

Original article

Boundary Layer Control in Exhaust Turbine Sails: Advances and Future Challenges

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Abstract

Against the backdrop of the rapid development of the global shipping industry and the deep advancement of “dual carbon” goals, energy transition, energy conservation, and emission reduction have become core issues in marine transportation. As a critical component of clean and renewable energy, the efficient development and utilization of wind energy are pivotal for achieving low-carbon shipping. Exhaust turbine sails, an innovative application of active suction control in marine aerodynamic propulsion, regulate boundary layer flow through active suction to enhance wind energy utilization efficiency, which has emerging as a research hotspot in the green transformation of modern shipping.

This paper aims to synthesize research on exhaust turbine sails. First, based on fundamental fluid mechanics principles, it analyzes the impact of boundary layer separation on the aerodynamic characteristics of structural bodies. Second, through case studies, it summarizes flow control effects under different suction parameters. It further introduces combined blowing and suction control strategies to explore their influence on boundary layer management. Finally, it details the research progress of exhaust turbine sails, explaining their core principle: active suction control delays or prevents boundary layer separation, effectively suppressing vortex shedding, thereby significantly reducing ship navigation resistance and enhancing lift. The study reveals that the aerodynamic performance of exhaust turbine sails is jointly influenced by oncoming flow conditions, suction power, and structural parameters, necessitating multi-objective optimization to achieve energy efficiency balance. The paper concludes by addressing key challenges in their marine applications and envisioning future directions for integrating these sails with emerging technologies, providing practical implications for promoting the green and low-carbon transformation of the shipping industry.

Keywords: Emission Reduction, Exhaust Turbine Sails, Active Suction Control, Boundary Layer

1. Introduction

1.1 Research Background

As the global population continues to grow and international trade intensifies, marine transportation has become the core engine driving world trade, with over 90% of global trade volume reliant on maritime channels (Tian, C.L., 2022)(James, C., 2021). However, the sector faces a severe energy structural challenge: approximately 99% of its energy demand still depends on fossil fuels such as fuel oil and diesel (Zhu, L.Q., 2024), leading to persistently high carbon emission intensity. Statistics show that in 2023, greenhouse gas (GHG) emissions from global shipping accounted for 2.2% of total global emissions, equivalent to approximately 8.334 gigatons (Gt) of CO₂ equivalent (“Data center”, 2024). The International Maritime Organization (IMO) forecasts that if current growth rates continue, shipping’s GHG emissions could surge by 250% by 2050 compared to 2008 (“Fourth IMO Greenhouse Gas Study”, 2020), thus posing a significant threat to the global ecosystem.

In response, the IMO has prioritized GHG reduction in shipping, setting targets to reduce carbon intensity by 40% by 2030 and 70% by 2050 (relative to a 2008 baseline), and to cut total annual GHG emissions by 50% by 2050. To meet these challenges, the shipping industry urgently needs to accelerate its transition to clean energy (Zuo, W.G., 2025)(Huang, J.S., 2023) (Jiao, Y.Q., 2022), reducing fossil fuel dependence to inject green momentum into achieving China’s “dual carbon” goals (carbon peaking and carbon neutrality) (Jiao, Y., 2025)(Wijianti, E.S., 2013) and promoting high-quality marine economic development (Li, S.N., 2024). Clean energy transition has emerged as the most direct and effective pathway to lower shipping emissions (Jin, L., 2025)(Florian, E., 2019), with renewable energy sources like wind, solar, and wave energy garnering significant attention. Among these, wind energy, due to its abundant reserves and developable potential, is seen as a key breakthrough for the industry’s decarbonization (Wang, P., 2022). Wind-assisted ship propulsion technologies, as a quintessential application of wind energy, are leading shipping toward a green and low-carbon future.

Human history of wind energy utilization spans thousands of years, a testament to our symbiosis with

nature. From primitive sails raised around 3000 BCE to the horizontal-axis windmills along China’s coast during the Han and Song dynasties, and today’s large-scale wind turbine generator system on plateaus and coastlines, humanity has harnessed wind energy for progress. The heyday of wind-propelled ships occurred between the 15th and mid-19th centuries (Carter, R.A., 2006) (Carter, W.E., 2010), when sailing vessels dominated maritime transport, enabling historic voyages such as Columbus’s discovery of the New World, Magellan’s circumnavigation, and Zheng He’s expeditions to the West (Charrier, B., 1985). Modern wind-assisted propulsion has evolved beyond traditional rigid sails, with technologies including Flettner rotors, kite sails, and exhaust turbine sails. Among these, exhaust turbine sails stand out for their exceptional performance in wind energy utilization, energy savings, and aerodynamic efficiency.

This innovative technology traces its origins to the pioneering work of Professor L. Malavard and the Cousteau Research Team, which opened new technical frontiers in marine wind energy applications. The team successfully conducted sea trials on the prototype vessel *Moulina Vent* and, by late 1984, partnered with Peehiney to build the *Alcyone* (Figure 1).



Figure 1. The "Alcyone" Trial Vessel

A 31.1-meter-long ship with a half-load displacement of 76.8 metric tons and two 115 kW diesel engines. The exhaust turbine sails, constructed from aluminum, feature 10.2-meter-tall cylinders with a surface area of 21 m² and a total weight of approximately 1600 kg. Test data showed that at wind speeds around 25 knots, the turbine sails deliver outstanding auxiliary propulsion, achieving 55%–60% energy savings. Notably, Malavard’s research did not fully define the geometric configurations of the turbine sails or suction inlets, leaving room for further optimization.

As an emerging and promising wind-assisted propulsion device, exhaust turbine sails offer significant advantages in emission reduction and cost control over traditional diesel and gas turbine systems. They drastically reduce fuel consumption, pollutants, and operational costs while enabling flexible installation (Luan, Y.L., 2015). International shipowners have already trialed these sails on various vessel types, with operational data confirming their compact design and lightweight structure—qualities that allow adaptation to bulk carriers, container ships, and other ship types without compromising cargo capacity (Zhao, B., 2025). This underscores their broad application potential and pivotal role in driving the industry's green and low-carbon transformation.

1.2 Research Significance

Studying exhaust turbine sails as auxiliary ship propulsion devices holds profound significance across key dimensions:

(1) Energy Conservation and Emission Reduction

The global shipping industry faces increasingly stringent environmental regulations, with the implementation of greenhouse gas emission reduction becoming a critical mandate and binding requirement for sectoral development. Innovative energy-saving technologies, as exemplified by exhaust turbine sails, can significantly diminish vessels' reliance on conventional fossil fuels and associated pollutant emissions by converting wind energy into viable auxiliary propulsion power, thereby driving the maritime industry's transition toward greener and low-carbon operations. This approach both fulfills obligations under international conventions and directly addresses the urgent imperative of mitigating the environmental footprint of maritime transport activities.

(2) Renewable Energy Utilization

Wind energy, as an abundant clean and renewable resource prevalent in marine environments, presents significant potential for maritime applications. Research on exhaust turbine sails facilitates the optimized harnessing of oceanic wind resources, enabling their conversion into viable auxiliary propulsion power for vessels. This technology not only elevates overall energy utilization efficiency but also fortifies the shipping industry's energy security and sustainability through

strategic diversification of marine fuel portfolios—transitioning from fossil-based systems toward renewable energy alternatives.

