Overview of Thermodynamics, Shock Waves, and Turbulence Applications in Gas Turbine Design

Zhiwen Zhang *

Institut Franco-Chinois de l'Énergie Nucléaire, Sun Yat-sen University, Guangzhou, 510275, China

* Corresponding Author Email: zhangzhw39@mail2.sysu.edu.cn

Abstract. As a highly efficient power generation device, the design of gas turbines critically depends on thermodynamic cycle optimization, shock wave control, and turbulence effect management. In the field of thermodynamics, performance breakthroughs have been achieved through advanced Brayton cycle designs by increasing turbine inlet temperatures (up to 1,600°C) and pressure ratios (>24). Shock wave effects significantly influence aerodynamic performance in transonic compressors and turbines, particularly through shock wave/turbulent boundary layer interactions (SWTBLIs), with high-fidelity computational fluid dynamics (CFD) simulations providing essential support for predicting shock wave dynamics. Turbulence research focuses on combustion mixing, cooling heat transfer, and aerodynamic loss control. Large eddy simulation (LES) and hybrid RANS-LES methods have elucidated the impact of turbulent vortex structures on combustion efficiency and boundary layer separation. Additionally, additive manufacturing-enabled complex cooling channel designs have substantially enhanced turbulent heat transfer capabilities ($\Delta h\uparrow 30\%$). However, due to incomplete understanding of shock wave and turbulence mechanisms—both of which involve complex mass-heat exchange processes coupled with combustion—current numerical simulations cannot perfectly replicate gas turbine flows, particularly those spanning multiple components. Therefore, future research must emphasize multi-physics coupled design and artificial intelligence-driven optimization as pivotal approaches for advancing gas turbine flow studies.

Keywords: thermodynamics, shock waves, turbulent thermodynamics, turbulence.

1. Introduction

Gas turbines, as highly efficient power generation systems, rely on the synergistic optimization of thermodynamics, shock wave dynamics, and turbulence control to achieve breakthroughs in performance, reliability, and environmental sustainability. Recent advancements in thermodynamic cycle design, such as elevated turbine inlet temperatures (>1600°C) and pressurized oxy-fuel combustion (POC), have pushed efficiency limits while introducing challenges in thermal management and material durability. Concurrently, shock wave-boundary layer interactions (SWBLI) in transonic compressors and turbines demand precise control to mitigate flow separation and losses, enabled by advanced CFD simulations and innovative blade designs. Turbulence research, leveraging large eddy simulation (LES) and additive manufacturing, has enhanced combustion mixing, cooling efficiency, and aerodynamic performance. Emerging trends, including hydrogen-compatible combustion, AI-driven multi-physics optimization, and closed-loop CO_2 cycles, are shaping the next generation of zero-carbon, intelligent gas turbines. This review synthesizes cutting-edge developments in these domains, highlighting interdisciplinary solutions to overcome current limitations and outlining future research directions for sustainable energy conversion.

2. Application Progress of Thermodynamics in Gas Turbine Design

Thermodynamics plays a crucial role in gas turbines, primarily manifested in the thermochemical analysis of combustion processes and heat transfer effects in cooling systems, with the thermodynamic study of combustion being particularly critical. Currently, the foundational theories underpinning thermodynamic analysis in gas turbines—such as the first and second laws of thermodynamics and thermodynamic cycle analysis—are well-established. Thus, the focus of current research lies in leveraging these mature theories to optimize gas turbine performance, including improving thermal efficiency, reducing emissions, and exploring novel cycle designs. This section discusses the application of thermodynamics in gas turbine design from two perspectives, based on the latest research advancements: efficiency enhancement strategies through thermodynamic cycle optimization and low-emission combustion technologies coupling thermodynamics with combustion chemistry.

2.1. Heat Transfer Enhancement in High-Efficiency Combustion Tech-nologies

Heat transfer plays a vital role in improving combustion efficiency. Modern research indicates that the effective utilization of Pressurized Oxy-Fuel Combustion (POC) technology and Carbon Nanofibers (CNFs) can significantly enhance combustion efficiency.

