International Journal of Heat and Fluid Flow 49 (2014) 53–61

Contents lists available at ScienceDirect

International Journal of Heat and Fluid Flow

journal homepage: www.elsevier.com/locate/ijhff

Characteristics and structures in thermally-stratified turbulent boundary layer with counter diffusion gradient phenomenon

Hirofumi Hattori *, Kosuke Hotta, Tomoya Houra

Department of Mechanical Engineering, Nagoya Institute of Technology, Gokiso-cho, Showa-ku, Nagoya 466-8555, Japan

ARTICLE INFO

Article history:
Available online 4 July 2014

Keywords:
Turbulent boundary layer
Stable thermal stratification
Heat transfer
Counter gradient diffusion phenomenon
DNS

ABSTRACT

The objectives of this study are to investigate the counter diffusion phenomenon (CDP) in a stably thermally-stratified turbulent boundary layer by means of direct numerical simulation (DNS). In this study, four cases of stably thermally-stratified turbulent boundary layers are simulated to reproduce the CDP, in which two Reynolds numbers and four Richardson numbers are set. The CDP is discovered in both the velocity and thermal fields in three cases. DNS clearly shows the CDP, which indicates the negative sign of the Reynolds shear stress and the wall-normal turbulent heat flux with the positive sign of mean velocity and temperature gradients. The turbulent heat flux tensor is also shown in order to indicate the variation of the thermal field, in which the streamwise turbulent heat flux tensor maintains a high value even in the case of strong CDP occurrence. The relation between the vortex structure and the Reynolds shear stress fluctuation is shown, where the negative value of Reynolds shear stress fluctuation frequently appears around the vortex structure in the case of CDP occurrence.

1. Introduction

The thermally-stratified turbulent boundary layer has often been encountered in real fluid flow, and it is very important to know the characteristics and structure of such a flow to satisfy our intellectual curiosity. Thus, in order to investigate and observe the thermally-stratified turbulent boundary layer in detail, direct numerical simulation (DNS) has been carried out (Hattori et al., 2007, 2012; Hattori and Nagano, 2007). In particular, a stably thermally-stratified boundary layer is focused on, because a counter gradient diffusion phenomenon can be observed in such a flow. The previous studies as for a stably thermally-stratified flow are: a thermally-stratified turbulent boundary layer (Ohya, 2001; Hattori et al., 2007, 2012; Hattori and Nagano, 2007), a stratified mixing layer (Uittenbogaard, 1988; Komori and Nagata, 1996; Nagata and Komori, 2001), stably stratified turbulent channel flows (Garg et al., 2000), turbulence closure for buoyant affected flows (Craft et al., 1996; Hattori et al., 2006), etc. In previous studies, a counter gradient diffusion phenomenon (CDP) was observed in a stably thermally-stratified turbulent boundary layer in both the velocity and thermal fields (Hattori and Nagano, 2007; Hattori et al., 2012). In a stably thermally-stratified turbulent boundary layer (Ohya, 2001), a strongly stably stratified mixing layer (Komori and Nagata, 1996), a non-premixed turbulent flame formed in a strong pressure-gradient flow (Tagawa et al., 2005), a turbulent boundary layer with separation and reattachment (Hattori and Nagano, 2012; Hattori et al., 2013a), etc., a CDP is sometimes observed contrary to the principle of gradient diffusion. Reynolds shear stress or turbulent heat flux are modeled using the relation of conventional gradient diffusion hypothesis with the eddy diffusivity, e.g., $-\overline{uv} = \nu_t(\partial \overline{U}/\partial y)$ for a velocity field. Thus, the eddy diffusivity indicates a negative value if a CDP occurs. Obviously, CDP suppresses the transport phenomena in turbulence due to the negative value of the eddy diffusivity. In order to cause a CDP, extra force such as a strong thermal stratification is needed. However, the criterion for triggering an occurrence of CDP is inarticulate. Therefore, the objectives of this study are to explore the causation of CDP occurrence, and to investigate it in detail in a stably thermally-stratified turbulent boundary layer by means of DNS. A striking discovery from a previous study is that CDP occurs in a high Richardson number of stable stratification, but a stably thermally-stratified turbulent boundary layer has never been explored for the variation of Reynolds numbers. Thus, DNSs have been conducted under various Reynolds and Richardson number conditions to detect the criterion for the occurrence of CDP. Also, the detailed turbulent statistics and structures, such as the anisotropy of turbulence in the stably thermally-stratified turbulent boundary

