23rd Australasian Fluid Mechanics Conference - 23AFMC
Sydney, Australia
4 – 8 December 2022

Paper No: AFMC2022-014

Turbulent statistics of a vertical natural convection boundary layer

Junhao Ke[1*], N. Williamson[1], S. W. Armfield[1], A. Komiya[2] and S. E. Norris[3]

[1] The School of Aerospace Mechanical and Mechatronic Engineering, The University of Sydney, Sydney, NSW 2006, Australia
[2] Institute of Fluid Science, Tohoku University, Sendai 980-8577, Japan
[3] Department of Mechanical Engineering, The University of Auckland, Auckland 1010, New Zealand
*mailto: junhao.ke@sydney.edu.au

1 Introduction

Turbulent vertical natural convection boundary layers (NCBL) frequently occur in geophysical and industrial flows. The fundamental characteristics of the turbulent NCBL are well studied since the 1950s for relatively low Grashof number (or, Rayleigh number) flows (Abedin et al., 2009; Nakao et al., 2017; Tsuji and Nagano, 1988). The NCBL flow undergoes a complex development with increasing Grashof number. While the outer region of the boundary layer undergoes transition to turbulent flow at relatively low Grashof number, the inner near-wall boundary layer may remain laminar up to a much higher Grashof number (Grossmann and Lohse, 2000; Ng et al., 2017). At a critical Grashof number, the near-wall region also becomes turbulent. To date, the turbulent statistics of the vertical natural convection boundary layers in the limit of high Grashof number flows remain largely unreported. This study aims to present turbulence statistics with a view to identify how and when the flow develops into a fully turbulent regime, and to reveal new insights of the turbulent flow structure in the limit of high Grashof number flow.

2 Results

The simulations reported here are direct numerical simulation (DNS) of turbulent temporally developing natural convection boundary layers adjacent to a vertical isothermal wall, and have been previously reported in Ke et al. (2020) (DNS-A), and Ke et al. (2021) (DNS-A and DNS-C). The grid resolution and the domain size of the simulations are listed in table 1. Figure 1 shows the Reynolds

Dataset	$L_x \times L_y \times L_z$	$N_x \times N_y \times N_z$	$\Delta^{\eta_k}_{min}$	$\Delta^{\eta_k}_{max}$
DNS-A	$1035L_s \times 1035L_s \times 2070L_s$	$1024 \times 512 \times 2048$	0.47	6.26
DNS-C	$2070L_s \times 2070L_s \times 2070L_s$	$3125 \times 1000 \times 3125$	0.45	11.28

Table 1. Number of grids N and the domain size L used for DNS-A and DNS-C. $\Delta^{\eta_k}_{min}$ and $\Delta^{\eta_k}_{max}$ are the minimum cell size (i.e., first cell adjacent to the wall) and the maximum cell size (i.e., the first cell adjacent to the far-field boundary) in the wall-normal direction (y) normalised by the Kolmogorov length scale η_k by the end of the simulation. $L_s = \kappa^{2/3}/(g\beta\theta_w)^{1/3}$ is the intrinsic length scale.

shear $\overline{u'v'}$ and normal (streamwise) $\overline{u'u'}$ stresses, normalised by the maximum mean velocity. In figure 1a, the magnitude of the peak shear stress in the present study is smaller than those of Tsuji and Nagano (1988) and Abedin et al. (2009). The discrepancy may due to the different laminar–turbulent transition process, as discussed in Ke et al. (2020). Nevertheless, the peak of the Reynolds shear stress $\overline{u'v'}$, which occurs at $y/\delta \approx 1$ for our DNS data, agrees well with the experimental measurements of