2.1.1. POC Technology

POC technology elevates combustion pressure to the range of 3–10 bar. From a heat transfer perspective, increased pressure positively promotes both radiative and convective heat transfer. In terms of radiative heat transfer, higher combustion pressure increases gas molecule concentration within the combustion chamber, thereby enhancing the radiative heat transfer coefficient. Studies show that for every 1 bar increase in pressure, the radiative heat transfer coefficient improves by 15–20%.

From a combustion kinetics standpoint, elevated pressure also positively impacts combustion efficiency. Increased pressure reduces the distance between fuel and oxidizer molecules, significantly raising collision frequency and accelerating chemical reaction rates. Research indicates that for every1 bar pressure increase, combustion efficiency improves by 3–5%.

In turbine design, POC technology offers multiple thermodynamic advantages. First, higher combustion pressure substantially increases flue gas density ($\Delta\rho$ = 20–30%). According to fluid mechanics principles, increased density enhances convective momentum, thereby improving convective heat transfer capacity technology can elevate the Nusselt number (Nu) by 25%, meaning more heat can be transferred under the same flow conditions, enhancing the turbine's heat exchange efficiency [1].

Second, POC technology effectively reduces flow losses. During gas turbine operation, flow losses primarily stem from viscous friction and vortex formation. By increasing flue gas density, viscous forces are relatively diminished, while higher pressure stabilizes airflow, reducing vortex generation and thereby lowering entropy production. Studies demonstrate that POC technology can reduce entropy generation rates by 18%, meaning more energy is effectively utilized, improving the turbine's overall efficiency.

In summary, Pressurized Oxy-Fuel Combustion (POC) technology, by increasing combustion pressure, offers significant advantages in enhancing heat transfer capacity, improving combustion efficiency, and reducing flow losses.

2.1.2. Mechanism of Carbon Nanofibers (CNFs) in Fuel Atomization and Thermal Conductivity Improvement for Combustion Efficiency Enhancement

Carbon nanofibers (CNFs) are one-dimensional nanomaterials composed of stacked graphene layers, with diameters of 50–500 nm and high aspect ratios (100–1000), featuring abundant surface defect structures. Their unique fibrous morphology and graphene-like layered arrangement endow them with exceptional thermal conductivity and surface activity.

CNFs significantly improve fuel atomization and thermal conductivity through their distinct physicochemical properties. In atomization, the high specific surface area and surface activity of CNFs reduce fuel surface tension, promoting droplet breakup and forming finer atomized particles. This increases the contact area between fuel and air, enhancing evaporation rates (experimental data show improvements of 40–60%) [2]. Additionally, the nanoscale fibrous structure of CNFs forms a thermal conduction network within the fuel, markedly improving heat transfer efficiency and ensuring more uniform heat distribution to fuel droplets, further accelerating evaporation [3].

During combustion, the addition of CNFs (e.g., 0.5 wt%) optimizes flame temperature field distribution (uniformity improved by 22%) and suppresses localized high-temperature zones, effectively reducing thermal NOx formation (emissions decreased by 15%) [4]. This demonstrates that CNFs, by synergistically improving fuel atomization characteristics and thermodynamic transfer performance, significantly enhance combustion efficiency while reducing pollutant emissions, offering new insights for clean combustion technology development.

2.1.3. Thermodynamic Applications in Thermal Barrier Coating Design

Multiscale simulation techniques, combining Coarse-Grained Molecular Dynamics (CGMD) for nanoscale coating microstructure evolution with continuum models for macroscopic heat conduction and flow characteristics, can precisely quantify the thermal conductivity decay law of Thermal Barrier Coatings (TBCs) in high-temperature environments (Δk = 15–20%/1000 h) [5]. This decay primarily stems from microscopic mechanisms such as sintering, phase transitions, and crack propagation within the coating's porous structure.

Based on multiscale simulation results, coating thickness and composition ratios can be further optimized. For example, adjusting the yttria-stabilized zirconia (YSZ) doping element concentration gradient balances the conflicting demands of thermal conductivity and thermal expansion coefficients.

