Turbulent boundary layers – overview

The outcomes of research into the behavior and modeling of wall turbulence pertain to any flow in which there are boundaries. Ideally, the effects of boundaries would be imposed by boundary conditions on the equations governing the turbulence, and when these are the Navier-Stokes equations, as in direct numerical simulation, this is indeed the case. But, in the case of large-eddy simulation, the presence of boundaries must be reflected in the equations as well as the boundary conditions. Thus, a complete set of equations governing anything less than the fully resolved turbulent flow requires a reliable, physically realistic and mathematically informed wall model. Despite many efforts, the ultimate model remains elusive, and we continue to investigate the physics of wall turbulence in search of key features that, when understood, will lead us to a successful description.

The key scientific issue making wall turbulence both difficult and fascinating is that it is one of the most inhomogeneous turbulent flows. Away from the wall, it is not unreasonable to formulate models around the limit of asymptotically infinite Reynolds number, and LES fomulations work quite well in this region. Close to the wall, the Reynolds number approaches zero, and the concept of sub-grid scale viscous motions and resolved scale motions fails- everything is viscous. Thus, a large eddy decomposition must change its character as the wall is approached. The situation becomes even more complicated when detailed features of the wall influence the outer flow, as when the wall is rough, or modified to reduce drag or increase heat transfer.

Direct numerical simulation of wall turbulence is an extremely valuable tool for investigating the structure of the flow near a wall and influenced by a wall. In addition, it continues to provide a basis for developing and validating large eddy models. The projects in this report exploit the massive data bases provided by DNS to advance our understanding in these areas.

Four projects used different eduction techniques to extract information from DNS databases of spatially developing BLs. Baltzer *et al.* computed POD modes and found results generally supporting the hairpin packet model of Adrian (2007). Bermejo-Moreno *et al.* studied the topology and multiscale geometrical character of the dissipative structures, and found that they change from sheet-like to tube-like objects depending on scale. Wallace *et al.* computed statistics in isolated turbulent spots during the transition process, and found remarkable similarities with fully developed turbulence. Khujadze *et al.* used a wavelet decomposition to conclude that fewer than 1% of wavelet modes are needed to account for the coherent structures.

Two projects considered different aspects of the laminar-to-turbulent transition problem. Watmuff *et al.* studied the nonlinear interaction between free-stream turbulence and Tollmien-Schlichting waves, specifically whether this may lead to bypass transition at lower turbulence levels. Moarref *et al.* considered localized control of channel flow, in which each actuator has access only to nearby sensors; they concluded that the localized nature must be directly integrated in the design of the controller.

Two projects investigated RANS models for engineering applications. O'Sullivan *et al.* computed the separated flow over a hill with the V2F and a structure-based model, and developed a novel implementation of the latter that improved the convergence behavior. George *et al.* proposed a way to include the effect of wall roughness into the V2F model.

The final two projects studied supersonic shock/boundary layer interactions using large eddy simulation. Hadjadj *et al.* investigated the 3D effects due to side walls in any experiment, and concluded that these are large. Pirozzoli *et al.* used different modal decomposition techniques to study the low-frequency oscillations, and deduced that the shock/separation-bubble system is a damped oscillator that is excited by the incoming turbulence.

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