicuticular waxes water droplets can't stick on the leaves. Water interaction is less with the surface, reducing drag forces associated with fluid flow. Microscopic structure (Papillae) of superhydrophobic lotus leaves achieve drag reduction in laminar flows due to micro-sized roughness [33]. Water droplets rolling off carry away surface contaminants. It possesses a unique inclination angle due to papillae resulting in anisotropic deflection, the edges of the leaf undergo asymmetric curling [34]. A thin layer of air between the surface and water is made which acts as a lubricant, reducing drag by decreasing direct water contact. Penguins have evolved specialized adaptations to minimize hydrodynamic drag and optimize their aquatic locomotion. Their streamlined body shapes, coupled with unique feather structures and wettability, contribute to efficient swimming and energy conservation. By inducing turbulent boundary layers and generating bubble clouds, penguins effectively reduce drag forces, enabling them to navigate through water with minimal resistance. These adaptations highlight the remarkable engineering principles employed by nature, offering potential insights for the development of novel drag-reducing technologies. The Nepenthe's pitcher plant has advanced a super-slippery surface to trap creepy crawlies and little creatures. This unique surface is characterized by micro/nano structures that trap liquid, creating a lubricant layer that repels oils on the feet of prey. Unlike traditional liquid-solid interactions, this slippery surface relies on liquid-liquid interactions, offering new possibilities for controlling the behavior of one liquid by altering the properties of another. Inspired by the pitcher plant, researchers have developed liquid-infused surfaces (SLIPS or LIS) that exhibit exceptional repellency, low friction, and anti-wetting, anti-fogging, anti-icing, and anti-fouling properties. These surfaces function similarly to superhydrophobic surfaces, relying on a lubricating air layer. However, the liquid molecules in SLIPS or LIS have minimal adhesive forces, resulting in low friction and reduced momentum transfer, leading to significant drag reduction [33]. Table 2 represents the phenomena of trends in drag reduction bio-inspired techniques of underwater vehicles.

Table 2: Trends in drag reduction bio-inspired techniques of underwater vehicles

Investigator	Drag Reduction Technology	Research Method	Drag Reduction Rate	Conditions	Advantages / Disadvantages	References
Han et al. (2008), Yu et al. (2020)	Shark Skin	Experimental	8.25%	Stored at 4°c in glutaraldehyde liquor	Reduce turbulence. Costly and limited application to use.	[4], [33]
Hu et al. (2017)	Lotus leaf	Experimental	77.2%	R_e up to 1320 at a speed of 200 rpm	Reduce the viscous drag of liquids.	[6]
Yu et al. (2020), Lee et al. (2019)	Nepenthe's pitcher plant	Experimental	18%	External shear conditions	Loss of lubricant under external flow.	[33], [35]
Parfitt et al. (2005)	Penguin inspired micro-bubble	Experimental	Average of 31%	———	Reduced energy expenditure	[36]

6. Recommendations & Challenges

The comparative analysis of conventional drag reduction techniques exhibit that microbubble flow technology [29] offers the most promising results for reducing drag in axisymmetric underwater bodies, achieving a drag reduction of 50% which surpasses other approaches such as superhydrophobic coatings (15% in submarines [27] and 38.5% in macroscopic model ships [28]) and the piezoelectric drag reducer method [30] (45.3% in micro underwater vehicles). A comprehensive analysis of biomimetic drag reduction techniques establishes the lotus leaf-inspired Surface [6] as the most effective approach for maximizing drag reduction in underwater vehicles. Achieving an impressive 77.2% reduction in drag, it far exceeds the performance of other biomimetic methods, such as the shark skin-inspired surface [4], [33] (8.25%), nepenthes pitcher plant surface (18%) [33], [35], and the penguin-inspired microbubble method [36] (31% on average). Here fig. 3 represents the drag reduction rate in conventional techniques and fig. 4 represents the drag reduction rate in bio-inspired techniques sequentially.