(3) Improved Transportation Efficiency

Exhaust turbine sails can enhance a ship's sailing speed and on-time performance. Under favorable wind conditions, these sails provide additional thrust, enabling vessels to reach their destinations faster and shorten voyage times. This benefit allows shipping companies to better meet customer demands, improve service quality, and optimize logistics efficiency, ultimately enhancing the competitiveness of maritime transport.

(4) Enhanced Energy Security

Reducing dependence on traditional fossil fuels and increasing the application of renewable energy in shipping directly strengthens national energy security. By integrating wind-assisted propulsion technologies like exhaust turbine sails, countries can reduce their vulnerability to fluctuations in global fuel markets, diversify energy sources, and build a more resilient and sustainable maritime energy system, which is vital for long-term economic and strategic stability.

2. Working Principle and Study on the Structure of Exhaust Turbine Sails

2.1 Structural diagram

As shown in Figure 2, this is a typical structural diagram of a exhaust turbine sail. It can be seen that the turbine sail primarily consists of an elliptical cylinder, a suction fan, pumping holes, and a separation plate, and is equipped with a bracket of ventilating fan and end plates.

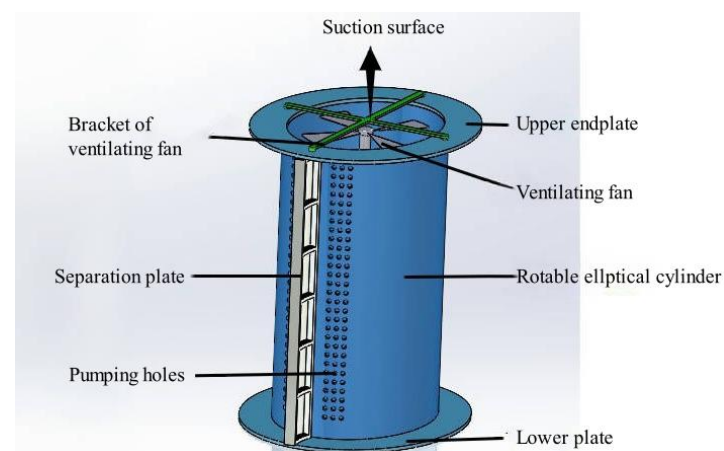


Figure 2. Structure diagram of exhaust turbine sail

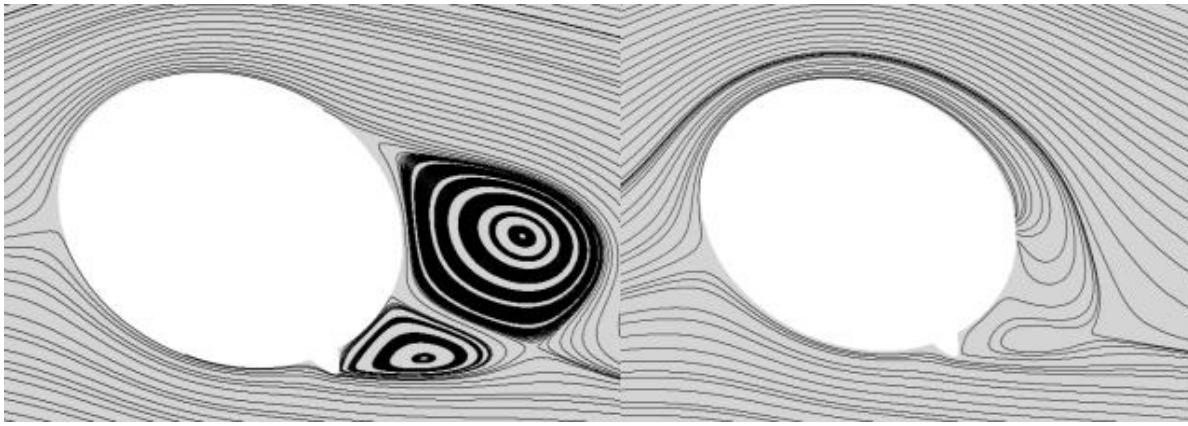


Figure 3. Working principle of turbine sail

Among which, the core of the exhaust turbine sail is a rotatable elliptical cylinder. Both sides of its trailing edge are covered with suction holes, and it is equipped with a streamlined splitter plate to block the corresponding suction holes when the wind direction changes. The design of the splitter plate helps to reduce the eddy current intensity in the suction area. To enhance the stability of the turbine sail, end plates are installed at its upper and lower ends respectively. There is also an air extractor on the upper end plate, which can comprehensively adjust the sail's angle and the amount of air extraction according to changes in wind speed, wind direction, and ship speed to achieve better air extraction efficiency (Luan, Y.L., 2015).

2.2 Working Principle

In fluid dynamics, when a bluff body is placed in a uniform flow field, flow separation at its trailing edge generates periodic vortex shedding, significantly increasing the pressure drag (form drag) acting on the object. Studies indicate that the streamlined characteristics of an object are negatively correlated with its aerodynamic performance: less streamlined bodies are more prone to vortex generation and shedding, resulting in higher pressure drag and no lift-inducing effects in such flow regimes.

The boundary layer separation, a key mechanism of flow instability, refers to the critical state in which the viscous flow around an object's surface loses momentum in the boundary layer and detaches from the surface due to inability to overcome the adverse pressure gradient. Downstream of the separation point, the originally attached laminar or turbulent boundary layer undergoes flow reversal, forming three-dimensional recirculation zones and vortex structures. These flow alterations drastically modify the surface pressure

distribution and overall aerodynamic loads. The forward or backward shift of the separation point directly governs the size of the flow separation region, thereby dominating the aerodynamic behavior of marine sails, aircraft, and vehicles.

Active suction control, developed based on this mechanism, involves fluid suction near the separation point to reduce pressure or accelerate the flow. This approach delays or suppresses vortex separation, effectively lowering the local pressure gradient and enhancing the kinetic energy of the boundary layer flow, thereby delaying the onset of flow separation. The principle of vortex suppression via energy injection constitutes the core technical pathway for exhaust turbine sails to achieve drag reduction and efficiency enhancement, as illustrated in Figure 3 (left: without suction; right: with suction).

3. Literature Review: Domestic and International Studies

The core technology of exhaust turbine sails lies in suction control, which achieves the primary objectives of drag reduction and efficiency enhancement through boundary layer control. As a critical method in fluid mechanics for regulating surface flow fields around objects, boundary layer control technologies encompass multiple approaches, including suction control, blowing control, and combined suction-blowing control. Building on this framework, this paper will take boundary layer control technologies as a starting point, sequentially analyze research progress across sub-technologies, and ultimately focus on the current state of aerodynamic performance studies for exhaust turbine sails. A systematic review will be conducted from the following dimensions:

- (1) Studies on boundary layer control characteristics—foundational for understanding fluid-surface interactions;
- (2) Active suction control (ASC) characteristics—aiming to clarify its mechanisms in diverse scenarios;
- (3) Suction and Forced-Jet Joint Control (SFJ) characteristics—exploring synergistic advantages and effects of combined techniques;
- (4) Aerodynamic performance of exhaust turbine sails—analyzing their aerodynamic properties at a systemic level.

