Wall Turbulence — overview

Turbulence analysis and modeling are two of the foundational research topics of the Center for Turbulence Research (CTR), and they remain at the core of the activities developed at the center. Even after more than a century, turbulence research is deemed in its infancy by the most critical researchers in the field. And they might be right, although we do possess a crude practical understanding of turbulence, we lack a comprehensive theory capable of providing the accurate predictions demanded by the industry at an affordable computational cost. The elusive nature of turbulence also makes the subject challenging to interpret and model in a field described by Liepmann as "the graveyard of theories". Despite these acute difficulties, technological considerations call for advances in the field, since wall turbulence accounts for 25% of the energy consumed by the industry in moving fluids along pipes, or vehicles through air or water, in addition to the 5% of the CO_2 dumped by mankind into the atmosphere.

During the 2018 CTR Summer Program, the projects dedicated to wall turbulence have contributed to the development of new, groundbreaking ideas in the field. The focus of the group revolves around the common theme of turbulent flows in the presence of bounding surfaces, and 20 scientists from 12 institutions worked for a month at Stanford University. The participants, supported by 13 hosts, tackled problems of fundamental and technological significance, ranging from basic understanding of turbulence to novel control and modeling strategies.

The activities during the Summer Program are naturally divided into two subgroups: analysis of wall turbulence, and non-equilibrium and rough-wall turbulence. The former is concerned with novel approaches for flow reconstruction from limited measurements and flow control. Efficient active control requires the knowledge of the flow at wall distances of the order of the size of the flow structures to be controlled. Jimenéz *et al.* argue that, to be of practical use, reconstruction techniques must comply with the current technological limits for time and length measurements at the wall. They show, using time-resolved channel direct numerical simulation (DNS) data, that wall-attached flow structures can be accurately reconstructed from their shear and pressure footprint at the wall, including flow motions whose sizes are comparable to the boundary layer thickness. The complementary control investigation is done by Farrell *et al.* using the framework provided by statistical state dynamics. In contrast to traditional transition control theory for systems with non-modal growth, the authors propose more efficient control strategies by targeting the first Lyapunov vectors of the perturbed velocity field. They demonstrate that inhibiting this component terminates the dynamic turbulent cycle and favors laminarization of the flow.

The insights accumulated during the last decades on eddy structure are exploited by Yang *et al.* to model the interaction between fluid and electric fields. The problem is especially significant for electrodialysis processes (e.g., purification of brackish water), which are poorly understood in a discipline where numerical simulations have become available only in recent years. The authors apply well-established turbulence methodologies, such as the multifractal formalism and Townsend's attached eddy model for physical understanding and reduced-order modeling. An even more fundamental question stems from the mathematics of turbulence itself and the equations that describe the fluid motion adequately. Are the Navier-Stokes equations well posed in the presence of walls?

Are they singular under certain conditions? The project by Kerr *et al.* employs vorticity moments to perform regularity diagnostics of the Navier-Stokes equations in turbulent boundary layers. The outcome of the research is not merely to satisfy the interest of mathematicians but is also relevant for the development of turbulence models at high Reynolds numbers, where dissipation becomes finite as viscosity vanishes.

The second subgroup is devoted to non-equilibrium and rough-wall boundary layers. Non-equilibrium flows with mean-flow three-dimensionality are particularly stimulating given their ubiquity (swept wings, stern regions of ships, etc.) and counter-intuitive behavior, such as drag and Reynolds stress depletion in the presence of enhanced strain. These observations have captivated many researchers in the field and pose new challenges for large-eddy simulation (LES) and Reynolds-averaged Navier-Stokes (RANS) modelers. The project by He *et al.* aims to unveil the mechanisms of turbulence reduction in transversely strained boundary layers. In their unique approach, the authors reinterpret temporally developing three dimensional turbulent boundary layers in the context of cross-flow and bypass transition theory. High-Reynolds-number, non-equilibrium wall turbulence also necessitates practical, single-point closures with non-local information. Yuan *et al.* address this matter through the structure-tensor concept to assess the effects of roughness and textures using a rich DNS/LES data set to inform structure-based closures. Equally important is the necessity of a unified theory for wall turbulence over complex surfaces and realistic roughness to hasten the development of wall modeling methodologies. To this end, Garcia-Mayoral *et al.* systematically analyze how various wall textures produce varying complexity of near-wall turbulence and scrutinize the validity of virtual origins theory as a framework for drag prediction in different technologies (riblets, superhydrophobic surfaces, porous coatings, canopies, etc.). The investigation of non-equilibrium flows in real-world applications is addressed by Lee *et al.*, who assess the impact of transverse shear on turbomachinery by means of LES.

Finally, I thank all of the participants in the Wall Turbulence group for many intellectually stimulating discussions and ideas that helped in opening new venues to advance the field.

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