

Compressibility Effects in Near-Wall Turbulence

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Summary for the general public

For more than sixty years, engineers designing aircraft, gas turbines, and rocket engines have relied on a simplifying assumption about high-speed turbulent flow near walls: only changes in mean temperature and density matter, while direct (or intrinsic) compressibility of the turbulent eddies themselves can be ignored. My PhD shows that this assumption—known as Morkovin’s hypothesis—is inaccurate at high Mach numbers. By performing dedicated supercomputer simulations that isolate direct compressibility effects, I discovered that pressure-driven expansions and contractions of fluid near the wall weaken the vortices that drive turbulent mixing. This changes how we predict drag and heat transfer. I developed new scaling laws and engineering models that reduce prediction errors from roughly 40% to below 4%, and implemented corrections in a leading commercial CFD code (ANSYS Fluent). The tools are open source and are already being adopted by researchers worldwide.

Scientific summary

Objectives. Compressible wall-bounded turbulent flows¹ govern the performance and safety of many engineering applications including aerospace vehicles, combustors, turbomachinery, and power-generation systems. These flows involve two distinct effects: *variable-property* effects (mean thermophysical property variations due to heat transfer) and *intrinsic compressibility* (IC) effects, whereby fluid elements change volume in response to pressure fluctuations (Fig. 1). Variable-property effects are well studied; IC effects have been largely neglected, justified by Morkovin’s hypothesis. My thesis revisits this assumption and answers a question posed by Otto Zeman in 1993: *are intrinsic compressibility effects significant in reality, and can they be isolated and verified?*

Methodology. I performed direct numerical simulations (DNS) of fully developed high-Mach-number turbulent channel flows, augmenting the energy equation with an external heat source to maintain approximately uniform mean thermophysical properties and thereby eliminating variable-property effects. This Coleman–Kim–Moser-inspired strategy isolates IC effects unambiguously. Building on the resulting physical insight, I derived a mean velocity transformation (the HLPP transformation), predictive one-dimensional models for skin friction and heat transfer, and compressibility corrections for Reynolds-averaged Navier–Stokes (RANS) turbulence models.

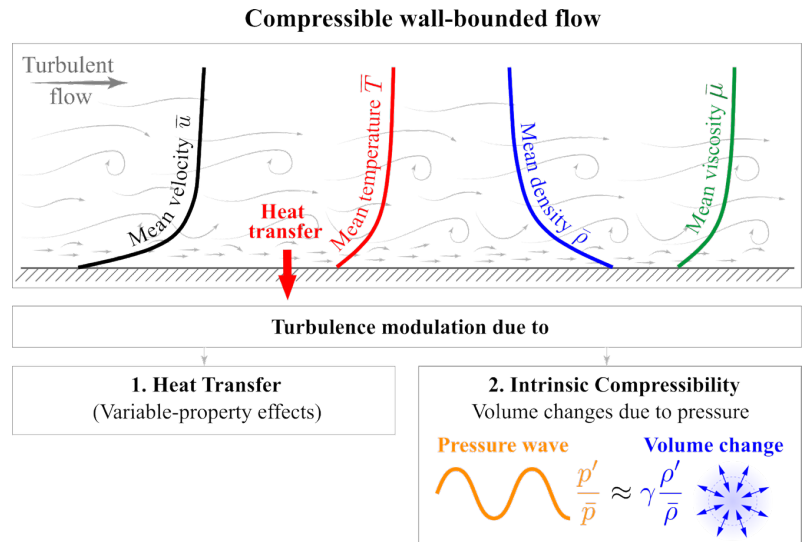


Figure 1: Classification of variable-property and intrinsic compressibility effects in wall-bounded turbulence.