By synthesizing prior research findings and methodologies, this review aims to establish a robust theoretical foundation for subsequent studies, ensuring that future exploration and innovation are grounded in rigorous scientific principles.

3.1 Working Principle

In aeronautics, the key to improving aerodynamic performance lies in eliminating or delaying boundary layer separation (Guerra, O., 2016). When applied to the maritime industry, this approach yields similar benefits. Boundary layer control (BLC) technology represents a breakthrough in wind energy utilization for ships and is a core component of exhaust turbine sails. By actively regulating the airflow boundary layer, through BLC—wind energy conversion efficiency can be significantly enhanced, with notable effects on drag reduction, lift augmentation, suppression of vortex-induced vibrations (VIV), and vortex shedding mitigation (Shi, X.Y., 2021). BLC has long been a pivotal research topic in fluid mechanics (Li, F., 2022).

(1) Classical Boundary Layer Theory

Prandtl, L. (1928) first proposed the boundary layer theory, elevating fluid mechanics to new heights. His student Blasius, H. (1907) introduced similarity assumptions to address laminar boundary layer flow over a semi-infinite flat plate. Using dimensional analysis, he transformed the complex 2D Navier-Stokes partial differential equations into ordinary differential equations, deriving the first analytical solution in series form. Von Kármán T. (1911) systematically combined experimental observations with theoretical analysis to reveal periodic vortex shedding caused by boundary layer separation at high Reynolds numbers (A dimensionless number characterizing fluid flow). When

fluid flows around a cylinder, two staggered rows of counter-rotating vortices form downstream of the separation point, known as the “Kármán vortex street”. This discovery not only advanced the understanding of flow separation mechanisms but also demonstrated significant engineering value in fields such as VIV suppression for offshore platforms and fluid machinery optimization.

(2) Modern PIV Observations

Particle Image Velocimetry (PIV), a non-contact optical method, extends the scope of flow measurement beyond single-point techniques. Ghaemi, S. et al. (2012) pioneered the use of PIV to measure boundary layer velocity fields and subsequently reconstruct instantaneous pressure fields. Dogan, E. et al. (2019) employed PIV to study statistical properties of turbulent boundary layers under varying mainstream conditions, focusing on coherent structures. Wang, K. et al. (2020) applied time-resolved PIV to track the dynamic behavior of coherent structures within boundary layers. Wei, K. et al. (2015) combined hot-wire anemometry and PIV to investigate interactions between secondary flows and developing turbulent boundary layers in rotating square channels. Their measurements of mean velocity and wall shear velocity distributions revealed that shear velocity on the suction side first decreases and then increases along the streamwise direction.

(3) DNS Simulations of Boundary Layers

Advances in computational technology have enabled Direct Numerical Simulation (DNS), allowing researchers to resolve flow field details numerically. Busemann, A. (1935), Brainerd, J.G. & Emmons, H.W. (1942), and Crocco, L. (1946) validated compressible flow governing equations through DNS of compressible boundary layers. Yang, Y.T. et al. (2024) systematically reviewed the evolution of BLC from traditional perturbations to novel modifications. They proposed transforming the boundary layer into a low-shear isolation layer to approximate the d’Alembert’s paradox of inviscid flow, thereby optimizing aerodynamic performance with high lift-to-drag ratios and low energy consumption. BLC has proven highly effective in suppressing laminar boundary layer separation. Ramsay, J. et al. (2020) demonstrated via DNS and optimization that boundary layer separation is nearly eliminated at $Re > 600$.

BLC significantly enhances the aerodynamic performance and power generation efficiency of wind turbines. Sadi, S. et al. (2025) used numerical simulations and CFD to address flow separation in fixed-geometry blades under off-design conditions, validating BLC's potential for performance improvement. Ma, C.Y. (2023) showed that BLC suppresses separation and boosts turbine efficiency. Arnold, B. et al. (2018) implemented BLC on industrial wind turbines, achieving 3.6 dB noise reduction and 4.75% total power increase.

In airfoil optimization, Burnazzi, M. et al. (2016) numerically studied internally blown BLC with drooped leading edges. Wen, Q. et al. (2024) demonstrated that internally blown flap BLC enhances lift for amphibious aircraft by energizing the boundary layer, eliminating separation, and expanding the main wing's low-pressure zone. Keller, D. et al. (2015) investigated the impact of propeller slipstreams on longitudinal stability in aircraft using equivalent disk methods.

3.2 Study on ASC Characteristics

(1) Multi-Parameter Optimization of Flow Around a Cylinder Fields

The FIV of cylindrical structures, widely used in engineering, is critical to structural safety. When fluid flows around a cylinder, periodic vortex shedding generates alternating fluctuating pressure fields on the surface. This fluid-induced cyclic loading not only causes structural fatigue but also triggers resonance when the vortex shedding frequency coincides with the structure's natural frequency, amplifying dynamic responses and failure risks (John Armit, 1980). In active flow control, ASC effectively delays flow separation and suppresses vortex generation by actively extracting boundary layer fluid. By modifying the surface flow distribution, ASC demonstrates unique advantages in mitigating VIV and reducing fluctuating load amplitudes.

ASC suppresses cylinder wake vortices. Shi, X.Y. et al. (2021) investigated the effects of suction port position and intensity on cylinder forces and wake vortices at $Re=200$, confirming that the feasibility of ASC depends on these parameters. While ASC alters boundary layer separation to suppress vortex shedding, its VIV control mechanisms and parameter optimization require further exploration. Tang, A.P. et al. (2016) compared ASC with passive suction, finding ASC superior in VIV suppression, especially when suction

devices are deployed near the separation point.

ASC reduces noise and eliminates VIV. Cao, Y. (2013) highlighted that vortex shedding from cylinders induces lift fluctuations and VIV, threatening structures like bridge cables. ASC transforms periodic vortex shedding into parallel shear layers, eliminating shear layer interactions. This raises rear pressure, reduces pressure drag, and diminishes fluctuating pressures. Hu, Z.X. et al. (2020) numerically demonstrated that ASC achieves 37.7 dB noise reduction (vs. 9.5 dB for blowing) when suction slots are placed at $\theta = \pm 110^\circ \sim 122.5^\circ$ with $0.2R$ (radius of the cross-section of a cylinder) depth and 33% mainstream velocity.

ASC enhances aerodynamic performance. Chen, N. Q. (1994) numerically studied ASC in cylinder flow, showing that suction reduces drag and suppresses asymmetric flows in the wake. Ramsay, J. et al. (2019) (2025) found that combining front suction and rear blowing minimizes total drag by lowering pressure resistance and adjusting boundary layer momentum. Non-uniform suction near the separation point outperforms uniform suction in separation elimination and drag reduction.

(2) Airfoil Aerodynamic Enhancement and Dynamic Stall Suppression

Advances in ASC enable effective vortex suppression. Genç, M.S. et al. (2011) noted that blowing control destabilizes reverse flows due to laminar separation bubble breakdown, whereas ASC stabilizes vortex suppression. Moussavi, S. A. et al. (2021) applied suction slots to a 2MW wind turbine blade, reducing flow separation and boosting the power coefficient by 8.1% with minimal structural impact.

