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Direct Numerical Simulation of Incompressible Flows in a Zero-Pressure Gradient Turbulent Boundary Layer

Chuanta Lin[1] and Zuojin Zhu[1,*]

[1] *Multiphase Reactive Flow Division, Department of Thermal Science and Energy Engineering, USTC, Hefei, 230026, China*

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Abstract. Direct numerical simulation (DNS) of incompressible flows in a zero-pressure gradient turbulent boundary layer (TBL) is conducted by a finite difference method in which a fourth order upwind scheme is applied to discretize the convective terms while a re-scaling approach is used to set inlet flow conditions. The Reynolds numbers based on free flow velocity and momentum thickness at the recycle section are respectively 687, 1074, and 1430. The DNS has obtained favorable results indicating that the turbulence statistics is quite satisfactory as compared with the existing numerical and experimental results. The three dimensional turbulent structures at the momentum thickness Reynolds number of 1430 in several different instants are illustrated by the iso-surface of swirl strength square (the square of imaginary part of the complex eigenvalue of velocity gradient tensor) together with velocity vectors in three different cross sections. It is found that there are three kinds of vortical structures: quasi-symmetrical and asymmetrical hairpin vortices, and worm-like vortices. The DNS based on the numerical method can certainly reveal the main characteristics of the TBL flows at the given Reynolds numbers.

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Key words: Direct numerical simulation, incompressible boundary layer flows, hairpin vortex, worm-like vortex.

1 Introduction

Zero-pressure gradient turbulent boundary layer (TBL) is a fundamental problem in the study of wall turbulence. Since turbulence plays a very important role in nature, civil and industrial engineering processes, the study of TBL is of great significance in the development of fluid mechanics. To date, much work has been done for the

*Corresponding author.
URL: `http://staff.ustc.edu.cn/~zuojin`
Email: zuojin@ustc.edu.cn (Z. J. Zhu), linchts@mail.ustc.edu.cn (C. T. Lin)

wall turbulence mechanism. The earlier experiments studied the mechanism of turbulence [1], the law of wake in a TBL [2], and the transition from laminar to turbulence [3, 4]. Significantly, a structural model named hairpin vortex was proposed [1] to explain the turbulent production and dissipation in a TBL. Low speed streaks [3] were found in the near wall region by flow visualization.

There were the TBL investigations in the period from 1960 to 1999 in the 20th century. They include the experiments [7–29] and numerical simulations [30–34]. Based on these studies, a consistent view was formed: There are coherent vortex structures in the TBL, leading to the ejection and sweeping of fluid motions that result in the irregular velocity and vorticity fluctuations with broad spatial and temporal scales. The findings of Bandyopadhyay and Head [11, 13] are noteworthy. In the range of momentum thickness Reynolds number from 500 to 1.75×10^4, hairpin vortex is a crucial feature of a zero-pressure gradient TBL with its shape depending on the Reynolds number. The hairpin vortex has a curve type at low Reynolds numbers, Ω type at moderate Reynolds numbers, and stretched hairpin type at higher Reynolds numbers.

Acarlar and Smith [19, 20] investigated the key role played by hairpin vortices in developing and sustaining the turbulence process in the near-wall region of TBL for the cases of hemisphere pro-turbulence- and fluid ejection-generated hairpin vortices in a developing boundary layer. Using flow visualization and hot film anemometry, they found the primary hairpin vortex can generate a downstream hairpin with a tertiary hairpin vortex occurring between the primary and downstream vortices. The scale of this kind of coherent structure in the main flow direction is several times that of a single hairpin. Strong inflectional profiles were found just downstream of the hairpin-vortex generation region, which evolved into fuller profiles with increasing downstream distance, eventually developing a remarkable similarity to a turbulent boundary layer velocity profile. While high sensitivity to external forcing is noted together with a tendency toward the organized development of larger, and more complex structures through a pairing-type process in the case of fluid ejection generation.

Recent experiments of TBL flows have emphasized the vortex properties [35–37], with DNS works involved with either heat convection [38] or supersonic flow characteristics [39, 40]. To improve the understanding of coherent structures and the scaling of the energy spectra, recent numerical studies have also dedicated turbulent channel flows [41–45]. Adrian [46] and Wallace [47] gave a broad view of the development of near-wall turbulence in their separate review articles.

This paper presents the DNS results of incompressible TBL flows with zero-pressure gradient. A re-scaling approach was used to set inlet flow conditions, and a relatively coarse grid ($241 \times 61 \times 81$) was used in the DNS. The grids in the streamwise and spanwise directions are uniform while in the vertical direction there are 61 grids distributed non-uniformly, with a larger grid density near-wall. The grid resolution is chosen on the basis of the comparison of friction and shape factors with existing results as shown in Fig. 1(a) and (b). In the DNS, the momentum thickness Reynolds numbers at the recycle section are respectively 687, 1074, and 1430. The primary objective of this work is to numerically explore the characteristics of velocity fluctuations and