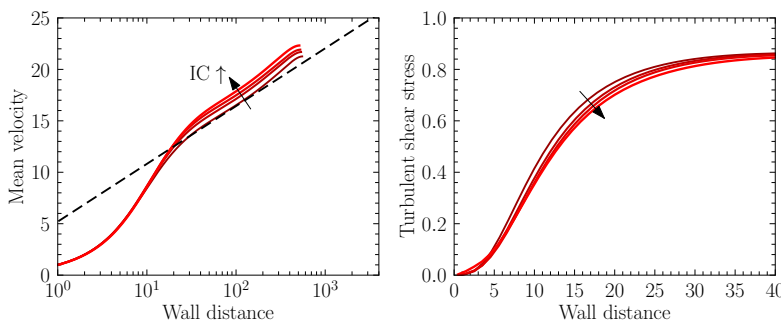


Figure 2: IC effects on mean velocity and turbulent shear stress.

Main results — physics. Increasing IC intensity produces a systematic upward shift in mean velocity profiles and a corresponding reduction in turbulent shear stress (Fig. 2). Because quasi-streamwise vortices near the wall are primarily responsible for turbulent mixing, the reduced shear stress implies weakened vortices. Using a conditional averaging technique (variable-interval space averaging), I traced this weakening to a previously unidentified mechanism: near-wall fluid expansions and contractions, driven by pressure fluctuations associated with sweep–ejection events, generate fluid mo-

¹Turbulent flows near solid walls in which the flow speed exceeds the speed of sound.

tions that spontaneously oppose the vortex-induced flow (Fig. 3). The vortices therefore lose strength, turbulent mixing decreases, and drag and heat transfer are reduced.

