

Shock-Dominated Flow

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This 2024 Special Issue of *Aerospace*, an open-access journal from MDPI, is entitled “Shock-Dominated Flow” and was guest-edited by Dr. He-xia Huang, Professor Hui-jun Tan, and Professor Ye Tian. It comprises 10 articles, primarily focusing on the fluid mechanics and associated flow control methods of shock-dominated flows. These contributions offer new insights into this academic research field.

For high-speed aircraft [1,2], engines [3,4], or missiles [5], the external and internal flow is characterized by shock-dominated flow [6], which determines the aerodynamic performance, practical envelope, and flight range. Specifically utilizing the compression effect of shocks, high-speed engines can decelerate the incoming supersonic/hypersonic flow to a suitable range to match the ramjet or scramjet combustion [7,8]. However, the shock also induces unfavorable drag [9], pressure/thermal load [10], flameout, and even structural failure [11]. Therefore, an efficient flow control method for shock-dominated flow is required [12]. With the development of the aerospace field towards higher speeds, better performance, and more intelligent control [13,14], there is an urgent need to propose related theories, reveal the flow mechanism of shock-dominated flow, and develop some flow control methods to eliminate the accompanying hazard.

This Special Issue publishes recent advances in shock-dominated flow features and flow control methods related to aerospace. The hypersonic inlet is an aerodynamic interface between the aircraft and the engine, which utilizes a series of shocks to compress the incoming flow [8]. Due to the existence of a surface boundary layer, it faces severe shock-boundary layer interactions [15]. Gao et al. [16] numerically studied the transient flow evolution in a hypersonic inlet/isolator under incoming wind shear and found that the cowl-shock-induced separation bubble moved downstream and upstream, with the total pressure recovery coefficients increasing by approximately 10%. Moreover, the wind shear had substantial impacts on the downstream shock train. While the shock train was located near the throat initially, the wind shear may force it to move upstream, resulting in an inlet unstart. Therefore, the operation of a hypersonic inlet/isolator should consider the wind shear effect. When the hypersonic nozzle operated at a low nozzle pressure ratio state, the flow was over-expanded, which induced a shock within the nozzle [17]. Yu et al. [18] numerically analyzed the effect of external flow on the shock-induced separation in a single-expansion ramp nozzle. As the external flow Mach number increased, the internal flow separation experienced a transition from restricted shock separation (RSS) to free shock separation (FSS) and was finally converted to a fully unseparated state. As the separation induced by the shock behaved with some unsteadiness, Wang et al. [19] proposed a dynamic mode decomposition criterion for the spiked-blunt body flow at $Ma = 2.2$. The results showed that using the energy sorting criterion, the dynamic mode decomposition (DMD) method had an advantage in identifying the dominated flow structures of such an unsteady flow. Moreover, they observed that the spiked-blunt flow appeared with multiple dominated frequencies, among which, the primary frequency was 3.3 kHz, originating from the periodic motion of the aftershock.

To control the shock-boundary layer interaction well, several flow control methods have been put forward [12]. Wang et al. [20] proposed a vortex generator with high-frequency oscillation to control the shock wave-boundary layer interaction (SWBLI) in



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the inlet. The “extrusion” and “suction” effects during the oscillation process charged the airflow, which enhanced the momentum exchange. The unsteady numerical results demonstrated that this method effectively suppressed the shock-induced separation, with the separation bubble reduced by 31.76% and the total pressure recovery coefficient increased by 6.4%. Yu et al. [21] proposed a passive flow control method based on micro-serrations; the height of the hair of serration was lower than the thickness of the boundary layer δ . The separation length was able to be shortened by 9.13%, with a leading stair of 0.1δ , a depth of the subsequent serrations of 0.2δ , and a width of 0.05δ . Compared to a vortex generator or a micro-serration, the plasma-based flow control method, as an active flow control method, had a shorter response time, an ability to regulate the control intensity, high levels of injected momentum, and no additional mass loss [22], which has become a hot research topic in recent years [23,24]. Yang et al. [25] utilized surface arc plasma actuators to control the two-stage compression corner shocks–boundary layer interaction. A wind tunnel experiment under Mach number 6.0 was conducted. The experimental results showed that this method could weaken the shock intensity to a certain extent. As the discharging voltage increased from 0.5 kV to 1 kV, the influence range of the hot plume was able to extend from 65 mm to 85 mm. Furthermore, Yang et al. [26] used a 30-channel discharge array to control the shock–boundary layer interaction and shock–shock interaction in a hypersonic double-wedge to reduce the wave drag, thermal load, and pressure load. The Edney V-type shock–shock interaction was effectively controlled, and such an interaction disappeared or was intermittent when the jet plume emerged. Cai et al. [27] used a dielectric barrier discharge plasma actuator to lower the noise level in a Mach 4.0 cavity flow. The delayed detached eddy simulation (DDES) and plasma phenomenological model were built as described in the paper. The results demonstrated that the dielectric barrier discharge (DBD) plasma actuator effectively suppressed the supersonic cavity flow noise by 2.27 dB. The movement of a dominating vortex was changed to affect the maximum noise level.