ASC boosts airfoil power output. Wang, P. et al. (2022) used RANS simulations to integrate suction slots on an NREL Phase VI turbine, achieving an 18.08% power increase at 10 m/s wind speed under low-to-medium tip-speed ratios. Chawla, J.S. et al. (2014) tested ASC on NACA0012 and S814 airfoils in low-Reynolds wind tunnels, showing significant lift coefficient improvements and boundary layer separation control. Zhang, W.L. (2014) studied ASC on low-aspect-ratio NACA0012 wings, revealing that higher suction coefficients enhance lift-to-drag ratios and reduce drag.

ASC delays dynamic stall. Chen, W.S. et al. (2021)

numerically analyzed ASC strategies for NACA0012 airfoils under dynamic stall at high Reynolds numbers. Their results confirm ASC as an energy-efficient method to suppress dynamic stall, particularly in high-*Re* conditions.

3.3 Study on Synergistic Control Characteristics of Hybrid Suction-Blowing Techniques

Synergistic Control Mechanisms of Hybrid Suction-Blowing Techniques. By reactivating boundary layer flow, hybrid suction-blowing control mechanisms effectively regulate boundary layer separation and delay stall onset under adverse pressure gradients (Greenblatt, D., 2000). The core principle lies in synergistically injecting high-momentum fluid (via blowing) and extracting low-momentum fluid (via suction) to continuously adjust momentum distribution within the boundary layer, thereby delaying flow separation caused by adverse pressure gradients.

(1) Flow Separation Suppression and Noise Reduction via Suction-Blowing Control

As an active flow control method, hybrid suction-blowing (HSB) demonstrates significant suppression of flow separation (Zhao, G.Q. 2015)(Yang, W.H. 2020). Feng, L.H. et al. (2010)(2014) observed that applying HSB through spanwise slits at the front and rear stagnation points of a cylinder creates a virtual aerodynamic shape. This interaction between HSB and the cylinder's shear layer induces a novel wake vortex evolution pattern, transforming alternating vortex shedding into symmetric shedding. Wang, H. et al. (2024) developed a reduced-order flow model using Proper Orthogonal Decomposition (POD) for hybrid underwater glider hydrofoils under steady HSB, revealing that optimized suction/blowing parameters effectively suppress separation.

HSB reduces noise and improves flow field characteristics. Zou, L. et al. (2022) demonstrated that HSB suppresses broadband noise in high-lift devices by actively controlling flow structures within slat cavities, significantly enhancing far-field acoustic performance. Li, D.W. et al. (2016) showed that HSB stabilizes the vorticity and Lamb vector fields in slat cavity shear layers, suppressing secondary separation flows and reducing turbulent kinetic energy, achieving a 24 dB reduction in far-field noise.

(2) Aerodynamic Performance Optimization via Synergistic HSB

HSB significantly enhances aerodynamic efficiency. Mei, Y.F. et al. (2021) reported a 139.62% increase in lift coefficient for a cylinder by combining blowing at the separation point and suction at the front stagnation point, highlighting the sensitivity of boundary layer control to blowing configurations. Zhang, G.Z. (2019) studied HSB on a NACA0012 airfoil using the momentum coefficient C_μ (ratio of blowing/suction momentum flux to freestream momentum). Experimental results under varying Reynolds numbers showed a 123% improvement in lift-to-drag ratio, 43% increase in maximum lift, and 5° delay in stall angle, confirming HSB's efficacy in aerodynamic optimization.

Kornilov, V.I. et al. (2018)(2019) investigated HSB via fine-perforated surfaces on a NACA0012 airfoil at $Re=0.7 \times 10^6$ and angles of attack $\alpha=-6^\circ \sim 6^\circ$. Blowing linearly enhanced lift, while suction reduced drag; their synergy maximized lift-to-drag ratios near zero angles, though excessive blowing increased drag. Sun, Y. et al. (2024)(2024) emphasized HSB's dual benefits: eliminating external airflow requirements and suppressing reverse flow. At $C_\mu=0.01$, HSB increased net power output by 45.68% and thrust by 23.98% under 10 m/s wind conditions (Table.1), with suction suppressing separation and blowing amplifying surface flow adhesion. Frede, A. et al. (2025) employed RANS simulations with the Menter $k-\omega$ SST turbulence model to optimize transonic airfoils via wall-normal HSB, demonstrating reduced total drag, improved aerodynamic efficiency, and potential reductions in aviation CO₂ emissions.

3.4 Aerodynamic Performance Study of Exhaust Turbine Sails

In recent years, ASC has matured and found applications across multiple fields. Among these, exhaust turbine sails, as a key implementation of suction control technology, demonstrate remarkable performance in energy conservation, emission reduction, and aerodynamic enhancement. Cherif, H. et al. (2016) emphasized that innovative turbine sail-based designs hold significant promise in wind energy and marine engineering, though further research and theoretical advancements remain essential.

Table 1. Net output power and thrust resulting from different jet strengths at 10 m/s.
(Data sourced from Reference [67])

| Case number | Free stream velocity (m/s) | C_μ | Net output powe (W) | Increase percentage(%) | Thrust (N) | Increase percentage(%) |
|-------------|----------------------------|---------|---------------------|------------------------|------------|------------------------|
| A1 | 10 | 0.001 | 12661.81 | 23.05 | 1892.66 | 13.77 |
| A2 | 10 | 0.005 | 14551.54 | 41.45 | 2063.85 | 23.75 |
| A3 | 10 | 0.01 | 14972.20 | 45.68 | 2067.45 | 23.98 |
| A4 | 10 | 0.05 | 14660.52 | 42.48 | 2075.63 | 24.62 |
| A5 | 10 | 0.1 | 14274.72 | 38.52 | 2083.80 | 25.07 |
| A6 | 10 | 0.2 | 12432.95 | 20.81 | 2089.74 | 25.50 |

(1) Geometric Parameter Studies of Elliptical Cylinders

The core component of exhaust turbine sails is a rotatable elliptical cylinder. Research on elliptical cylinders not only enables the development of aerodynamic load prediction models for turbine sails but also identifies critical control parameters — such as optimal attack angle ranges and rotational speed thresholds — through sensitivity analysis, providing high-fidelity flow field databases for ASC strategy optimization.

Minor-to-major axis ratio (AR) significantly influences aerodynamic performance. Wu, Y. et al. (2024) numerically investigated the effects of AR and rotation rate on FIV at $Re=100$, revealing that rotating elliptical cylinders exhibit distinct FIV responses compared to circular cylinders. Enhanced wake instability at low rotation rates was identified as the primary driver of increased vibration amplitudes. Li, Y. et al. (2024) conducted 3D large eddy simulations (LES) of elliptical cylinders with $AR=0.6\sim 1.4$ at subcritical $Re=16,000$, showing that increasing AR reduces total and pressure drag coefficients, slightly increases friction drag contribution, and significantly suppresses root-mean-square lift coefficients due to delayed boundary layer separation. Cui, S.N. et al. (2023) used LES to analyze $AR=0.5:1\sim 1:1$ elliptical cylinders, demonstrating that higher AR reduces mean drag and mildly suppresses lift fluctuations while increasing vortex shedding frequency through curvature modulation.