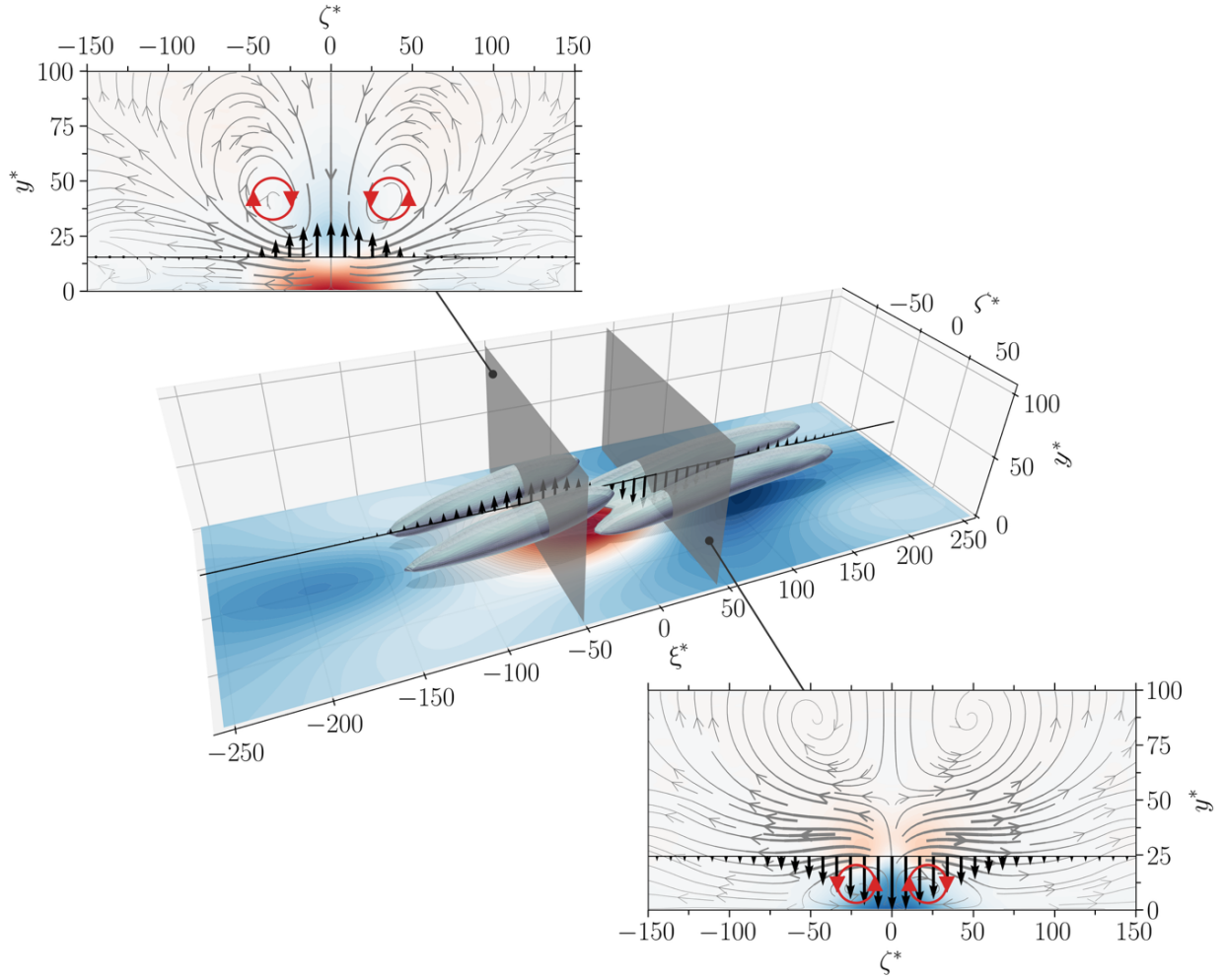


Figure 3: Opposition of near-wall vortices by fluid expansions and contractions.

Main results — modelling and engineering.

The HLPP velocity transformation accounts for both variable-property and IC effects and collapses compressible mean velocity profiles across 70 literature cases—including cooled and adiabatic boundary layers, channel flows, supercritical fluids, and non-air-like fluids—with substantially improved accuracy over the Trettel-Larsson/Patel transformation, especially in the inner layer (Fig. 4). Combining inner-layer scalings derived from this transformation with Van Driest scaling in the outer layer yields full mean velocity and temperature profiles; skin-friction and heat-transfer predictions for 26 boundary layers remain within $\sim 4\%$ and $\sim 8\%$, respectively, compared with errors up to $\sim 40\%$ for state-of-the-art methods (Fig. 5). In collaboration with Florian Menter (ANSYS), I implemented HLPP-consistent corrections to the $k-\omega$ SST model in ANSYS Fluent, achieving significant improvements over the conventional model. All models and user-defined functions are released open source.

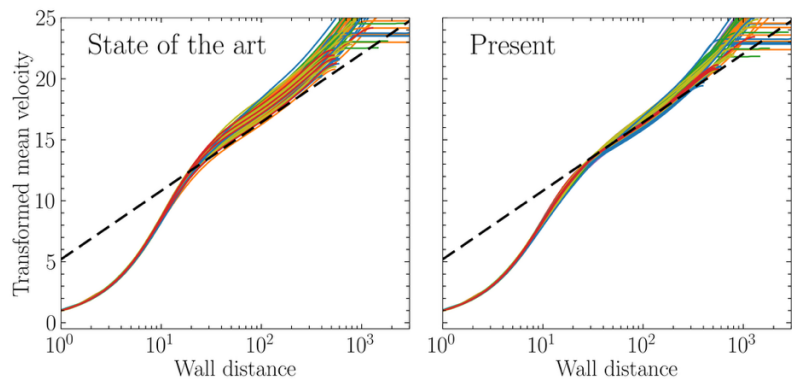


Figure 4: HLPP transformation vs. state of the art (70 cases).