* Corresponding author. Tel./fax: +81 52 735 5359.
E-mail address: hattori@nitech.ac.jp (H. Hattori).

http://dx.doi.org/10.1016/j.ijheatfluidflow.2014.06.005
0142-727X/

Nomenclature

a_j	turbulent heat flux tensor, $=\overline{u_j\theta}\Big/\left(\sqrt{\overline{u_{(j)}u_{(j)}}}\sqrt{\overline{\theta^2}}\right)$
b_{ij}	anisotropy tensor of Reynolds stress, $=\overline{u_iu_j}/\overline{u_ku_k}-(1/3)\delta_{ij}$
C_f	local friction coefficient $=2\tau_w/(\rho\overline{U}_0^2)$
c_p	specific heat at constant pressure
k	turbulence energy, $=\overline{u_iu_i}/2$
k_θ	temperature variance, $=\overline{\theta^2}/2$
g_i	gravitational acceleration
$Gr_{\delta_{2,\mathrm{in}}}$	Grashof number, $=g\beta\delta_{2,\mathrm{in}}^3\Delta\Theta/\nu^2$
$\overline{P}$	mean static pressure
Pr	Prandtl number, $=\nu/\alpha$
Re_{δ_2}	Reynolds number based on the free stream velocity and the momentum thickness at the inlet of the driver part, $=\overline{U}_0\delta_{2,\mathrm{in}}/\nu$
Re_{Δ_2}	Reynolds number based on the free stream velocity and the enthalpy thickness at the inlet of the driver part, $=\overline{U}_0\Delta_{2,\mathrm{in}}/\nu$
Ri_{δ_2}	bulk Richardson number based on the free stream velocity, the momentum thickness at the inlet of the driver part, $=g\beta\delta_{2,\mathrm{in}}\Delta\Theta/\overline{U}_0^2$
Ri_l	local Richardson number, $=g\beta(\partial\bar{\Theta}/\partial y)/(\partial\overline{U}/\partial y)^2$
s_{ij}	strain tensor, $=(1/2)(\partial u_i/\partial x_j+\partial u_j/\partial x_i)$
St	local Stanton number $=q_w/[\rho c_p\overline{U}_0(\Theta_w-\Theta_\infty)]$
$\overline{U}$, $\overline{V}$	mean velocity in x- and y-directions, respectively
u, v, w	turbulent fluctuation in x-, y- and z-directions, respectively
$\overline{U}_i$	mean velocity in x_i-direction
$\overline{U}_0$	free stream mean velocity
u_i	turbulent fluctuation in x_i-direction
u_τ	friction velocity, $=\sqrt{\tau_w/\rho}$
x_i	Cartesian coordinate in i-direction
x, y, z	Cartesian coordinate in streamwise, wall-normal and spanwise directions, respectively
y^+	nondimensional distance from wall surface, $=u_\tau y/\nu$

Greek symbols

α	molecular diffusivity for heat
α_t	eddy diffusivity for heat
β	coefficient of volume expansion
δ	boundary layer thickness defined at location where mean velocity is equal to 99% of free-stream velocity
δ_2	momentum thickness
δ_{ij}	Kronecker delta
ϵ_{ijk}	Eddington epsilon
Δ	thermal boundary layer thickness defined at dimensionless mean temperature, $\bar{\Theta}=(\theta-\overline{\Theta}_0)/\Delta\Theta$, is equal to 99%.
$\Delta\Theta$	temperature difference, $=\overline{\Theta}_\infty-\overline{\Theta}_0$
Δ_2	enthalpy thickness
ν	kinematic viscosity
ν_t	eddy diffusivity for momentum
ω_{ij}	vorticity tensor, $=(1/2)(\partial u_i/\partial x_j-\partial u_j/\partial x_i)$
ω_k	vorticity in x_k-direction, $=(\partial u_i/\partial x_j)\epsilon_{ijk}$
ρ	density
τ_w	wall shear stress
$\overline{\Theta}$	mean temperature
$\overline{\Theta}_0$	wall temperature at the inlet of the driver part
$\overline{\Theta}_w$, $\overline{\Theta}_\infty$	wall and free-stream temperature
θ	temperature fluctuation
θ_τ	friction temperature, $=q_w/(\rho c_p u_\tau)$
$\overline{(\ )}$	ensemble- or time-averaged value
$(\ )^+$	normalization by inner variables (u_τ,θ_τ,ν)