For the muzzle launch system, owing to the high levels of kinetic energy at the muzzle, a significant shock diffraction phenomenon occurs when the muzzle expels out of the tubes [28,29]. Li et al. [30,31] experimentally and numerically studied transient shock evolution during muzzle jets and their interaction with the confined boundaries. The initial shock–shock collisions were formed, which delayed the evolution of the shocks and multiple reflected shocks. As the adjacent boundaries confined the expansion of the jet, the jet exhibited a circumferential asymmetric shape and induced transverse flow, forming a complex vortical flow. Once the jet approached the ground, the shock and the vortices were intensified, yielding a reflected shock, which increased the flight Mach number of the moving body from 1.4 to 1.6.

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References

1. Küchemann, D. Hypersonic aircraft and their aerodynamic problems. *Prog. Aerosp. Sci.* **1965**, *6*, 271–353.
2. Van Wie, D.M. Hypersonics: Past, present, and potential future. *Johns Hopkins APL Tech. Dig.* **2021**, *35*, 335–341.
3. Zhao, D. Ramjets/Scramjets aerodynamics: A progress review. *Prog. Aerosp. Sci.* **2023**, *143*, 100958.
4. Urzay, J. Supersonic combustion in air-breathing propulsion systems for hypersonic flight. *Annu. Rev. Fluid Mech.* **2018**, *50*, 593–627.
5. Tracy, C.L.; Wright, D. Modeling the performance of hypersonic boost-glide missiles. *Sci. Glob. Secur.* **2020**, *28*, 135–170.
6. Matsuo, K.; Miyazato, Y.; Kim, H.D. Shock train and pseudo-shock phenomena in internal gas flows. *Prog. Aerosp. Sci.* **1999**, *35*, 33–100.
7. Gnani, F.; Zare-Behtash, H.; Kontis, K. Pseudo-shock waves and their interactions in high-speed intakes. *Prog. Aerosp. Sci.* **2016**, *82*, 36–56.
8. Huang, H.; Tan, H.; Li, F.; Tang, X.; Qin, Y.; Xie, L.; Xu, Y.; Li, C.; Gao, S.; Zhang, Y.; et al. A review of the shock-dominated flow in a hypersonic inlet/isolator. *Prog. Aerosp. Sci.* **2023**, *143*, 100952.