Tilt angle critically affects VIV. Song, M. et al. (2025) numerically studied VIV behavior of elliptical cylinders

at varying tilt angles. Aligning the major axis with the flow ($\theta=0^\circ$) reduced amplitudes by 44.6% and narrowed lock-in ranges, whereas $\theta=30^\circ\sim 90^\circ$ increased amplitudes and expanded lock-in regions. Rotation angle also governs lift and drag coefficients. Luan, Y.L. et al. (2015) found that turbine sail lift coefficients are highly sensitive to elliptical cylinder rotation angles, with optimal performance achieved at $-15^\circ\sim 0^\circ$.

(2) Parameter Optimization of Exhaust Turbine Sails

Suction port location plays a pivotal role in boundary layer separation suppression. Low, H.T. et al. (1991) analyzed the effects of suction zones and flap angles (α) on aerodynamic performance. Suction effectively delays separation, but distant suction ports trigger premature separation, causing abrupt lift loss and drag surge. Flap angles of $\alpha=80^\circ\sim 120^\circ$ minimally affect lift and drag.

Suction port geometry impacts aerodynamic efficiency. Guerri, O. et al. (2016) numerically optimized grid parameters for elliptical sails, showing that ASC enhances lift-to-drag ratios by suppressing vortex shedding and reducing vibration risks. Wider suction grids and increased slot numbers further improve performance.

High Reynolds numbers boost lift coefficients. Sooraj, P. (2018) combined PIV and computational methods to measure drag coefficients of elliptical cylinders across broad Re ranges, linking drag characteristics to flow evolution. Wijianti, E.S. et al. (2013) optimized turbine sail geometries using the K-Omega Two-Scale model, revealing that lift and drag coefficients increase with Re , with superior lift performance at high Re .

Splitter plate design alters flow structures. Hu, Y. et al. (2017) demonstrated that streamlined splitter plates

suppress trailing-edge vortex shedding, stabilize wake fields, and enhance lift coefficients. Optimal plates with aspect ratio=2.0 minimize drag, while poorly streamlined plates promote vortex shedding and drag amplification.

3.5 Summary

This chapter focuses on the active suction control of exhaust turbine sails, systematically describing the characteristics of boundary layer control technology, as illustrated in Figure 4. This technology delays or eliminates boundary layer separation through active suction. For instance, suction applied at specific locations and intensities on cylinder flow can reduce noise and drag. In airfoil applications, it enhances the lift-to-drag ratio. Combined suction and blowing control overcomes the limitations of single techniques, improving the lift-to-drag ratio of airfoils and reducing slat noise.

HSB control overcomes the limitations of single-technique approaches, enhancing airfoil lift-to-drag ratios and reducing slat noise. As a core technology for the low-carbon transition in maritime industries, exhaust turbine sails demonstrate that ASC delays boundary layer separation and suppresses vortex shedding, significantly improving aerodynamic efficiency. This mechanism has been validated in wind turbine and airfoil optimizations.

Research on the aerodynamic performance of exhaust turbine sails focuses on structural parameters and external conditions. Key findings include:

The geometric shape of elliptical cylinders significantly affects lift and drag forces. Splitter plates stabilize flow fields. Higher Reynolds numbers enhance lift performance but require optimized suction intensity. Existing studies have revealed the potential of active suction control in enhancing aerodynamic performance and reducing energy consumption and emissions.

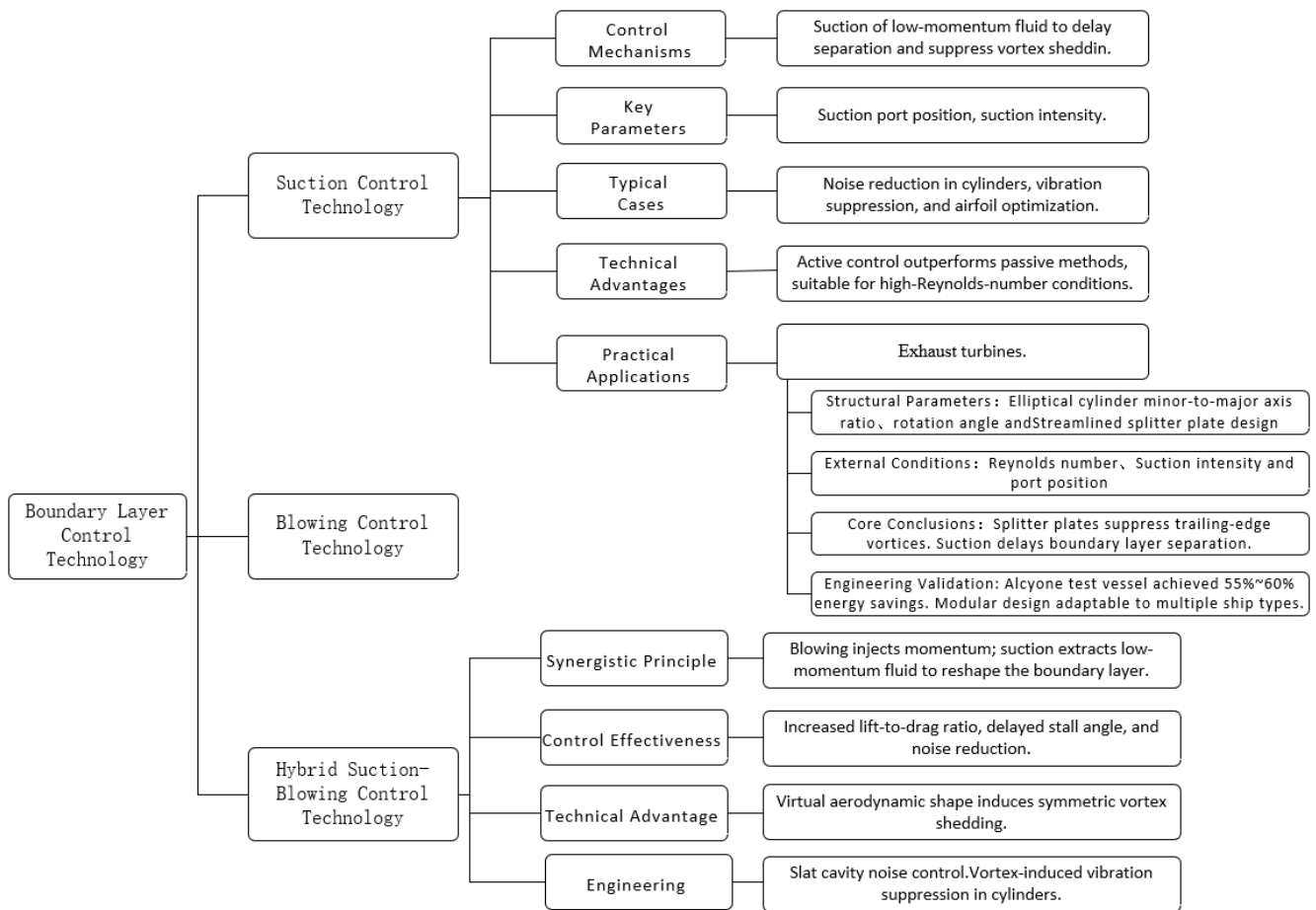


Figure 4. Characteristics of Boundary Layer Control Technology

4. Research Challenges and Future Directions

The aerodynamic performance of exhaust turbine sail faces significant challenges due to complex

marine environmental factors during ship operations. The challenges are systematically categorized into three aspects below, with proposed future research directions.