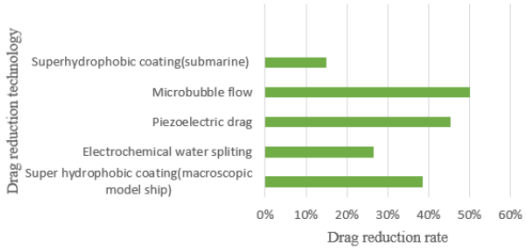


Fig. 3. Drag reduction rate in conventional techniques

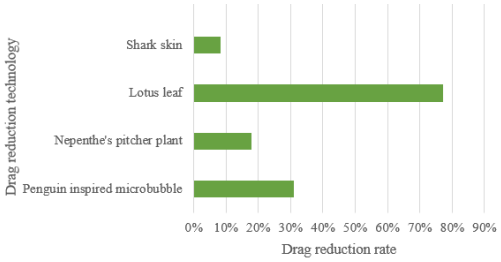


Fig. 4. Drag reduction rate in biomimetic techniques

Bionic textured microstructures have shown potential for drag reduction. Challenges in fabricating these complex structures include material limitations and manufacturing equipment constraints. Developing advanced fabrication technologies and achieving large-scale, low-cost production are essential for practical application. Moreover, improving the durability and self-repairing properties of these surfaces is essential, as they are prone to wear and damage, limiting their long-term use [19]. The shape of riblets on fast-swimming sharks varies significantly, even within the same shark. Creating riblets for research and large-scale use has been a significant challenge due to the limitations of typical microscale manufacturing techniques. These methods are often expensive for large-scale production [11]. It is challenging to prevent entrapped gas from escaping underwater surface structures. This necessitates a constant gas supply to maintain the interface and achieve drag reduction. While active gas supplementation is effective, it requires specialized equipment and additional energy, limiting its practicality. Cavitation or super cavitation offers passive gas generation but is suitable only for high-speed vehicles. Superhydrophobic surfaces, when submerged, struggle to retain entrapped gas due to mechanical shearing and thermodynamic diffusion, hindering their practical application for underwater drag reduction [13]. The main limitation of superhydrophobic coatings in practical applications is their poor mechanical durability and low resistance to abrasion, especially when in contact with solid surfaces [37]. Additionally, repeated testing shows that as the coating's wetting properties degrade, drag forces increase, further limiting their effectiveness [28].

7. Conclusion

The aim of this paper was to summarize various drag-reduction techniques for underwater vehicles. Among the various methods studied, two key techniques were identified as highly promising. The first is a conventional method, microbubble flow technology, which was applied to axisymmetric underwater bodies and demonstrated a drag reduction rate of 50% in simulations. In experimental trials, the Lotus Leaf-Inspired Surface Technology, a biomimetic approach, achieved an impressive 77.2% drag reduction rate. This study concentrated on a targeted examination of specific conventional and biomimetic drag reduction methods. A comprehensive analysis of all available techniques was beyond the scope of this review, such an extensive investigation could offer valuable insights, enabling engineers and researchers to make well-informed decisions and advance the development of more effective drag-reduction strategies.

8. References

[1] G. Yunqing, L. Tao, M. Jiegang, S. Zhengzan, and Z. Peijian, "Analysis of Drag Reduction Methods and Mechanisms of Turbulent," *Appl. Bionics Biomech.*, vol. 2017, pp. 1–8, 2017, doi: 10.1155/2017/6858720.

[2] M. N. Sudin, M. Abdullah, S. Shamsudin, F. Ramli, and M. Tahir, "Review of research on vehicles aerodynamic drag reduction methods," *Int. J. Mech. Mechatron. Eng.*, vol. 14, pp. 35–47, Apr. 2014.

[3] K. R. Cooper, "Commercial Vehicle Aerodynamic Drag Reduction: Historical Perspective as a Guide," in *The Aerodynamics of Heavy Vehicles: Trucks, Buses, and Trains*, vol. 19, R. McCallen, F. Browand, and J. Ross, Eds., in Lecture Notes in Applied and Computational Mechanics, vol. 19. , Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 9–28. doi: 10.1007/978-3-540-44419-0_2.

[4] X. Han, D. Zhang, X. Li, and Y. Li, "Bio-replicated forming of the biomimetic drag-reducing surfaces in large area based on shark skin," *Sci. Bull.*, vol. 53, no. 10, pp. 1587–1592, May 2008, doi: 10.1007/s11434-008-0219-3.

[5] M. O. Kramer, "THE DOLPHINS' SECRET," *J. Am. Soc. Nav. Eng.*, vol. 73, no. 1, pp. 103–108, Feb. 1961, doi: 10.1111/j.1559-3584.1961.tb02422.x.

[6] H. Hu *et al.*, "Significant and stable drag reduction with air rings confined by alternated superhydrophobic and hydrophilic strips," *Sci. Adv.*, vol. 3, no. 9, p. e1603288, Sep. 2017, doi: 10.1126/sciadv.1603288.