9. Ahmed, M.Y.M.; Qin, N. Forebody shock control devices for drag and aero-heating reduction: A comprehensive survey with a practical perspective. *Prog. Aerosp. Sci.* **2020**, *112*, 100585.
10. McQuellin, L.P.; Neely, A.; Currao, G. Considerations for a hypersonic flight test investigating fluid-thermal-structural interactions. In Proceedings of the 23rd AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Montréal, QC, Canada, 10–12 March 2020.
11. Chang, J.; Li, N.; Xu, K.; Bao, W.; Yu, D. Recent research progress on unstart mechanism, detection and control of hypersonic inlet. *Prog. Aerosp. Sci.* **2017**, *89*, 1–22.
12. Huang, W.; Wu, H.; Yang, Y.; Yan, L.; Li, S.-B. Recent advances in the shock wave/boundary layer interaction and its control in internal and external flows. *Acta Astronaut.* **2020**, *174*, 103–122.
13. Rabault, J.; Kuchta, M.; Jensen, A.; Réglade, U.; Cerardi, N. Artificial neural networks trained through deep reinforcement learning discover control strategies for active flow control. *J. Fluid Mech.* **2019**, *865*, 281–302.
14. Ma, Y.; Guo, M.; Tian, Y.; Le, J. Recent advances and prospects in hypersonic inlet design and intelligent optimization. *Aerosp. Sci. Technol.* **2024**, *146*, 108953.
15. Holger, B.; Harvey, J.K. (Eds.) *Shock Wave-Boundary-Layer Interactions*; Cambridge University Press: Cambridge, UK, 2011; Volume 32.
16. Gao, S.; Huang, H.; Meng, Y.; Tan, H.; Liu, M.; Guo, K. Transient Flow Evolution of a Hypersonic Inlet/Isolator with Incoming Windshear. *Aerospace* **2023**, *10*, 1021. [\[CrossRef\]](#)
17. Lv, Z.; Xu, J.; Song, G.; Li, R.; Ge, J. Review on the aerodynamic issues of the exhaust system for scramjet and turbine based combined cycle engine. *Prog. Aerosp. Sci.* **2023**, *143*, 100956.
18. Yu, Y.; Mao, Y.; Yu, T.; Yang, Y.; Xu, S.; Liang, S. The Influence of External Flow Field on the Flow Separation of Overexpanded Single-Expansion Ramp Nozzle. *Aerospace* **2023**, *10*, 958. [\[CrossRef\]](#)
19. Wang, Y.; Xu, J.; Qin, Q.; Guan, R.; Cai, L. Experimental Investigation of the Shock-Related Unsteadiness around a Spiked-Blunt Body Based on a Novel DMD Energy Sorting Criterion. *Aerospace* **2024**, *11*, 188. [\[CrossRef\]](#)
20. Wang, M.; Wang, Z.; Zhang, Y.; Cheng, D.; Tan, H.; Wang, K.; Gao, S. Control of Cowl Shock/Boundary Layer Interaction in Supersonic Inlet Based on Dynamic Vortex Generator. *Aerospace* **2023**, *10*, 729. [\[CrossRef\]](#)
21. Yu, F.; Gao, Z.; Zhang, Q.; Yue, L.; Chen, H. Mitigation of Shock-Induced Separation Using Square-Shaped Micro-Serrations—A Preliminary Study. *Aerospace* **2024**, *11*, 148. [\[CrossRef\]](#)
22. Wu, Y.; Li, Y. Progress and outlook of plasma flow control. *Acta Aeronaut. Astronaut. Sin.* **2015**, *36*, 381–405.
23. Huang, H.-X.; Tan, H.-J.; Sun, S.; Zhang, Y.-C.; Cheng, L. Transient interaction between plasma jet and supersonic compression ramp flow. *Phys. Fluids* **2018**, *30*, 041703.
24. Yang, H.; Liang, H.; Yang, B.; Zong, H.; Li, J.; Zhang, D.; Xiong, Y.; Wu, Y.; Li, Y. Experimental study on the hypersonic double incident shock wave/boundary layer interaction regulated by plasma actuation array. *Phys. Fluids* **2024**, *36*, 066116.
25. Yang, B.; Yang, H.; Zhang, C.; Zhao, N.; Liang, H.; Zhang, D. Experimental Investigation on the Control of Hypersonic Shock Wave/Boundary Layer Interaction Using Surface Arc Plasma Actuators at Double Compression Corner. *Aerospace* **2023**, *10*, 1016. [\[CrossRef\]](#)
26. Yang, B.; Yang, H.; Zhao, N.; Liang, H.; Su, Z.; Zhang, D. Experimental Study on Hypersonic Double-Wedge Induced Flow Based on Plasma Active Actuation Array. *Aerospace* **2024**, *11*, 60. [\[CrossRef\]](#)
27. Cai, H.; Zhang, Z.; Li, Z.; Li, H. Noise Prediction and Plasma-Based Control of Cavity Flows at a High Mach Number. *Aerospace* **2023**, *10*, 922. [\[CrossRef\]](#)
28. Li, Z.; Wang, H.; Chen, C.; Huang, H. Effects of different constrained boundary structures on the evolution of shock waves and vortexes in muzzle jets. *J. Mech. Sci. Technol.* **2023**, *37*, 5239–5249.
29. Qin, Y.; Huang, H.X.; Tang, X.B.; Tan, H.-J.; Li, F.-B. On the double-sided shock diffractions in quiescent and supersonic crossflows. *Phys. Fluids* **2024**, *36*, 016111.
30. Li, Z.; Wang, H. Evolution of Shock Waves during Muzzle Jet Impinging Moving Bodies under Different Constrained Boundaries. *Aerospace* **2023**, *10*, 908. [\[CrossRef\]](#)
31. Li, Z.; Wang, H. Mechanism of Evolution of Shock Wave of Muzzle Jet under Initial Interference and Its Simplified Model. *Aerospace* **2024**, *11*, 381. [\[CrossRef\]](#)

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