I. Challenge Analysis

(1) Aerodynamic Performance Fluctuations Induced by Ship Motions

Ship motions (roll, pitch, and heave) driven by wind and waves directly alter the attitude of turbine sails. During roll and pitch motions, the angle of attack (AoA) between the turbine sail's mounting axis and incoming flow periodically fluctuates. When the AoA exceeds a critical threshold, flow separation occurs on the blade surface, accompanied by vortex shedding at the trailing edge. This results in a substantial lift reduction and a sharp drag increase. Dynamic stall hysteresis further induces unsteady stall phenomena, causing aerodynamic losses far exceeding those under steady-state conditions. Heave motion modifies the turbine sail's height relative to sea level. Combined with the logarithmic wind profile near the sea surface, this leads to inlet velocity maldistribution, further degrading turbine sail performance.

(2) Aggravated Flow Losses Due to Non-Uniform Flow Distribution

Coupling effects between ship motions and environmental turbulence markedly increase inflow turbulence intensity, destabilizing the blade boundary layer and amplifying flow losses. Additionally, any deviation between the suction inlet orientation and the incoming flow direction immediately distorts local flow structures. Resultant velocity non-uniformity drastically reduces suction efficiency, severely compromising the turbine sail's propulsion assistance effectiveness.

(3) Performance Instability Caused by Multi-Parameter Coupling Effects

Turbine sail performance depends on multiple interactive parameters (suction characteristics, geometric configuration, inflow conditions, etc.) featuring intricate coupling relationships. Concurrently, severe ship motions induce tilt and vibration in the suction system, triggering flow rate fluctuations. This instability in suction efficiency directly degrades overall turbine sail performance, hindering stable and efficient operation.

II. Future Research Directions

(1) Research on Dynamic Control Strategies Based

on Ship Motion Characteristics

Conduct in-depth studies on ship roll, pitch, and heave motion patterns and their impact mechanisms on turbine sail aerodynamic performance. Develop adaptive dynamic control strategies that monitor real-time ship motion attitudes to dynamically adjust turbine sail angles and suction parameters. This approach minimizes adverse effects on aerodynamic performance, suppresses boundary layer separation, optimizes lift and drag coefficients, and enhances turbine sail stability and efficiency under complex motion conditions.

(2) Development of Flow Field Optimization and Flow Loss Suppression Techniques

Address flow distribution non-uniformity through numerical simulations and experimental investigations to elucidate correlations between flow distortion and losses. Innovate flow optimization technologies—such as specialized flow-guiding devices and optimized suction inlet geometries—to homogenize velocity distribution, reduce inflow turbulence intensity, and stabilize blade boundary layers. These advancements will effectively mitigate flow losses while improving suction efficiency and aerodynamic performance.

(3) Construction of Multi-Parameter Cooperative Optimization Framework with AI-Driven Control

Establish a synergistic optimization framework integrating suction parameters, geometric configurations, inflow conditions, and other variables. Prioritize dual objectives: maximizing lift-to-drag ratio while minimizing energy consumption ratio, utilizing advanced multi-objective optimization algorithms. Concurrently, implement artificial intelligence technologies by deploying multi-sensor networks on turbine sails for real-time environmental/operational data acquisition. AI algorithms will process this data to enable intelligent multi-parameter regulation, precisely monitor operational states, and achieve holistic performance optimization for stable and efficient turbine sail operation.

5. Conclusion

Boundary layer control, as a frontier of multidisciplinary integration, has achieved remarkable progress in aerospace, biomedicine, ship engineering and other fields in recent years. Its core objective is to

realize efficient, safe and intelligent system operation through precise regulation of gas flow and energy conversion. In the field of ship engineering, the research and application of active suction control are evolving from single drag reduction to full-system energy efficiency optimization, which centers on hydrodynamic regulation, energy utilization improvement and environmental protection technology breakthroughs. The rational application of active suction control can improve ship navigation efficiency, reduce resistance, save fuel, lower emissions, decrease noise, enhance stability and extend hull life.

Current studies confirm that the aerodynamic performance of exhaust turbine sails is governed by coupled factors, including the Reynolds number, suction parameters, and structural geometry. Numerical and experimental analyses reveal that the minor-to-major axis ratio and rotation angle of elliptical cylinders critically modulate lift coefficients, while streamlined splitter plates effectively suppress trailing-edge vortex shedding. Active Suction Control in exhaust turbine sail effectively delays or eliminates boundary layer separation, suppresses vortex shedding phenomena, significantly reduces pressure drag, and enhances lift coefficients. Its core mechanism lies in energizing the boundary layer by extracting low-momentum fluid, thereby mitigating adverse pressure gradient effects (as validated by flow field comparisons in Figure 3). Numerical simulations and experimental studies reveal that turbine sail performance exhibits high sensitivity to structural parameters, particularly the elliptical cylinder's geometric characteristics (minor-to-major axis ratio, rotation angle, etc.). A streamlined splitter plate demonstrably stabilizes trailing-edge flow fields and inhibits vortex shedding, yielding higher lift coefficients and lower drag coefficients compared to non-streamlined designs. Full-scale trials aboard the vessel *Alcyone* (Figure 1) further confirm fuel savings of 55%–60% under wind speeds of approximately 25 knots. Current research exhibits the following limitations: aerodynamic performance fluctuations induced by ship motions, aggravated flow losses due to non-uniform flow distribution and performance instability caused by multi-parameter coupling effects.

Regarding the above limitations, future research will prioritize a synergistic optimization framework encompassing multiple variables-including suction

parameters, geometric configurations, and inflow conditions-with the core objectives of maximizing lift-to-drag ratio while minimizing energy consumption ratio. This will be achieved through computational intelligence-driven multi-objective performance optimization using advanced algorithms.

As a key carrier for the green transformation of the shipping industry under the "Double Carbon" strategy, the exhaust turbine sail not only demonstrates environmental value by reducing fuel consumption and carbon emissions, but its high lift-drag ratio characteristics and modular design also bring significant economic benefits to shipping enterprises. With the deep integration of active suction control and intelligent algorithms, the exhaust turbine sail is expected to become the core power unit of future zero-carbon ships, providing an innovative solution for the sustainable development of the global shipping industry.

References

- Tian, C.L., Yang, D. (2022), An Empirical Analysis of the Impact of Transportation Structure on Transportation Carbon Emissions, *Transport Research*, 8(6):10-18,39.
- James, C., Marco, V., Richard, G., et al. (2021), Numerical optimisation of a ship wind-assisted propulsion system using blowing and suction over a range of wind conditions, *Ocean Engineering* 240.
- Zhu, L.Q., Liu, Q.Y. (2024), *Ocean of Opportunities-Special Series on Zero-Emission Transition in Shipping: Overview of Global Shipping Market and Clean Energy Technologies*, Blogger.
- "Data center", (2024), UNCTAD.
- "Fourth IMO Greenhouse Gas Study", (2020), IMO.
- Zuo, W.G., Wang, P.T., Zhang, X.L., Wang, H.Z. (2025), Reform and Practical Exploration of Innovation and Entrepreneurship Education in Port and Shipping under "Double Carbon" Goals, *Tianjin of Navigation*, 1: 68-70.
- Huang, J.S., Mao, B.H., Wu, X.Y. (2023), Research on Carbon Emission Reduction Strategy of China's Transportation Industry under Carbon Neutrality Strategy, *Journal of Beijing Jiaotong University (Social Sciences Edition)*, 22(2):107-116.
- Jiao, Y.Q. (2022), Optimization and Upgrading Ideas of Bulk Carriers Towards Carbon Peaking and Carbon Neutrality Goals, *Journal of Ship Design*, (02): 1-7.
- Jiao, Y. (2025), Current Status and Recommendations of Promoting Integrated Development of Water, Wind, Solar and Sto

