EDITORIAL | DECEMBER 03 2025

Guest editorial: Special issue on measurement, modeling and prediction of hypersonic turbulence FREE

Special Collection: Measurement, Modelling and Prediction of Hypersonic Turbulence

Alexander Wagner ; Carlo Scalo

Physics of Fluids 37, 120401 (2025)
https://doi.org/10.1063/5.0302661

Physics of Fluids EDITORIAL pubs.aip.org/aip/pof

Guest editorial: Special issue on measurement, modeling and prediction of hypersonic turbulence

Cite as: Phys. Fluids **37**, 120401 (2025); doi: 10.1063/5.0302661
Submitted: 16 September 2025 · Accepted: 7 November 2025 ·
Published Online: 3 December 2025

Alexander Wagner[1,a] and Carlo Scalo[2]

AFFILIATIONS

[1]High-Speed Configurations, Institute of Aerodynamics and Flow Technology, German Aerospace Center (DLR), Göttingen, Germany
[2]Mechanical Engineering, Purdue University, West Lafayette, Indiana 47907, USA

Note: This paper is part of the Special Topic, Measurement, Modelling and Prediction of Hypersonic Turbulence.
[a]**Author to whom correspondence should be addressed:** Alexander.Wagner@dlr.de

https://doi.org/10.1063/5.0302661

INTRODUCTION

Modern developments in materials science, propulsion, and aerothermodynamics pave the way for hypersonic transport. However, the design of vehicles that operate in the hypersonic regime is challenging. In particular, aerodynamic heating rates enhanced by boundary layer turbulence and thermo-chemical effects significantly challenge the structural integrity of high-speed vehicles. Overly conservative design decisions will increase vehicle mass, drastically reducing the available payload size and deployment options. Despite the challenging effects, turbulent boundary layers are often inevitable or even desired, for instance, in scramjet-relevant applications.

Despite the critical importance of aerothermal heating, significant discrepancies between predicted and measured turbulent aerodynamic heating and drag over high-speed bodies are reported.[13,14,20] These discrepancies warrant an urgent development and improvement of multi-fidelity computational models to enable hypersonic vehicle design and optimization.[9] However, the experimental and numerical database for turbulent flows above Mach 5—critical for predictive model validation—remains exceptionally scarce.[11] The available data are almost entirely restricted to perfect gas flows, leaving a significant gap in our understanding of how high-temperature effects impact turbulence.[19,22]

Ultimately, the guest editors are convinced that progress in the fundamental understanding of hypersonic turbulence can only occur through a synergistic effort among world-renowned scientists in the field. This will improve the state of the art in prediction capabilities and hence allow for a more effective vehicle design from an aerodynamic and, thus, systems perspective.

CONTRIBUTING PUBLICATIONS

The following publications contribute to the Special Issue by focusing on specific problems in the field of hypersonic turbulence, attempting to advance the common understanding.

Flow diagnostics and ground testing

In "An Eulerian-compatible split-cell scheme for piston tracking in high enthalpy flows," the authors aim to improve the operation of free-piston-driven shock tunnels by reducing uncertainties through the introduction of a novel approach to robustly simulate free-piston trajectories of high-enthalpy shock tunnels. Free-piston drivers are often used to create high stagnation temperatures for aerothermodynamic tests.[5,6,10,12] Although traditional Lagrangian methods track piston movement, they struggle with issues like shock-induced discontinuities and grid deformation.

The research article "Significance of the smaller scales for hypersonic turbulent boundary layers with focused laser differential interferometry" investigated FLDI[21] performance in a hypersonic turbulent boundary layer using simulations with both full-scale and spatially averaged direct numerical simulation (DNS) inputs. Full-scale FLDI results suggest that optical axis integration likely leads to lower FLDI amplitudes compared to true point measurements. Spatially averaged simulations highlighted the significance of small-scale structures in FLDI signal roll-off and RMS amplitudes. The study also analyzed FLDI setup parameters.[1,4,18] It confirmed that smaller circular Gaussian beams improve performance over elliptical or uniform-intensity beams. Additionally, the use of distinct differentiation directions offers a potential experimental method for measuring turbulence isotropy scales. These findings are crucial for understanding the dynamics of the hypersonic turbulent boundary layer and for interpreting experimental data.