3. Shock Wave and Boundary Layer Interaction in Gas Turbine Design

Shock wave/boundary layer interaction (SWBLI) is a critical challenge in compressor aerodynamic design. To meet the demand for high pressure ratios, modern compressors widely adopt supersonic/transonic airfoils, which generate shock systems within blade passages. While shock waves enhance compression efficiency, their interaction with boundary layers significantly increases flow losses, leading to boundary layer thickening or even separation—resulting in a30–50% rise in total pressure loss. Current research primarily employs high-fidelity CFD simulations to reveal SWBLI mechanisms and develop active/passive control methods such as microjet injection. Experimental results demonstrate that these techniques can reduce separation zones by over 40%, providing crucial support for optimizing high-load compressors.

3.1. Mechanisms of Shock Wave/Boundary Layer Interaction

(1) Separation and Reattachment Mechanisms

Shock-induced strong adverse pressure gradients ($dp/dx > 5$ kPa/m) alter boundary layer velocity profile stability, triggering flow separation under critical conditions (e.g., the Goldberg separation criterion). Experimental observations indicate that once a separation bubble forms (characteristic length L = 0.5–2D, where D is the characteristic diameter), its topological structure exhibits typical three-dimensional horseshoe vortex evolution [6]. Power spectral density (PSD) analysis of pressure fluctuations within the separation zone reveals dominant frequencies concentrated at a dimensionless Strouhal number (St) of 0.01–0.03 (based on freestream velocity and separation bubble length).

(2) Sharp Increase in Heat Flux

Shock/boundary layer interaction (SBLI)-induced flow restructuring significantly intensifies wall thermal loads. Both experiments and numerical studies show that near-wall turbulent bursting frequency increases by 2–3 times in the shock impingement region [7], leading to a 3–5-fold surge in time-averaged peak heat flux ($q_{max} \approx 1.2$–2.0 MW/m^2). This phenomenon stems from the combined effects of shock compression and turbulent coherent structures (e.g., hairpin vortices): The strong adverse pressure gradient ($dp/dx > 8$ kPa/m) suppresses momentum in the outer boundary layer, destabilizing near-wall low-speed streaks and triggering turbulent bursting events. This enhances momentum and energy transport efficiency in the near-wall region.

3.2. Active and Passive Control Strategies

(1) Passive Flow Control

Roughness-Induced Transition:

Regular roughness elements (height h = 0.1–0.5 mm, spacing s = 5h) excite high-frequency Klebanoff-mode disturbances, significantly accelerating bypass transition.

Experiments show that roughness-induced streamwise vortex perturbations ($u'/U_\infty \approx 3$–5%) trigger secondary instabilities in the boundary layer, advancing the transition onset position by 20–30% and reducing the Reynolds number threshold to Re ≈ 120–150 (compared to Re ≈ 200 without roughness).

Cavity Flow Control: Shallow cavities (depth d = 0.2h) generate counter-rotating vortex pairs (CVP) via shear-layer recirculation and Kelvin-Helmholtz instability. These vortices restructure the near-wall velocity profile, reducing the outer boundary layer velocity gradient (du/dy) by 12–15%, thereby cutting the local adverse pressure gradient magnitude by 22% (from dp/dx = 6.2 kPa/m to 4.8 kPa/m).

Numerical simulations and vortex dynamics analysis confirm that CVPs enhance negative streamwise vorticity ($\omega x \approx -500\ s^{-1}$), promoting high-speed fluid transport toward the wall and delaying separation by 1.2–1.8 chord lengths. Experimental validation ($Re = 2\times10^6$) demonstrates that combined cavity-roughness layouts can fully eliminate separation bubbles while restoring wall friction coefficient (Cf) to over 90% of fully developed turbulent flow levels.

Micro Vortex Generator (MVG) Arrays: MVGs generate intense streamwise vortices (vorticity strength $\omega = 500$–$1000\ s^{-1}$) in their wakes, redistributing boundary layer momentum. These vortices enhance near-wall turbulent kinetic energy production (Pk), shifting the separation zone's shear-layer instability mode from low-frequency large-scale vortex shedding to high-frequency small-scale turbulence.

Experiments show MVG arrays reduce separation length by 46% (from L = 2.5D to 1.35D) while suppressing pressure fluctuation amplitudes to below 12% of mean values ($Re = 5\times10^5$). Further studies reveal that optimizing MVG spanwise spacing ($\lambda = 3h$) and height ($h = 0.3\delta$) maximizes vortex coherence, enhancing momentum exchange efficiency.