- rage Energy Under the “Dual Carbon” Goal, *China Water Resources*, (04):1-6.
- Wijianti, E.S., Wahyudi, I., Setiawan, Y. (2013), Daya Angkatdan Tarik Kapal Barang Menggunakan Turbosasi Dengan Model Simulasi K-Omega Two Scale, *TURBO*, 2(1), 1 – 5.
- Li, S.N., Chang, W.R., Qiao, X. (2024), Analysis of the Current Status and Strategies for the Green Development Model of Liaoning's Marine Economy Under the Background of “Double Carbon” Goals, *Liaoning Economy*, (06):68-72.
- Jin, L. (2025), Direction Adjustment and Implementation Path of Shanghai's Transportation Structure under the “Double Carbon” Goal, *Shanghai Energy Saving*, 03:339-403.
- Florian, E., Bjarne, S., Tobias, S. (2019), Learning in the Financial Sector Is Essential for Reducing Renewable Energy Costs, *Nature Energy*, 4, 835-836.
- Wang, P., Liu, Q., Li, C., Miao, W., Yue, M., Xu, Z. (2022), Investigation of the aerodynamic characteristics of horizontal axis wind turbine using an active flow control method via boundary layer suction, *Renew Energy*, 198:1032 – 48.
- Carter, R.A. (2006), Boat Remains and Maritime Trade in the Persian Gulf During Sixth and Fifth Millennia BC, *Antiquity*, 80(307):52-63.
- Carter, W.E., Carter, M.S. (2010), The Age of Sail: A Time When the Fortunes of Nations and Lives of Seamen Literally Turned With the Winds Their Ships Encountered at Sea, *Navig*, 63 (4):717-731.
- Charrier, B., Constans, J., Cousteau, J-Y., et al. (1985), Foundation Cousteau and Windship Propulsion 1980-1985 system Cousteau-Pechiney, *Journal of Wind Engineering And Industrial Aerodynamics*, 20(1):39-60.
- Luan, Y.L., Hu, Y.H., Li, Z.Q. (2015), Kinetic Analysis of Exhaust Turbine Sails, *Ship Engineering*, 37(02):21-23,49.
- Zhao, B. (2025), Latest Developments in Sail-Assisted Ships, *China Ship Survey*, (01):30-37.
- Guerra, O., Liberge, E., Hamdouni, A. (2016), Numerical Simulation of the Turbulent Flow around an Oval-Sail, *Journal of Applied Fluid Mechanics*, 9(6):2009-2023.
- Shi, X.Y., Sun, J.J., Huang, D.G. (2021), Effects of Boundary Layer Suction on the Structure of Wake Vortex Shedding around a Cylinder and the Force on the Cylinder, *Journal of Engineering for Thermal Energy and Power*, 36(06):63-69.
- Li, F., Wang, Y.Y., Cui, E.J. (1994), Numerical Simulation of Separation Control by Suction, *Acta Aerodynamica Sinica*, 12(1):36-42.
- Prandtl, L. (1928), Motion of Fluids with Very Little Viscosity. Technical Report, NACA-TM-452.
- Blasius, H. (1907), Grenzschichten in Flüssigkeiten mit kleiner Reibung, Druck von BG Teubner.
- von Kármán T. (1911), Ueber den Mechanismus des Widerstandes, den ein bewegter Körper in einer Flüssigkeit erfährt. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse* 1911 (1911): 509-517.
- Ghaemi, S., Ragni, D., Scarano, F. (2012), PIV-based Pressure Fluctuations in the Turbulent Boundary Layer, *Exp Fluids*, 53:1823-1840.
- Dogan, E., Hearst, R.J., Hanson, R.E., et al. (2019), Spatial characteristics of a zero-pressure-gradient turbulent boundary layer in the presence of freestream turbulence, *Phys Rev Fluids*, 4:084601.
- Wang, K., Li, B., Liu, L., et al. (2020), Experimental Measurement of Coherent Structures in Turbulent Boundary Layers Using Moving Time-Resolved Particle Image Velocimetry, *Phys Fluids*, 32:115102.
- Wei, K., Tao, Z., Deng, H.W., et al. (2015), Interaction of Secondary Flow with Developing, Turbulent Boundary Layers in a Rotating Duct. In: *Proceedings of the ASME Turbo Expo 2015: Turbine Technical Conference and Exposition*. Montreal, 1 – 9.
- Busemann, A. (1935), Gasströmung mit laminarer Grenzschicht entlang einer Platte, *Zeitschrift für Angewandte Mathematik und Mechanik*, 15:23-25.
- Brainerd, J.G., Emmons, H.W. (1942), Effect of Variable Viscosity on Boundary Layers, with a Discussion of Drag Measurements, *Journal of Applied Mechanics*, 9: A1-A6.
- Crocco, L. (1946), High-speed wind tunnels. Technical Report. Ohio: Headquarters-Air Force Materiel Command, 1-180.
- Yang, Y.T., Zhu, J.Y., Wu, J.Z. (2024), Boundary Layer Control: from Perturbation to Transformation, *Aerodynamic Research & Experiment*, 2(2):1-35.
- Ramsay, J., Sellier, M., Ho, W.H. (2020), Effects of Boundary Layer Suction Control on Flow Through an Axisymmetric Diverging Channel, *Journal of the Royal Society of New Zealand*, 51(2):389-408.
- Sadi, S., Asayesh, M.R., (2025), Moussavi. Improving Wind Turbine Power with Boundary Layer Suction, *Journal of Applied Fluid Mechanics*, 363-373.
- Ma, C.Y., Xu, H.Y. (2023), Parameter-based Design and Analysis of Wind Turbine Airfoils with Conformal Slot Co-flow Jet, *Journal of Applied Fluid Mechanics*, 16(2):269-283.
- Arnold, B., Lutz, T., Kramer E. (2018). Design of Aboundary