[7] D. S. Nath, P. C. Pujari, A. Jain, and V. Rastogi, "Drag reduction by application of aerodynamic devices in a race car," *Adv. Aerodyn.*, vol. 3, no. 1, p. 4, Dec. 2021, doi: 10.1186/s42774-020-00054-7.

[8] R. Verzicco, M. Fatica, G. Iaccarino, P. Moin, and B. Khalighi, "Large Eddy Simulation of a Road Vehicle with Drag-Reduction Devices," *AIAA J.*, vol. 40, no. 12, pp. 2447–2455, Dec. 2002, doi: 10.2514/2.1613.

[9] J. W. Nicholson and A. J. Healey, "The Present State of Autonomous Underwater Vehicle (AUV) Applications and Technologies," *Mar. Technol. Soc. J.*, vol. 42, no. 1, pp. 44–51, Mar. 2008, doi: 10.4031/002533208786861272.

[10] S. Cohan, "Trends in ROV Development," *Mar. Technol. Soc. J.*, vol. 42, no. 1, pp. 38–43, Mar. 2008, doi: 10.4031/002533208786861335.

[11] B. Dean and B. Bhushan, "Shark-skin surfaces for fluid-drag reduction in turbulent flow: a review," *Philos. Trans. R. Soc. Math. Phys. Eng. Sci.*, vol. 368, no. 1929, pp. 4775–4806, Oct. 2010, doi: 10.1098/rsta.2010.0201.

[12] G. D. Bixler and B. Bhushan, "Fluid Drag Reduction with Shark-Skin Riblet Inspired Microstructured Surfaces," *Adv. Funct. Mater.*, vol. 23, no. 36, pp. 4507–4528, Sep. 2013, doi: 10.1002/adfm.201203683.

[13] J. Wang, B. Wang, and D. Chen, "Underwater drag reduction by gas," *Friction*, vol. 2, no. 4, pp. 295–309, Dec. 2014, doi: 10.1007/s40544-014-0070-2.

[14] N. Vedachalam, G. A. Ramadass, and M. A. Atmanand, "Review of Technological Advancements and HSE-Based Safety Model for Deep-Water Human Occupied Vehicles," *Mar. Technol. Soc. J.*, vol. 48, no. 3, pp. 25–42, May 2014, doi: 10.4031/MTSJ.48.3.7.

[15] K. Lakshmi Vasudev, "Review of Autonomous Underwater Vehicles," in *Autonomous Vehicles*, G. Dekoulis, Ed., IntechOpen, 2020. doi: 10.5772/intechopen.81217.

[16] W. Kohnen, "2007 MTS Overview of Manned Underwater Vehicle Activity," *Mar. Technol. Soc. J.*, vol. 42, no. 1, pp. 26–37, Mar. 2008, doi: 10.4031/002533208786861236.

[17] B. Zhang, D. Ji, S. Liu, X. Zhu, and W. Xu, "Autonomous Underwater Vehicle navigation: A review," *Ocean Eng.*, vol. 273, p. 113861, Apr. 2023, doi: 10.1016/j.oceaneng.2023.113861.

[18] L. G. García-Valdovinos, T. Salgado-Jiménez, M. Bandala-Sánchez, L. Nava-Balanzar, R. Hernández-Alvarado, and J. A. Cruz-Ledesma, "Modelling, Design and Robust Control of a Remotely Operated Underwater Vehicle," *Int. J. Adv. Robot. Syst.*, vol. 11, no. 1, p. 1, Jan. 2014, doi: 10.5772/56810.

[19] G. Tian, Y. Zhang, X. Feng, and Y. Hu, "Focus on Bioinspired Textured Surfaces toward Fluid Drag Reduction: Recent Progresses and Challenges," *Adv. Eng. Mater.*, vol. 24, no. 1, p. 2100696, Jan. 2022, doi: 10.1002/adem.202100696.

[20] H. A. Abdulbari, H. D. Mahammed, and Z. B. Y. Hassan, "Bio-Inspired Passive Drag Reduction Techniques: A Review," *ChemBioEng Rev.*, vol. 2, no. 3, pp. 185–203, Jun. 2015, doi: 10.1002/cben.201400033.

[21] L. Zhang, X. Shan, and T. Xie, "Active Control for Wall Drag Reduction: Methods, Mechanisms and Performance," *IEEE Access*, vol. 8, pp. 7039–7057, 2020, doi: 10.1109/ACCESS.2020.2963843.

[22] J.-K. Choi and G. L. Chahine, "Numerical Study on the Behavior of Air Layers Used for Drag Reduction".