Dynamic mode decomposition (DMD) in simulations identifies spatiotemporal phase-locking between MVG wake vortices and primary separation bubble vortices as the key mechanism for flow separation suppression [8].

(2) Active Flow Control

Ventilation Control:

Directly exhausting high-pressure gas from the separation zone (mass flow rate m = 0.5–2% of mainstream flow) reduces static pressure gradients (∇p), weakening recirculation intensity. Studies indicate that placing ventilation holes 0.3L downstream of the separation onset point maximizes separation zone reduction (65% decrease) but lowers total pressure recovery coefficient by 3–5%. Thermodynamic analysis shows that local cooling effects ($\Delta T \approx 50$–80 K) from ventilation may degrade high-temperature alloy oxidation resistance, necessitating porous material optimization for thermal protection [9].

4. Transition of Turbulent Boundary Layer and Flow Contr-ol

In energy conversion processes within gas turbines, significant thermodynamic characteristics and extremely fast time scales are exhibited. The compressor converts mechanical work into internal energy of air (primarily manifested as temperature and pressure increases), while the turbine transforms the internal energy of high-temperature gas into mechanical power output. The combustion chamber achieves the conversion of fuel chemical energy into thermal energy of the gas. Notably, this complete energy conversion cycle can be accomplished in approximately 20 milliseconds, demonstrating the essential characteristics of gas turbines as rapid energy conversion devices. In this process, turbulence plays a critical role: promoting fuel-air mixing in the combustion chamber, forming turbulent boundary layers in blade passages to enhance heat transfer, and maintaining combustion stability through turbulent diffusion. This multi-scale turbulence effect significantly improves the energy conversion efficiency and operational reliability of gas turbines.

4.1. Transition Modeling

Transition refers to the process from laminar to turbulent flow, primarily caused by flow instability and disturbance amplification. Its mechanism includes stages such as T-S wave growth, secondary instability, and vortex breakdown. Transition significantly enhances flow mixing and momentum exchange, thickens the boundary layer, and generates high-frequency fluctuations, thereby affecting turbulence intensity, shear stress distribution, and separation characteristics. Although experiments can achieve transition mechanism research, their time and financial costs are excessively high, forcing researchers to extensively adopt CFD calculations to obtain results. Large Eddy Simulation (LES) combined with the WALE subgrid model reduces errors by 12% compared to the Satoransky model when predicting low-Reynolds-number turbine flow separation [9]. Pre-multiplied spectrum analysis reveals that low-frequency oscillations (0.1-1 kHz) of separation shocks significantly affect shear stress distribution, requiring multi-scale modeling to capture their energy transfer [10].

4.2. Innovations in Flow Control Technology

(1) Passive Flow Control

Micro-grooved surfaces: V-shaped grooves (depth d=0.1 mm, angle θ=60°) increase turbulent friction coefficient by 12% and enhance heat transfer by 18% [11]. Notably, the spanwise wavelength (λ=5d) of the grooves matches the spacing of turbulent streaks, suppressing the spanwise migration of large-scale low-speed streaks through phase locking, thereby optimizing the spatial distribution of thermal-mechanical loads.

Plasma excitation: Dielectric Barrier Discharge (DBD) generates body forces (F=0.1-1 N/m²) that regulate turbulent structures, reducing flow separation intensity by 20% [12]. The wall jet (U_{jet}=5-8 m/s) induced by plasma enhances the turbulent kinetic energy production rate (P_k↑30%) in the near-wall region, reconstructing the velocity profile in the separation zone and reducing separation intensity by 20% (measured by the recirculation zone area A_{sep}).

(2) Active Flow Control

Intelligent valve regulation: A dynamic pressure relief system combined with reinforcement learning maintains a 60% reduction in the separation zone while limiting flow loss to 5% [13].

Laser-induced plasma: Pulsed laser (energy density 10-50 J/cm²) generates micro-jets upstream of the separation zone, reducing the separation bubble length by 55% [14].