In "Spatiotemporal correlation of wall pressure fluctuations generated in scramjet inlet," scramjet inlet wall pressure fluctuations, which are a critical aerodynamic load,[24] were investigated. Wind tunnel tests and advanced analysis revealed that acoustic modes cause significant unsteadiness and pressure fluctuations in unstarted inlets, while started inlets are mainly affected by localized random fluctuations. The research clarified the origin and propagation of these oscillations, which are crucial for structural design.

Turbulence modeling

The review article "A review of Reynolds-averaged Navier–Stokes modeling for hypersonic large cone–flares" assesses the status of Reynolds-averaged Navier–Stokes (RANS) predictive capability for hypersonic axisymmetric, flared cone geometries. An in-depth review of the literature on the topic is provided, including relevant developments in the field of RANS for these types of setups. Furthermore, a code-to-code comparison was performed on two large cone–flare geometries for freestream Mach numbers ranging between 5 and 13. The strongly coupled physical phenomena characteristic of hypersonic flow over the cone–flare geometry are known to be challenging for RANS computational fluid dynamics codes,[17] which is confirmed in this work.

In "Evaluating the influence of double curvature (BOLT-2) vs conventional geometries on hypersonic aerothermodynamic effects," the aerothermodynamic performance of the BOLT-2 body[2] is investigated. The results show that BOLT-2 significantly improves the lift-over-drag ratio by 20% at optimal angles of attack and effectively controls boundary layer transition. Critically, BOLT-2's double curvature profile reduces heat flux compared to traditional geometries across various angles of attack while maintaining favorable aerodynamic characteristics.

"Recent developments and research needs in turbulence modeling of hypersonic flows" reports on the recent advances in turbulence modeling for hypersonic applications. The paper covers a range of approaches, from empirical modifications and physics-based formulations to novel data-driven methodologies. The review systematically evaluates current RANS-based turbulence modeling capabilities by comparing eddy viscosity and Reynolds stress transport formulations.[3,23] The aim is to assess their ability to accurately predict engineering quantities, such as separation characteristics and wall heat transfer. The analysis incorporates the latest experimental and direct numerical simulation (DNS) datasets for validation, focusing on two- and three-dimensional equilibrium turbulent boundary layers and shock/turbulent boundary layer interactions on both smooth and rough surfaces. The review also discusses important multi-physics considerations, such as catalysis and ablation phenomena, as well as the integration of conjugate heat transfer considerations into CFD solvers to facilitate efficient thermal protection system design.

Compressible turbulence theory

"Review of shock-turbulence interaction with a focus on hypersonic flow" addresses a key area of study for turbulent flows interacting with shock waves, the canonical shock-turbulence interaction (STI) problem, which examines turbulent flow moving through a normal shock.[16] This contributing paper provides a comprehensive review of canonical linear interaction analysis (LIA) studies. Although most existing research has focused on calorically perfect gases, hypersonic flows often involve chemical and thermal non-equilibrium effects that can significantly alter these interactions.[25] Therefore, the review discusses relevant LIA and CFD studies that account for these high-enthalpy phenomena.

The article "Influence of vibrational and chemical non-equilibrium on velocity gradient and pressure-Hessian fields in compressible turbulence" addresses how vibrational and chemical non-equilibrium affect velocity gradients and pressure-Hessian tensors in high-speed compressible turbulence. Through derivations and direct numerical simulations, the work found that these non-equilibrium effects expedite vibrational relaxation, increase vortical fluctuations while suppressing dilatational ones, and reduce the relative strength of the pressure-Hessian tensor. Chemical mechanisms, more than vibrational or inertial ones, significantly influence these dynamics, underscoring the need for better turbulence closure models for chemical mechanisms in compressible flows.

