

# Turning Turbulence On and Off: High-Fidelity DNS of Transiently Forced Channel Flows

## Drag Reduction and Thermal Performance in Turbulent Channel Flows with Transient Pumping

**S. R. G. Polasanapalli, H. Schmidt**, *Lehrstuhl Numerische Strömungs- und Gasdynamik, Brandenburgische Technische Universität Cottbus-Senftenberg*

### In Short

- Investigate the impact of transient pressure-gradient forcing on drag, heat transfer, and energy efficiency in turbulent channel flows using three-dimensional direct numerical simulations.
- Systematically assess the influence of pressure-gradient waveforms, forcing time periods, and active pumping phases.
- Provide physical insight into turbulence modulation under time-dependent forcing and generate high-fidelity benchmark data to support the development of energy-efficient flow control strategies.

**Motivation:** Flows in closed channels and pipes are ubiquitous in industrial applications such as oil and gas transport, where frictional losses over long distances lead to substantial pumping power requirements. Drag, commonly quantified by the skin-friction coefficient, depends strongly on the flow regime and Reynolds number. Increasing the Reynolds number results in a lower skin-friction coefficient within the same regime. Nonetheless, turbulent flow regimes generally exhibit higher skin-friction coefficients compared to laminar regimes, indicating greater drag in turbulent conditions. The sizes and operative flow rates in the pipelines are mostly turbulent in nature. Consequently, a large portion of the energy wasted in fluid flows is caused by viscous dissipation. Numerous drag-reduction strategies have been proposed, including surface modifications, polymer additives, and relaminarization techniques; however, many of these approaches require changes to fluid properties or the addition of mechanical components, resulting in increased complexity and maintenance demands.

Recent studies have demonstrated that drag reduction can be achieved by intermittently manipulating the pressure gradient to induce partial or intermittent relaminarization. Scarselli et al. [1] showed that pulsatile pipe flow driven by cardiac-like waveforms can reduce turbulent drag and improve energy efficiency by incorporating rest phases into the

pumping cycle. Similarly, Rota et al. [2] reported energy savings of up to 22% in turbulent channel flows subjected to transient pressure-gradient forcing.

Building on these findings, the present study investigates the effects of transient pressure-gradient profiles on drag, heat transfer, and pumping power in turbulent channel flows. Three-dimensional direct numerical simulations (DNS) will be performed using the open-source solver Xcompact3d [3]. A range of pressure-gradient waveforms, including sinusoidal, step-wise, piecewise-smooth, linear, and cardiac-cycle-inspired profiles, will be examined across different forcing periods and active pumping durations. Particular emphasis is placed on assessing whether drag reduction can be achieved without detrimental impacts on heat transfer, which is critical for applications such as heat exchangers. The results are useful for the development of energy-efficient pumping and thermal management strategies in internal flow systems.

**Numerical Methods:** The proposed study employs three-dimensional direct numerical simulation (DNS) of incompressible turbulent channel flow subjected to transient pressure-gradient forcing. Simulations will be performed using Xcompact3d, a high-order finite-difference solver designed for massively parallel DNS of incompressible flows. The solver employs sixth-order compact schemes for spatial discretization, providing spectral-like accuracy while resolving sharp near-wall gradients.

**Goals:** This study investigates how transient pressure-gradient forcing influences flow dynamics, drag, energy efficiency, and heat transfer in turbulent channel flows. The objectives of the current proposal are listed as below:

- Quantify drag modification and near-wall turbulence response under different transient pumping profiles.
- Assess energy efficiency by evaluating trade-offs between drag reduction and pumping power over complete forcing cycles.
- Analyze heat transfer behavior and near-wall thermal transport under transient forcing.
- Provide high-fidelity benchmark data to support the development and validation of reduced-order models for transiently forced turbulent flows.

**Case Setup and Preliminary Results:** In the present proposal, three-dimensional direct numerical simulations (DNS) of turbulent channel flow will

be conducted to investigate the effects of transient pumping. A time-dependent pressure gradient is imposed in the streamwise ( $x$ ) direction to drive the flow. Periodic boundary conditions are applied in both the streamwise ( $x$ ) and spanwise ( $z$ ) directions, ensuring statistical homogeneity along these directions. The top and bottom walls are maintained at two distinct, constant temperatures, and no-slip boundary conditions are enforced for the velocity field at both walls. Thermal transport is modeled using a passive scalar formulation, enabling detailed analysis of scalar transport and heat transfer characteristics under transient forcing.