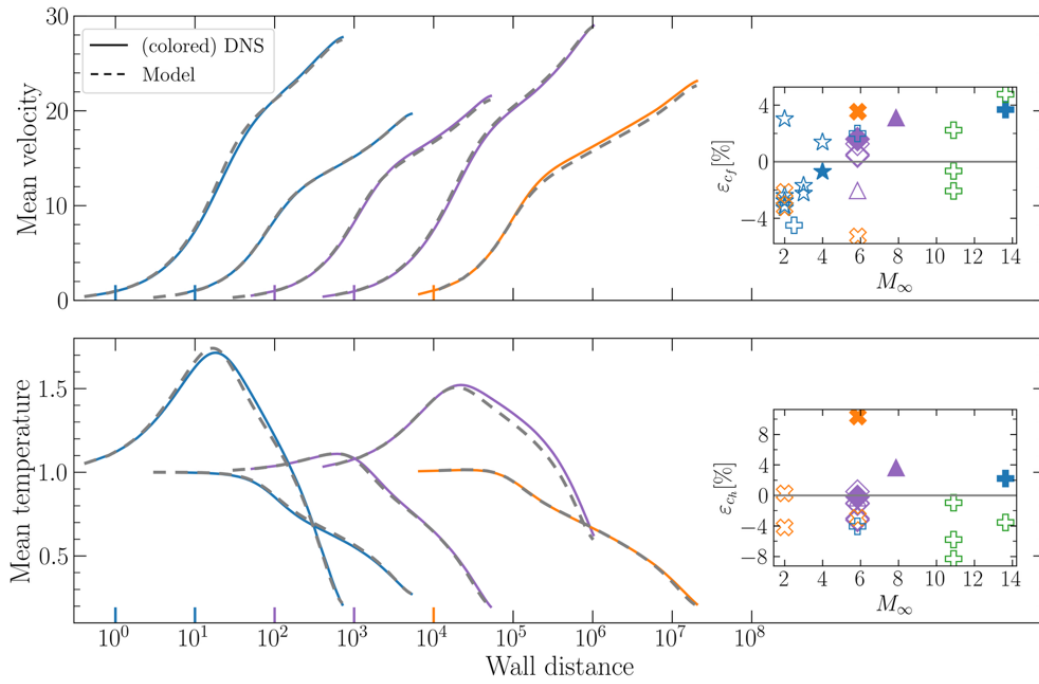


Figure 5: Predicted profiles; wall-flux errors $\lesssim 4\%$.

Novelty, originality, and impact. This work invalidates a cornerstone assumption of compressible turbulence theory (Morkovin’s hypothesis), identifies the physical mechanism underlying compressibility effects, and delivers a coherent modelling framework from DNS to RANS and commercial CFD. The 2023 *Physical Review Fluids* letter was selected as an Editors’ Suggestion. The HLPP transformation is now cited and adopted as a benchmark by independent groups—including Danis & Durbin (Iowa State / Los Alamos) and the Center for Turbulence Research (Stanford)—and serves as the reference for collapsing compressible DNS and experimental data worldwide.

Selected publications (5 of 8 total outputs)

1. A.M. Hasan, J. Larsson, S. Pirozzoli, R. Pecnik, Incorporating intrinsic compressibility effects in velocity transformations for wall-bounded turbulent flows, *Phys. Rev. Fluids* **8**, L112601 (2023) [**Editors’ Suggestion**].
2. A.M. Hasan, J. Larsson, S. Pirozzoli, R. Pecnik, Estimating mean profiles and fluxes in high-speed turbulent boundary layers using inner/outer-layer scalings, *AIAA J.* **62**, 848–853 (2024).
3. A.M. Hasan, P. Costa, J. Larsson, S. Pirozzoli, R. Pecnik, Intrinsic compressibility effects in near-wall turbulence, *J. Fluid Mech.* **1006**, A14 (2025).
4. A.M. Hasan, A.J. Elias, F. Menter, R. Pecnik, Variable-property and intrinsic compressibility corrections for turbulence models using near-wall scaling theories, *J. Fluid Mech.* **1019**, A8 (2025).
5. A.M. Hasan, P. Costa, J. Larsson, R. Pecnik, Scaling of wall pressure and the streamwise turbulence intensity peak in compressible wall flows, *J. Fluid Mech.* **1027**, A26 (2026).

Total research output: six peer-reviewed journal articles (five first-author, one co-author), one invited book chapter, and one PhD thesis (defended 8 October 2025, *cum laude*).