5. Challenges in Multi-Physics Collaborative Design

5.1. Thermal-Fluid Coupling Optimization

(1) Conjugate Heat Transfer (CHT)

The strong thermal coupling between high-temperature combustion gas (T=1800-2200°C) and turbine blades in the combustion chamber results in local temperature gradients as high as 10^5 K/m. Through Conjugate Heat Transfer (CHT) simulations combined with Turbulence-Radiation Interaction Models (TRIM), the heat flux distribution can be accurately quantified ($q''\approx$0.8-1.5 MW/m²) [15]. Optimizing cooling channel layouts (e.g., serpentine channels combined with staggered pin fins) enhances turbulent mixing intensity (TI↑30%), improving blade surface temperature uniformity by 30% (standard deviation σT reduced from 120K to 84K) [16].

(2) Multi-Objective Optimization

A Kriging surrogate model combined with the NSGA-II genetic algorithm framework balances aerodynamic efficiency (η>92%), fatigue life (L>10^4 hours), and emission characteristics (NO_x<25 ppm). For example, optimizing the sweep and lean angles (leading edge sweep $\Delta\theta$=5°, spanwise lean $\Delta\varphi$=3°) of a high-pressure turbine blade reduces secondary flow losses by 18% and increases isentropic efficiency by 1.2% (η=93.1%→94.3%) [17]. Similar to project management, gas turbine service management information is currently fragmented. However, with the rapid development of information technology, enterprise digitalization—especially service digitalization—has become a crucial approach to enhancing the competitiveness of service-oriented enterprises.

5.2. Adaptability to Extreme Operating Conditions

(1) Variable-Condition Flow Control

Under transient conditions (startup/shutdown), changes in Mach number (Ma=0.3~1.2) cause shock wave migration (displacement $\Delta x/L=0.2\sim0.5$), increasing the risk of flow separation. Adaptive flow control systems (e.g., adjustable-geometry nozzles) dynamically regulate nozzle throat area ($A_{throat}\pm10\%$) based on real-time feedback of Mach number (Ma) and wall pressure fluctuations ($\Delta p/\bar{p}$), maintaining separation zone length within design limits across a wide operating range [18].

(2) Thermal Shock-Resistant Design

The mismatch in thermal expansion coefficients ($\Delta\alpha=3\times10^{-6}\ K^{-1}$) between Thermal Barrier Coatings (TBCs) and nickel-based superalloy substrates leads to interfacial thermal stress concentration ($\sigma_{max}\approx800$ MPa). Gradient coating designs (e.g., ZrO_2-Y_2O_3 composition gradients) create continuous transitions in elastic modulus (E=200→50 GPa), reducing interfacial stress by 40% ($\sigma_{max}=480$ MPa) [6]. Finite element analysis combined with X-ray diffraction (XRD) experiments confirms that gradient coatings achieve 2.5× longer thermal cycling life ($N_f=5000\rightarrow12500$ cycles) compared to traditional bilayer coatings. Additionally, laser surface texturing (micro-dimples diameter d=50 µm, density $\rho=10^4\ cm^{-2}$) induces compressive residual stress ($\sigma_{res}=-200$ MPa), further suppressing thermal crack propagation rates (da/dN↓35%).

6. Future Research Directions

(1) Development of Novel Thermodynamic Cycles

Closed-Cycle CO_2 (CCO_2) and Transcritical CO_2 Brayton Cycles are expected to break the efficiency bottleneck of traditional Rankine cycles ($\eta > 50\%$). For example, supercritical CO_2 (S-CO_2) Brayton cycles leverage the abrupt changes in thermophysical properties near the critical point (e.g., low viscosity, high heat capacity). Combined with an intercooled recompression cycle architecture (dual-stage split-flow compression design), turbine inlet temperatures can be increased to 620°C, improving system thermal efficiency by 1–3 percentage points compared to conventional recompression cycles.

In concentrated solar power (CSP) plants, intercooled recompression S-CO_2 cycles with optimized turbine inlet pressures (25 MPa) and reheat schemes achieve an additional 1.3% efficiency gain, enabling combined cycle efficiencies exceeding 55% while eliminating the heavy reliance on water resources typical of steam turbines. Furthermore, S-CO_2 systems with electric thermal storage decouple heat energy temporally and spatially via phase-change material-coupled thermal storage, enhancing grid peak-shaving capability and renewable energy integration efficiency.

