Thermal vs. vortical coherent structures in a channel flow with pressure gradients and roughness

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Abstract

Wall roughness, even with bumps, is a common feature in both nature and technology. In this study, we investigate the heat transfer of a channel with a heated wall with a constant temperature with a large-scale spanwise sinusoidal bump overlaid with fine-scale longitudinal square grooves (GW). We study these via direct numerical simulation of incompressible Navier-Stokes equations with temperature as a passive scalar. The bump perturbation introduces pressure gradients, challenging the applicability of the Reynolds analogy for explaining heat transport. The failure of the Reynolds analogy is examined via instantaneous flow visualization and phase-averaged vortical coherent structures (CSs) extracted from the vorticity field and thermal coherent structures (TCSs) extracted from the temperature field. Maximum differences between wall-normal heat and momentum fluxes are in the region of flow acceleration on the upstream side of the bump and in the separation bubble (SB) past the bump peak. Through CS analysis, we demonstrate that the spanwise rollers (SRs) formed by the rollup of the shear layer above the SB are the source of the difference between turbulent heat and momentum fluxes in the SB. In contrast, for vortices aligned with the streamwise direction (as they indeed occur in a flat channel), the Reynolds analogy remains valid. In the acceleration region, we show that streamwise vortices, which are predominant in this region forming vortex dipoles, induce flow where the coherent heat and momentum transports are similar, yet coherent heat and momentum fluxes at the wall are not analogous. This is because the CS induces a local, instantaneous adverse wall pressure gradient, counterintuitively in the region of flow acceleration.

Keywords: heated turbulent boundary layer, coherent structrures, pressure gradients

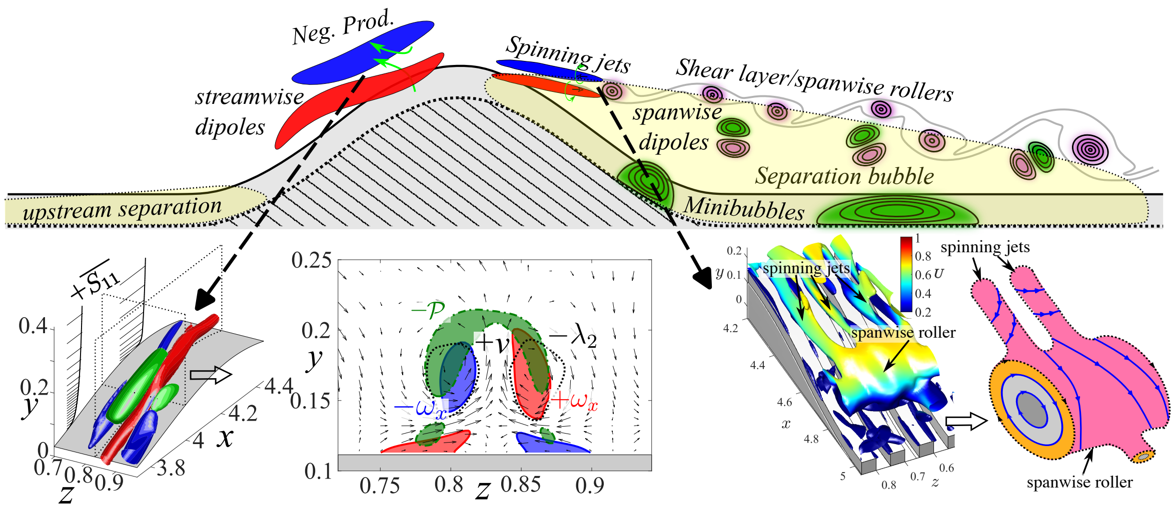

Figure 1. Schematic denoting the regions of interest and important flow features.

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