Center for Turbulence Research
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Fundamentals group: overview

A fundamental understanding serves as the basis upon which something else can be built. Predicting an airplane's lift, a ship's drag, or how contrails impact global greenhouse emissions requires one to break the problem into its basic components and to develop creative solutions using ones expertise and tools. Engineering is precisely that: It is about finding order in nature's chaos – patterns we can predict and perhaps control. At the 2024 Summer Program of the Center for Turbulence Research at Stanford University, the Fundamentals subgroup brought together 20 participants and 14 hosts, making up nine teams representing government laboratories, industry, and academic institutions, each working to deepen the understanding of complex multiphysics turbulent flows. Their research, spanning ice crystal formation, advanced flow tracking methods, and the intricacies of surface roughness, demonstrates the power of collaborative exploration in tackling some of the most challenging problems in fluid dynamics.

To accurately predict real-world environments, the projects focused on pushing beyond canonical turbulent flows through addressing multiphysics and nonequilibrium effects. Throughout the program, we recognized three lines of research pushing the boundaries of our current modeling capabilities and our understanding of, specifically, pressure gradient effects, wall-bounded turbulent flows over rough surfaces, and instabilities in turbulent flows such as bypass transition and Crow instabilities. Several teams focused on two or even all three of these topics at once, highlighting the coupled nature of these flow fields. By connecting these fundamental research areas to practical engineering problems, the Summer Program fostered an environment where researchers could contribute to advancements with tangible benefits.

These topics map to real-world engineering examples such as improving wind turbine efficiency, ensuring aircraft safety in icy conditions, and enhancing ship performance by managing hull roughness. Studying these phenomena is essential for solving key engineering problems, such as predicting flow separation and stall, controlling instabilities in turbines and compressors, and reducing the climate impact of contrails and cirrus clouds. To this end, we summarize the key contributions of the nine projects, highlighting their impact on the field.

A new intermittency correlation formula proposed by Gonzalez et al. is informed by a comprehensive set of direct numerical simulations (DNS) of bypass transition. The new correlation, which expands the Abu-Ghannam and Shaw correlation, improves the prediction of early-stage transition. Gonzalez et al. also highlighted that Reynolds-averaged Navier-Stokes (RANS) simulations are highly sensitive to the chosen reference length scale in the k–ω model and argued for the dissemination of the readily available DNS database for turbulence modelers.

Ferreira et al. explored inducing the Crow instability to reduce contrail radiative forcing. Contrary to initial expectations, simulations of an aircraft plume showed that artificially triggering the instability increases the radiative forcing compared to natural instability development, highlighting the need for additional studies that might lead to radiative cooling in the atmosphere.

Yazdani et al. studied soot particle morphology in nucleation and early postnucleation growth at long timescales. They found that smaller fractal dimensions delay nucleation but enhance post-nucleation growth, impacting contrail formation and detection. Hayat and Park introduced novel Eulerian methods for tracking Lagrangian kinematics and statistics without particle tracking, offering new insights into flow dynamics and particle dispersion.

Using recent particle image velocimetry (PIV) and hotwire data from the University of Southampton's wind tunnel, Preskett et al. analayzed high Reynolds number flows with pressure gradient history effects. They showed that adverse pressure gradients amplify large-scale boundary layer motions, with upstream shear differences playing a key role. Griffin et al. developed an improved $k-\omega$ shear-stress transport model for predicting separation, combining a pressure gradient criterion with an intermittency transport equation for accurate predictions near stall in a variety of airfoils relevant for both wind-turbine and aviation applications.

Garcia and Hussain studied heat transfer over a heated wall with spanwise bumps and fine-scale longitudinal grooves as roughness, observing significant differences in heat and momentum flux between cases with and without grooves. Their findings emphasize the importance of understanding thermal and vortical structures in controlling heat and mass transfer.

Uncertainty in model parameters for rough surfaces can lead to a wide range of results for the modeling of surface terrain in atmospheric boundary layers. Shin et al. applied a data-driven approach to quantify model form uncertainty in an idealized urban environment, reducing the error in boundary layer wind speed by up to 75% compared to traditional models.

Finally, Hu et al. conducted DNS studies of icing-induced surface roughness and its impact on developing boundary layers, revealing large impacts on the flow's inner layer while maintaining both outer-layer similarity and a logarithmic region. They then tested rough-wall correlations in both large eddy simulation– and RANS-based approaches, demonstrating reasonable response from equilibrium models to the spatially varying rough-surface flow.

We thank everyone in the Fundamentals group of the CTR Summer Program for their hard work and dedication. The range of topics and the thought-provoking, engaging discussions showed that we all share the same aim—to understand the chaotic flows that never give up their secrets. We believe that bringing together theorists, experimentalists, and computationalists under one roof pushes the field forward, and we appreciate everyone's contributions toward that goal.

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