- Layer Suction System for Turbulent Trailing Edge Noise Reduction of Wind Turbines, *Journal of Renewable Energies*, 1(23):249-262.
- Arnold, B., Lutz, T., Krämer, E., Rautmann, C. (2018), Wind-Turbine Trailing-Edge Noise Reduction by Means of Boundary-Layer Suction, *Renewable Energy*, 56:1843-1854.
- Burnazzi, M., Thiemeier, J., Radespiel, R. (2016), Numerical Stall Behavior Investigation of an Aircraft Equipped with Coanda Flap and Droop Nose, Berlin: Springer.
- Wen, Q., Yang, K.Z., Peng, X.C., et al. (2024), Research on the Boundary Layer Control of Inner-blown Flaps, *Aerodynamic Research & Experiment*, 2(05):52-57.
- Keller, D., Rudnik, R. (2015), Numerical Investigation of Engine Effects on a Transport Aircraft with Circulation Control, *Journal of Aircraft*, 52(2):421-438.
- John Armit. (1980), Wind Loading on Cooling Towers, *Journal of the Structural Division*, 106(ST3):623-641.
- Tang, A.P., Tao, S.B. (2016), Experimental Research on Properties of Vortex-Induced Vibration for Cylinders with Suction, *Journal of Huazhong University of Science and Technology (Natural Science Edition)*, 44(02):97-101.
- Cao, Y. (2013), Numerical Study on Flow Control of Flow Around a Circular Cylinder Using Steady Suction Method, Harbin Institute of Technology.
- Hu, Z.X., Liu, H.R., Zhang, R.P., Tong, F. (2020), Numerical Study on Vortex Shedding and Aerodynamic Noise of Circular Cylinder with Blowing/Suction Control, Abstracts of the 11th National Academic Conference on Fluid Mechanics.
- Chen, N.Q. (1994), A Numerical Simulation of Unsteady Separated Flow Around a Circular Cylinder at Suction Boundary Condition, *Acta Aerodynamica Sinica*, 12(3):288-294.
- Ramsay, J., Sellier, M., Ho, W.H. (2019), Non-Uniform Suction Control of Flow around a Circular Cylinder, *International Journal of Heat and Fluid Flow*.
- Ramsay, J., Sellier, M., Ho, W.H. (2025), Passive Fluidic Control of Flow Around Circular Cylinder, *International Journal of Heat and Fluid Flow*, 112:109750.
- Genç, M.S., Kaynak, Ü., Yapici, H. (2011), Performance of Transition Model for Predicting Low Re Aerofoil Flows without/with Single and Simultaneous Blowing and Suction, *European Journal of Mechanics-B/Fluids*, 30:218 - 235.
- Moussavi, S.A., Ghaznavi, A. (2021), Effect of Boundary Layer Suction on Performance of a 2 MW Wind Turbine, *Energy*, 232:121072.
- Chawla, J.S., Suryanarayanan, S., Puranik, B., et al. (2014), Efficiency Improvement Study for Small Wind Turbines Through Flow Control, *Sustainable Energy Technologies and Assessments*, (7):195-208.
- Zhang, W.L. (2014), Suction Control and Its Optimization of Boundary Layer Separation at Low Reynolds Numbers, Nanjing University of Science and Technology, 118.
- Chen, W.S., Sun, X.J. (2021), Influence of Different Suction Strategies on Dynamic Stall Characteristics of Wind Turbine Airfoil, *Journal of Chinese Society of Power Engineering*, 41(7):581-587.
- Greenblatt, D., Wygnanski, I.J. (2000), The Control of Flow Separation by Periodic Excitation, *Progress in Aerospace Sciences*, 36:487-545.
- Zhao, G.Q., Zhao, Q.J., Gu, Y.S., et al. (2015), Experimental Investigation of Synthetic Jet Control on Large Flow Separation of Airfoil During Stall, *Chinese Journal of Theoretical and Applied*, 47(2):351-355.
- Yang, W.H., Chen, W.L., Li, H. (2020), Suppression of Vortex-Induced Vibration of Single-Box Girder with Various Angles of Attack by Self-issuing Jet Method, *Journal of Fluids and Structures*, 96:103017.
- Feng, L.H., Wang, J.J. (2014), The Virtual Aeroshaping Enhancement by Synthetic Jets with Variable Suction and Blowing Cycles, *Physics of Fluids*, 26(1):014105.
- Feng, L.H., Wang, J.J. (2010), Circular Cylinder Vortex-Synchronization Control with a Synthetic Jet Positioned at the Rear Stagnation Point, *Journal of Fluid Mechanics*, 662:232-259.
- Wang, H., Du, X., Hu, Y. (2024), Investigation on the Reduced-Order Model for the Hydrofoil of the Blended-Wing-Body Underwater Glider Flow Control with Steady-Stream Suction and Jets Based on the POD Method, *Actuators*, 13:194.
- Zou, L., Zuo, C.H., Liu, D.W., et al. (2022), Active Flow Control of Wavy Cylinder Based on Steady Blowing and Suction, *Chinese Journal of Theoretical and Applied*, 54(11):2970-2983.
- Li, D.W., Li, G.J., Liu, Y.S. (2016), Airfoil Noise Reduction Using Boundary Layer Control, *Technical Acoustics*, 35(3):23-29.
- Mei, Y.F., Zheng, C., Aubry, N., et al. (2021), Active Control for Enhancing Vortex Induced Vibration of a Circular Cylinder Based on Deep Reinforcement Learning, *Physics of Fluids*, 33(10):103604.
- Zhang, G.Z. (2019), Airfoil Flow Control Using Blowing and Suction, Harbin Institute of Technology.
- Kornilov, I.V. (2018), Control of Turbulent Boundary Layer on a Wing Section by Combined Blowing/suction, *Thermophysics and Aeromechanics*, 25(2):155-167.
- Kornilov, I.V., Kavun, N.I., Popkov, N.A. (2019), Modification of Turbulent Airfoil Section Flow Using a Combined Control

Action, Thermophysics and Aeromechanics, 26(2):165-178.

Sun, Y., Qian, Y., Gao, Y., et al. (2024), Stall Control on the Wind Turbine Airfoil Via the Single and Dual-Channel of Combining Blowing and Suction Technique, Energy, 290:130224.

Sun, Y., Qian, Y., Yu, L., et al. (2024), Investigation of the Wind turbine Aerodynamic Performance via the Combining Blowing and Suction Flow Control, Energy, 307:132505.

Frede, A., Gatti, D. (2025), Investigation of Blowing and Suction for Turbulent Flow Control on a Transonic Airfoil. International Journal of Heat and Fluid Flow, 113:109769.

Cherif, H., Essia, A., Badreddine, K., David, A. (2016), Numerical Prediction for the Aerodynamic Performance of Turbosail Type Wind Turbine Using a Vortex Model, Energy, (109):287-293.

Wu, Y., Huang, Y., Zhao, J. (2024), In-line Flow-Induced Vibration of Rotating Elliptical Cylinders, Journal of Fluids and Structures, 130:104186.

Li, Y., Li, B., Li, T., Zhang, Y. (2024), Numerical Study on the Flow Around an Elliptic Cylinder with Different Aspect Ratios in the Subcritical Regime Using Large Eddy Simulation, Physics of Fluids, 36(1):015154.

Cui, S.N., Jing, H.M., Yu, C.F., et al. (2023), LES Study on Aerodynamic Characteristics and Flow Field of Elliptical Cylinder with Small Aspect Ratio, Proceedings of the 32nd National Academic Conference on Structural Engineering.

Song, M., Li, Y., Guo, S., et al. (2025), Research on Vortex Induced Vibration of Elliptic Cylinder at Different Inclination Angles, Ocean Engineering, 318:120148.

Low, H.T., Luo, S.C., Winoto, S.H. (1991), Flow past a wind-assisted ship propulsion device, Ocean Engineering, 18(6), 555-565.

Sooraj, P., Agrawal, A., Sharma, A. (2018), Measurement of Drag Coefficient for an Elliptical Cylinder, Journal of Energy and Environmental Sustainability.

Hu, Y., Wang, T., Luan, Y. (2017), Numerical Simulation and Kinetic Analysis of Turbine, Journal of Energy and Power Engineering, (11):127-134.

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