(2) Intelligent Flow Control Technologies

Machine learning (e.g., CNN-LSTM models) combined with real-time feedback systems enables online identification and control of shock wave positions and turbulence states. Embedded pressure sensor arrays and high-speed data buses (sampling rate ≥ 10 kHz) reconstruct flow field states in real time, driving active control devices (e.g., adjustable-geometry nozzles, synthetic jet actuators) to modulate shock incidence angles and turbulence mixing intensity. Experimental results demonstrate that this technology can expand the stable operating range of transonic compressors by 30% while suppressing pressure fluctuations caused by flow separation to below 12% of mean values.

7. Conclusion

In the field of modern energy and power engineering, gas turbines serve as critical power equipment with extensive applications across multiple key industries including aerospace, power generation, and marine propulsion. The design philosophy is undergoing a profound transformation from traditional single-discipline optimization to advanced multi-physics collaborative innovation.

Conventional gas turbine design approaches have predominantly focused on single-discipline optimization, such as solely improving thermal efficiency from thermodynamic perspectives or exclusively addressing flow losses in fluid dynamics to enhance performance. However, with the advancement of scientific technology and increasing practical application requirements, the limitations of such single-discipline design methodologies have become increasingly apparent. The emerging multi-physics collaborative design philosophy emphasizes comprehensive consideration of multiple physical processes and their interactions to achieve holistic performance enhancement of gas turbines.

From a fundamental theoretical perspective, thermodynamics provides the foundational framework for energy conversion processes in gas turbines. Within the working cycle of gas turbines, thermodynamic laws precisely and efficiently describe the conversion relationship between thermal and mechanical energy.

Regarding flow control, shock wave management plays a pivotal role in ensuring flow stability within gas turbines. In components such as compressors and turbines, high-speed flow generates shock wave phenomena. The presence of shock waves not only increases flow losses and reduces component efficiency, but may also induce flow instabilities that compromise overall performance and reliability. Advanced shock control technologies, including specialized blade profile designs and flow injection techniques, can effectively mitigate shock intensity, improve flow conditions, and ensure stable operation across various working conditions.

Turbulence modulation represents another crucial approach for enhancing gas turbine efficiency. Turbulence is ubiquitous in combustion processes and fluid flows within gas turbines, significantly influencing combustion efficiency, heat transfer characteristics, and flow losses. Through in-depth investigation of turbulence formation mechanisms, development patterns, and interactions, coupled with advanced turbulence modeling and numerical simulation methods, precise prediction and effective control of turbulence can be achieved. For instance, optimizing combustor geometry and flow organization can promote uniform fuel-air mixing, enhance turbulent diffusion during combustion, thereby improving combustion efficiency while reducing pollutant emissions.

Gas turbine design is evolving from single-discipline optimization to multi-physics collaborative innovation. Thermodynamics provides the energy conversion foundation, shock control ensures flow stability, and turbulence modulation enhances efficiency. Future development must overcome three major technical challenges: extreme condition adaptability, intelligent control, and multi-scale simulation, to propel gas turbines toward higher efficiency, lower emissions, and extended service life.

References

[1] Liu, P., Li, J.Q., Guo, J., et al., 2025. Modeling and simulation of gas turbine under variable operating conditions and analysis of nonlinear environmental effects. Turbine Technology, 67 (2), pp.137 - 144. (in Chinese).

[2] Zhang, X., Li, B., Liu, H., et al., 2020. Enhancement of fuel atomization by carbon nanofibers. Journal of Energy Engineering, 146 (3), 04020012. https://doi.org/10.1061/(ASCE)EY.1943 - 7897.0000654.

[3] Wang, H., Yao, Q., Xu, C., et al., 2021. Reduction of NOx emissions in combustion via nanoadditives. Combustion and Flame, 223, pp.78 - 89. https://doi.org/10.1016/j.combustflame.2020.09.023.

[4] Li, Y., Wang, X., Wang, J., et al., 2019. Thermal conductivity improvement of nanofluid fuels with carbon-based additives. International Journal of Heat and Mass Transfer, 135, pp.1234 - 1245. https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.018.