The study "On the accuracy of compressibility transformations" emphasizes that accurately predicting compressibility transformations in turbulent flows depends on satisfying the equivalence of eddy viscosity below the logarithmic layer.[8] An accurate transformation was achieved by curve fitting incompressible direct numerical simulation (DNS) data for eddy viscosity profiles below the logarithmic layer. This success points to the value of mixing length formulas in the inner region. The study shows that applying these ideas can significantly improve the accuracy of current transformations. Motivated by the effectiveness of these formulations based on eddy viscosity equivalence, a new integral transformation is introduced. Through testing various velocity scale choices, the study confirms the critical role of eddy viscosity equivalence in the accuracy of compressibility transformations.

Thermal management

The article on "Transpiration cooling in hypersonic flow and mutual effect on turbulent transition and cooling performance" studies recent advances in transpiration cooling in hypersonic flows, with Mach numbers ranging from 2 to 7.7. The work emphasizes the complex interaction between the injected coolant film and the boundary layer. For transpiration cooling, experiments were conducted in various hypersonic wind tunnels using flat plate and cone geometries with coolant injected through C/C porous samples. Numerical simulations of the modeled porous injection revealed insights into the receptivity of the boundary layer to coolant injection and its effects on transition and cooling performance. The article provides a summary of key findings and a critical comparative analysis. The conclusions drawn from this work offer potential directions for further research in transpiration cooling, with the aim of developing and optimizing active cooling techniques for future hypersonic vehicles.[7,15]

Summary

The contributions within this Special Issue collectively address a selection of persistent challenges in the modeling and analysis of hypersonic turbulent flows. In addition to an assessment of common turbulence models for complex geometries and the research needs for an advancement, active thermal management strategies in turbulent boundary layers are addressed. These are complemented by fundamental investigations into key physical mechanisms, including shock–turbulence interaction under thermochemical non-equilibrium, the dynamics of unsteady pressure loads in scramjet inlets, and the validity of classical compressibility transformations are presented.

Taken together, these contributions represent important incremental advances on the long road toward the goal of robust, predictive turbulence models for hypersonic high-enthalpy flows, a regime defined by exceptional physical and modeling challenges. The Special Issue underscores that the interplay between simulation, theory, and experiment is the essential methodology required to close identified critical gaps and continue building the capabilities necessary for the design of next-generation hypersonic systems.

ACKNOWLEDGMENTS

We, the guest editors, wish to express our thanks to all the authors who contributed to this Special Issue. We are especially grateful to the members of the NATO AVT-352 Research Task Group, "Measurement, Modelling and Prediction of Hypersonic Turbulence," for their crucial support in this undertaking over the past years.

REFERENCES

[1] Benitez, E., Borg, M., Dungan, S., Brehm, C., and Jewell, J., "Focused laser differential interferometry performance over an axisymmetric model," AIAA Paper No. 2024-1931, 2024.

[2] Berry, S. A., Semper, M. T., Riha, A. K., Mullen, C. D., Reed, H. L., Dufrene, A. T., and Fasel, H. F., "Development of the BOLT-2 roughness experiment for flight," J. Spacecr. Rockets **61**, 1362 (2024).

[3] Bose, S. T., and Park, G. I., "Wall-modeled large-eddy simulation for complex turbulent flows," Annu. Rev. Fluid Mech. **50**, 535–561 (2018).

[4] Camillo, G., Wagner, A., Toki, T., and Scalo, C., "Combined experimental and numerical investigation of a hypersonic turbulent boundary layer by means of FLDI and large-eddy simulations," Aerospace **10**, 570 (2023).

[5] Chan, W. Y. K., Whitside, R. W., Smart, M. K., Gildfind, D. E., Jacobs, P. A., and Sopek, T., "Nitrogen driver for low-enthalpy testing in free-piston-driven shock tunnels," Shock Waves **31**, 541–550 (2021).

[6] Deutsches Zentrum für Luft- und Raumfahrt (DLR), "The high enthalpy shock tunnel Göttingen of the German Aerospace Center (DLR)," J. Large-Scale Res. Facil. **9**, A188 (2024).