[23] S. Kumar, K. M. Pandey, and K. K. Sharma, "Advances in drag-reduction methods related with boundary layer control – A review," *Mater. Today Proc.*, vol. 45, pp. 6694–6701, 2021, doi: 10.1016/j.matpr.2020.12.150.

[24] J.-H. Lee and H. J. Sung, "Response of a spatially developing turbulent boundary layer to a spanwise oscillating electromagnetic force," *J. Turbul.*, vol. 6, p. N39, Jan. 2005, doi: 10.1080/14685240500293977.

[25] O. Iida, N. Kasagi, and Y. Nagano, "Direct numerical simulation of turbulent channel flow under stable density stratification," *Int. J. Heat Mass Transf.*, vol. 45, no. 8, pp. 1693–1703, Apr. 2002, doi: 10.1016/S0017-9310(01)00271-X.

[26] Y. Kametani and K. Fukagata, “DIRECT NUMERICAL SIMULATION OF SPATIALLY DEVELOPING TURBULENT BOUNDARY LAYER FOR SKIN FRICTION DRAG REDUCTION BY WALL SURFACE-HEATING OR COOLING”.

[27] S. Zhang *et al.*, “Underwater Drag-Reducing Effect of Superhydrophobic Submarine Model,” *Langmuir*, vol. 31, no. 1, pp. 587–593, Jan. 2015, doi: 10.1021/la504451k.

[28] H. Dong, M. Cheng, Y. Zhang, H. Wei, and F. Shi, “Extraordinary drag-reducing effect of a superhydrophobic coating on a macroscopic model ship at high speed,” *J. Mater. Chem. A*, vol. 1, no. 19, p. 5886, 2013, doi: 10.1039/c3ta10225d.

[29] C. Wu, S. He, D. Zhu, and M. Gu, “Numerical simulation of microbubble flow around an axisymmetric body,” *J. Hydrodyn. Ser B*, vol. 18, no. 3, pp. 217–222, Jul. 2006, doi: 10.1016/S1001-6058(06)60056-5.

[30] L. Zhang, X. Shan, S. Yan, and T. Xie, “Arrangement and Control Parameter Selection Methods for Achieving High-Efficiency Underwater Active Drag Reduction by Micropiezoelectric Actuator,” *IEEE Trans. Ind. Electron.*, vol. 70, no. 2, pp. 1729–1739, Feb. 2023, doi: 10.1109/TIE.2022.3156145.

[31] X. Li, D. Zhang, M. Zhao, X. Wang, and Y. Shen, “Hydrodynamic Analysis and Drag-Reduction Design of an Unmanned Underwater Vehicle Based on Computational Fluid Dynamics,” *J. Mar. Sci. Eng.*, vol. 12, no. 8, p. 1388, Aug. 2024, doi: 10.3390/jmse12081388.

[32] Y. Jeung and K. Yong, “Underwater superoleophobicity of a superhydrophilic surface with unexpected drag reduction driven by electrochemical water splitting,” *Chem. Eng. J.*, vol. 381, p. 122734, Feb. 2020, doi: 10.1016/j.cej.2019.122734.

[33] C. Yu *et al.*, “Bio-inspired drag reduction: From nature organisms to artificial functional surfaces,” *Giant*, vol. 2, p. 100017, Jun. 2020, doi: 10.1016/j.giant.2020.100017.

[34] D. Zhang, J. Ji, C. Yan, J. Zhang, Z. An, and Y. Shen, “Research advances in bio-inspired superhydrophobic surface: Bridging nature to practical applications,” *J. Ind. Eng. Chem.*, p. S1226086X24003587, May 2024, doi: 10.1016/j.jiec.2024.05.051.

[35] S. J. Lee, H. N. Kim, W. Choi, G. Y. Yoon, and E. Seo, “A nature-inspired lubricant-infused surface for sustainable drag reduction,” *Soft Matter*, vol. 15, no. 42, pp. 8459–8467, 2019, doi: 10.1039/C9SM01576K.

[36] A. R. Parfitt and J. F. V. Vincent, “Drag reduction in a swimming humboldt penguin, Spheniscus humboldti, when the boundary layer is turbulent,” *J. Bionic Eng.*, vol. 2, no. 2, pp. 57–62, Jun. 2005, doi: 10.1007/BF03399481.

[37] T. Verho, C. Bower, P. Andrew, S. Franssila, O. Ikkala, and R. H. A. Ras, “Mechanically Durable Superhydrophobic Surfaces,” *Adv. Mater.*, vol. 23, no. 5, pp. 673–678, Feb. 2011, doi: 10.1002/adma.201003129.