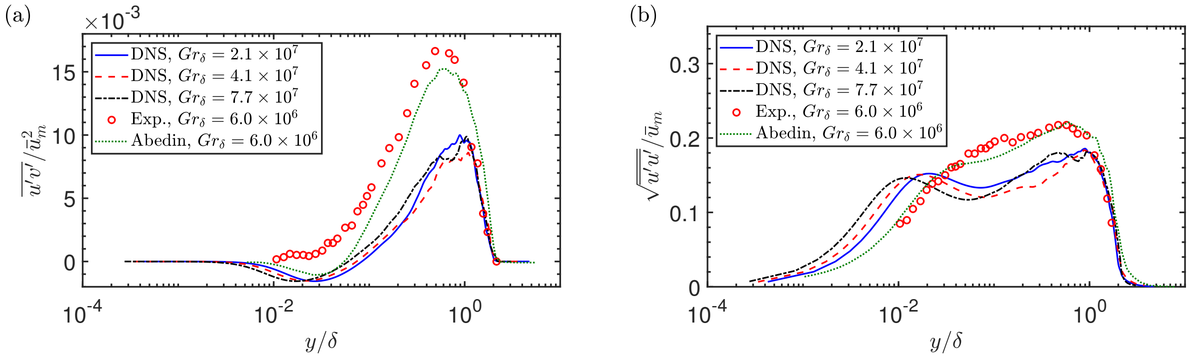

Figure 1. The Reynolds shear stress $\overline{u'v'}$ (a); and (streamwise) normal stress (b). Experimental measurements taken from Tsuji and Nagano (1988); and the DNS data of Abedin et al. (2009)

Tsuji and Nagano (1988) and the DNS results of Abedin et al. (2009). Meanwhile, a negative $\overline{u'v'}$ can be found in the close vicinity of the wall, similar to Abedin et al. (2009); whereas such a negative $\overline{u'v'}$ is missing for the measurements of Tsuji and Nagano (1988). In figure 1b the magnitude of the $\overline{u'u'}$ stress is found to be smaller than the measurements of Tsuji and Nagano (1988) and Abedin et al. (2009). In addition, there exists two local peaks (at $y/\delta \approx 10^{-2}$ and $y/\delta \approx 1$) for the $\overline{u'u'}$ stress, indicating a double shear layer structure for our NCBL flow; while such a structure is not as evident for Tsuji and Nagano (1988) and Abedin et al. (2009). Interestingly, this double shear layer structure appears more comparable to a wall jet flow under similar geometric configuration (Naqavi et al., 2018).

3 Conclusions

The present study investigates a temporally developing natural convection boundary layer with $Pr = 0.71$ using direct numerical simulation. The Reynolds shear stress and the streamwise normal stress are compared with the experimental measurements for a spatially developing flow (Tsuji and Nagano, 1988) and the DNS data for a temporally developing flow at relatively low Gr_δ (Abedin et al., 2009). According to our DNS results, there exists a double shear layer for our temporally developing flow, similar to the observations in Naqavi et al. (2018); whereas such a structure is not as evident in the previous NCBL studies (Abedin et al., 2009; Tsuji and Nagano, 1988).

References

Abedin, M. Z., Tsuji, T., and Hattori, Y.. 2009, Direct numerical simulation for a time-developing natural-convection boundary layer along a vertical flat plate, **52**, 4525–4534.

Grossmann, S. and Lohse, D.. 2000, Scaling in thermal convection: a unifying theory, **407**, 27–56.

Ke, J., Williamson, N., Armfield, S. W., Norris, S. E., and Komiya, A.. 2020, Law of the wall for a temporally evolving vertical natural convection boundary layer, **902**, A31.

Ke, J., Williamson, N., Armfield, S. W., Komiya, A., and Norris, S. E.. 2021, High Grashof number turbulent natural convection on an infinite vertical wall, **929**, A15.

Nakao, K., Hattori, Y., and Suto, H.. 2017, Numerical investigation of a spatially developing turbulent natural convection boundary layer along a vertical heated plate, **63**, 128–138.

Naqavi, I., Tyacke, J., and Tucker, P.. 2018, Direct numerical simulation of a wall jet: flow physics, **852**, 507–542.

Ng, C. S., Ooi, A., Lohse, D., and Chung, D.. 2017, Changes in the boundary-layer structure at the edge of the ultimate regime in vertical natural convection, **825**, 550–572.

Tsuji, T. and Nagano, Y.. 1988, Characteristics of a turbulent natural convection boundary layer along a vertical flat plate, **31**, 1723–1734.