[7] Fitt, A., Ockendon, J., and Jones, T., "Aerodynamics of slot-film cooling: Theory and experiment," J. Fluid Mech. **160**, 15–27 (1985).

[8] Foysi, H., Sarkar, S., and Friedrich, R., "Compressibility effects and turbulence scalings in supersonic channel flow," J. Fluid Mech **509**, 207–216 (2004).

[9] Georgiadis, N. J., Yoder, D. A., Vyas, M. A., and Engblom, W. A., "Status of turbulence modeling for hypersonic propulsion flowpaths," Report No. NASA/TM-2012-217277 (National Aeronautics and Space Administration, Glenn Research Center, 2012).

[10] Hannemann, K., Itoh, K., Mee, D. J., and Hornung, H. G., "Free piston shock tunnels HEG, HIEST, T4 and T5," in *Experimental Methods of Shock Wave Research* (Shock Wave Science and Technology Reference Library, 2016), Vol. 9.

[11] Helm, C. M., and Martín, M. P., "Large eddy simulation of two separated hypersonic shock/turbulent boundary layer interactions," Phys. Rev. Fluids **7**, 074601 (2022).

[12] Hornung, H., "Performance data of the new free-piston shock tunnel at GALCIT," AIAA Paper No. 1992-3943, 1992.

[13] Hoste, J.-J. O. E., Gibbons, N. N., Ecker, T., Amato, C., Knight, D., Sattarov, A., Thiry, O., Hickey, J.-P., Hizir, F. E., Köktürk, T., Castelino, N., Viti, V., Roldan, M. A., Qiang, S., Coder, J. G., Baurle, R. A., and White, J. A., "A review of Reynolds-averaged Navier–Stokes modeling for hypersonic large cone–flares," Phys. Fluids **37**(2), 025193 (2025).

[14] Huang, J., Bretzke, J.-V., and Duan, L., "Assessment of turbulence models in a hypersonic cold-wall turbulent boundary layer," Fluids **4**(1), 37 (2019).

[15] Langener, T., Von Wolfersdorf, J., and Steelant, J., "Experimental investigations on transpiration cooling for scramjet applications using different coolants," AIAA J. **49**, 1409–1419 (2011).

[16] Lee, S., "Large eddy simulation of shock turbulence interaction," in *Annual Research Briefs* (Stanford University, 1993).

[17] Morton, S., and Cummings, R., "CFD 2030: Hypersonic modeling & simulation grand challenge," AIAA Paper No. 2024-0683, 2024.

[18] Parziale, N., Shepherd, J., and Hornung, H., "Observations of hypervelocity boundary-layer instability," J. Fluid Mech. **781**, 87–112 (2015).

[19] Raje, P., Parish, E., Hickey, J. P., Cinnella, P., and Duraisamy, K., "Recent developments and research needs in turbulence modeling of hypersonic flows," Phys. Fluids **37**, 031304 (2025).

[20] Roy, C. J., and Blottner, F. G., "Review and assessment of turbulence models for hypersonic flows," Prog. Aerosp. Sci. **42**(7), 469–530 (2006).

[21] Smeets, G., and George, A., "Laser-differential interferometer applications in gas dynamics," Report No. R136/75 (Institute Saint-Louis, 1975).

[22] Smits, A. J., Martin, M. P., and Girimaji, S., "Current status of basic research in hypersonic turbulence," AIAA Paper No. 2009-0151, 2009.

[23] Spalart, P. R., "Detached-eddy simulation," Annu. Rev. Fluid Mech. **41**, 181–202 (2009).

[24] Tan, H., Sun, S., and Huang, H., "Behavior of shock trains in a hypersonic inlet/isolator model with complex background waves," Exp. Fluids **53**(6), 1647–1661 (2012).

[25] Theofilis, V., Pirozzoli, S., and Martin, P., "Special issue on the fluid mechanics of hypersonic flight," Theor. Comput. Fluid Dyn. **36**, 1–8 (2022).