DNS OF TURBULENT WALL BOUNDED FLOWS WITH A PASSIVE SCALAR

by

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ABSTRACT

In this thesis, Direct Numerical Simulations (DNS) of the velocity and temperature fields are performed for incompressible turbulent flows in plane channels and spatially-developing boundary layers. The main goal is to numerically analyze the behavior of the momentum and thermal boundary layers subjected to different external and upstream conditions, the main focus is given to: *i) local flow perturbations, ii) different Reynolds numbers, and, iii) external pressure gradient.*

Two types of turbulent wall-bounded flows are examined in this investigation. One of them consists of the fully developed turbulent channel. Furthermore, after the developing section, the boundary layers generated by the lower and upper walls collapse. From this point to downstream, periodic boundary conditions are applicable due to the existent homogeneity. The second type of wall bounded flow explored possesses no restriction in the upper zone; consequently, the boundary layer may grow infinitely downstream. This streamwise non-homogeneous state does not allow to prescribe periodic boundary conditions along the direction of the flow. Therefore, time-dependent turbulent information must be assigned at the domain inlet, turning the numerical problem into a very challenging one. The spatially-developing turbulent boundary layer in a flat plate is a typical example of non-homogeneous flow.

In the first part of this thesis, the influence of local forcing on an incompressible turbulent channel flow is numerically investigated. The extensive information provided by the DNS enable us to have a better understanding of the physical mechanism responsible for local heat transfer enhancement and drag reduction. Time-periodic blowing/suction is applied by means of thin spanwise slots located at the lower and upper walls of the channel at several forcing frequencies. It was found in Araya *et al*. (2008-a) the existence of a characteristic frequency, i.e. of $\overline{f} = 0.64$ or $f^{+} = 0.044$, at which maximum local augmentation of the molecular and turbulent heat transfer rates were obtained downstream from the local forcing source. Furthermore, the key role of pressure fluctuations in the energy exchange and redistribution of energy among the components was confirmed by Araya *et al.* (2008-b) by analyzing the budget of wall-normal turbulent heat fluxes in locally forced turbulent flows at the characteristic

frequency. Additionally, the analysis of power spectra and cospectra of fluctuations in Araya *et al.* (2008-b) demonstrated that the largest energy increases due to periodic blowing/suction are attained by the wall-normal velocity fluctuations and wall-normal turbulent heat fluxes at very low wavenumbers or large scales.

The latter part of this work is principally devoted to the analysis of the rescaling-recycling method on the generation of time-dependent turbulent inflow conditions on spatially evolving boundary layers in zero (ZPG) and adverse (APG) pressure gradient flows. The rescaling-recycling method shows promising features as a turbulent inflow generator, particularly on pressure gradient (PG) flows. Its simplicity permits to avoid the calculation of the laminar-transition stage, and, as a consequence, a huge amount of computational time can be saved. Not to mention that the computational domain is drastically reduced due to the short developing section needed. Nevertheless, the original procedure proposed by Lund *et al*. (1998) was limited to flows without streamwise pressure gradients due to the single scaling assumption. This is indeed the first time that a recycling approach successfully worked for PG flows. In this study, an alternative multi-scale similarity method for the generation of inflow turbulent momentum/thermal information is introduced for flows with and without streamwise pressure gradients for Reynolds numbers up to 2300 based on the momentum thickness, i.e. Re_θ. The velocity scaling laws for the mean flow are based on the works by George and Castillo (1997) and Castillo and George (2001). In the same way, the mean temperature scaling is derived from the investigations performed by Wang (2003) and Wang and Castillo (2003). Finally, DNS of spatially-developing turbulent boundary layers on a flat plate (ZPG) at low and high Reynolds numbers are performed. To the best of our understanding, the thermal boundary layer simulations carried out at $\mathrm{Re}_\theta = 1940 - 2300$ represent the numerical predictions at the highest Reynolds number available in the turbulence community. Additionally, direct simulations of a turbulent boundary layer subjected to a moderate adverse pressure gradient (APG) are also presented based on the novel multi-scale method. Turbulence parameters are compared with experimental data and other numerical predictions found in the literature. Furthermore, the effects of the Reynolds number and pressure gradient are discussed for the velocity-temperature analogy, turbulent Prandtl number, energy budgets and turbulence structures.