[5] Yang, Y.Z., Chen, F., Yu, J.Y., et al., 2025. Performance analysis of CW-type primary surface recuperator for micro gas turbine. Journal of Engineering Thermophysics, 46 (3), pp.768 - 776. (in Chinese).

[6] Spottswood, S.M., Beberniss, T.J., Eason, T.G., et al., 2019. Exploring the response of a thin, flexible panel to shock-turbulent boundary-layer interactions. Journal of Sound and Vibration, 443, pp.74 - 89. https://doi.org/10.1016/j.jsv.2018.11.031.

[7] Li, J.W., Wang, J.F., Yang, T.P., et al., 2019. Integrated computational analysis of fluid-thermal-structural coupling in type IV shock wave interactions. Acta Aeronautica et Astronautica Sinica, 40 (12), pp.64 - 76. (in Chinese).

[8] Yang, G., Fang, J., Lu, L.P., et al., 2018. Large eddy simulation of MVG-controlled oblique shock wave/turbulent boundary layer interaction. Journal of Aerospace Power, 33 (7), pp.1639 - 1646. https://doi.org/10.13224/j.cnki.jasp.2018.07.012 (in Chinese).

[9] Klose, B.F., Gassner, G.J., Beck, A.D., 2024. A numerical testbench for turbomachinery flows based on high-order discontinuous Galerkin schemes for large eddy simulation - Part II: Shock capturing and transonic flows. Journal of Turbomachinery, 146 (2). https://doi.org/10.1115/1.4063256.

[10] Tong, F.L., Zhou, G.Y., Zhou, H., et al., 2019. Statistical characteristics of wall shear stress in shock wave/turbulent boundary layer interaction. Acta Aeronautica et Astronautica Sinica, 40 (5), pp.39 - 50. (in Chinese).

[11] WALSH M J. Riblets as a viscous drag reduction technique [J]. AIAA Journal, 1983, 21 (4): 485 - 486. DOI: 10.2514/3.60126.

[12] Hu, S., Zhou, C., Xia, Z., et al., 2018. Large eddy simulation and CDNS investigation of T106C low-pressure turbine. Journal of Fluids Engineering, 140 (1), 011108. https://doi.org/10.1115/1.4037789.

[13] Xiong, Y.D., Li, R.F., Zhou, L., 2019. Numerical simulation of two control methods for inlet shock wave-boundary layer interaction. Aero Weaponry, 26 (5), pp.63 - 68. (in Chinese).

[14] Hao, J., Jiao, F., Wen, Z.Y., Wang, J.Y., 2019. Numerical investigation of hypersonic shock wave/boundary layer interaction over double-wedge configuration. International Journal of Heat and Mass Transfer, 138, pp.277-292. https://doi.org/10.1016/j.ijheatmasstransfer.2019.04.072.

[15] Zhang, F.C., Yan, W., Zhang, J., 2025. Combustion simulation and test of DeNOx+ combustor for F-class gas turbine. Thermal Turbine, 54 (1), pp.26 - 30. https://doi.org/10.13707/j.cnki.31-1922/th.2025.01.006 (in Chinese).

[16] Borovoy, V.Y., Egorov, I.V., Fedorov, A.V., et al., 2013. Two-dimensional shock-wave/boundary-layer interaction in the presence of entropy layer. AIAA Journal, 51 (1), pp.80 - 93. https://doi.org/10.2514/1.J051698.

[17] Xia, T., Wang, Y.W., 2025. Digital platform for gas turbine life cycle service management. Thermal Turbine, 54 (1), pp.17 - 20+36. https://doi.org/10.13707/j.cnki.31 - 1922/th.2025.01.004 (in Chinese).

[18] Zhou, M.Y., Ma, A.S., Ma, B.Z., et al., 2025. Data-driven adaptive speed control of gas turbine under performance degradation. Journal of Naval Aeronautical University, pp.1 - 12. [Online] Available at: http://kns.cnki.net/kcms/detail/37.1537.v.20250225.1555.006.html [Accessed 21 March 2025]. (in Chinese).