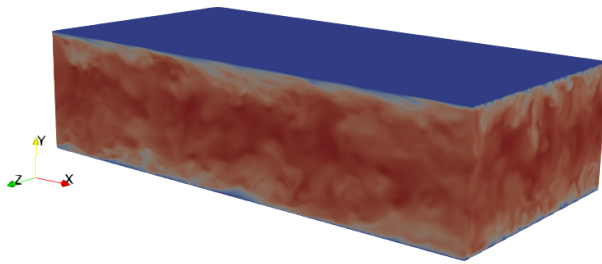


Figure 1: Instantaneous streamwise velocity field.

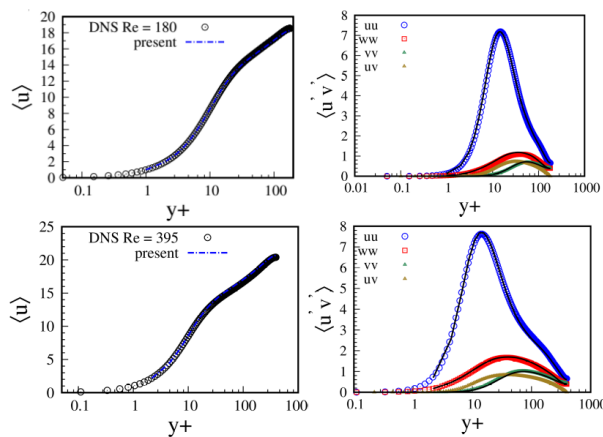


Figure 2: Verification of solver.

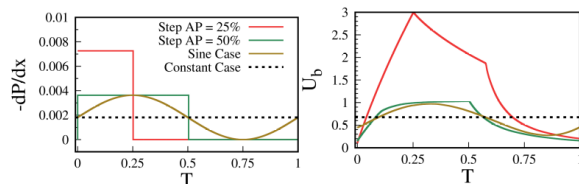


Figure 3: Transient pumping profiles.

Figure 1 presents the instantaneous streamwise velocity field for a turbulent channel flow driven by a constant pressure gradient at  $Re_\tau = 180$ , demonstrating the solver's ability to resolve near-wall and core flow structures. Figure 2 compares the present DNS results with established benchmark

data for constant pressure-gradient channel flows at  $Re_\tau = 180$  and  $Re_\tau = 395$ , showing excellent agreement and thereby validating the accuracy of the numerical implementation. Figure 3 illustrates representative transient pressure-gradient waveforms considered in the proposed study, along with preliminary results highlighting the corresponding temporal evolution of the bulk velocity response.

Through the proposed study, a deeper understanding of the effects of transient pressure-gradient forcing on turbulent channel flow will be achieved, with particular emphasis on drag reduction and heat transfer behavior. The simulations will be conducted at turbulent friction Reynolds number of  $Re_\tau = 180$ . A range of pressure-gradient waveforms will be considered, along with variations in forcing time period and active pumping phase, to quantify their influence on turbulence modulation, energy efficiency, and thermal transport.

WWW

<https://www.b-tu.de/fg-stroemungsmodellierung/>

More Information

[1] D. Scarselli, J. M. Lopez, A. Varshney, and B. Hof, *Nature* **621**, 71–74 (2023). doi: 10.1038/s41586-023-06473-9

[2] G. Foggi Rota, A. Monti, M. E. Rosti, and M. Quadrio, *Scientific Reports* **13**, 1299 (2023). doi:10.1038/s41598-023-28458-2

[3] P. Bartholomew, G. Deskos, R. A. S. Frantz, F. N. Schuch, E. Lamballais, and S. Laizet, *SoftwareX* **12**, 100550 (2020). doi: 10.1016/j.softx.2020.100550

[4] S. R. G. Polasanapalli, M. Klein, and H. Schmidt, *PAMM* **24**(4), e202400183 (2024). doi:10.1002/pamm.202400183

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<https://www.b-tu.de/en/energie-innovationszentrum>

DFG Subject Area

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