layers, have shed light on the turbulent characteristics of such a flow field.

2. DNS of stably thermally-stratified boundary layer

Assuming that the Boussinesq approximation is approved for the Navier–Stokes equation, the governing equations used in the present DNS are indicated as follows (Hattori et al., 2007):

$$\frac{\partial u_i^*}{\partial x_i^*}=0 \tag{1}$$

$$\frac{Du_i^*}{Dt}=-\frac{\partial p^*}{\partial x_i^*}+\frac{1}{Re_{\delta_{2,\mathrm{in}}}}\frac{\partial^2u_i^*}{\partial x_j^*\partial x_j^*}+\delta_{i2}Ri_{\delta_{2,\mathrm{in}}}\theta^* \tag{2}$$

$$\frac{D\theta^*}{Dt}=\frac{1}{PrRe_{\delta_{2,\mathrm{in}}}}\frac{\partial^2\theta^*}{\partial x_j^*\partial x_j^*} \tag{3}$$

where the Einstein summation convention applies to repeated indices, and u_i^* is the dimensionless velocity component in x_i direction, θ^* is the dimensionless temperature difference, p^* is the dimensionless pressure, t^* is the dimensionless time, and x_i^* is the dimensionless spatial coordinate in the i direction, respectively. In the governing equations, the dimensionless variables are given using the free stream velocity, U_0, and the free stream temperature, Θ_0, at the inlet of the driver part, and the wall temperature, Θ_w.

For efficiently conducting the DNS of thermal boundary layers, the computational domain is composed of two parts; one is the driver part where a zero-pressure-gradient (ZPG) flow with an isothermal wall is generated and used as the inflow boundary condition for the main simulation, and the other is the main part where stable thermal boundary layer flows are simulated. A central finite-difference method of second-order accuracy is used to solve the equations of continuity, momentum and energy (Hattori and Nagano, 2004), where $x\times y\times z=384\times128\times128$ of grid points are used for the main part. Although a value thirty times the momentum thickness at the inlet of the driver part region (about three times of the 99% boundary layer thickness) for wall-normal direction is set, the 70% grid points are distributed in the turbulent boundary layer. The Prandtl number is set to 0.71, assuming the working fluid to be air. The Reynolds numbers are set to 1000 and 300, and the Richardson numbers are set to 0.06 ($Re_{\delta_{2,\mathrm{in}}}=1000$), 0, 0.01, 0.02 and 0.04 ($Re_{\delta_{2,\mathrm{in}}}=300$).

As for the grid resolution normalized by the local inner scale, u_τ, $\delta_{2,\mathrm{in}}$ and ν, which is the fundamental parameter of DNS, the relevance of grid resolution in our DNS has been confirmed in several DNS of turbulent boundary layer (Hattori et al., 2007, 2013a,b; Hattori and Nagano, 2012). In this study, it is evident that the grid resolutions as shown in Table 1 properly satisfy DNS requirements

Table 1
Grid resolutions.

$Re_{\delta_{2,\mathrm{in}}}$	$Ri_{\delta_{2,\mathrm{in}}}$	Δx^+		Δy^+		Δz^+	
		Inlet	Outlet	Inlet	Outlet	Inlet	Outlet
1000	0	12.2	12.1	0.27–34.7	0.27–34.6	7.29	7.28
	0.06	12.2	6.3	0.27–34.7	0.14–17.8	7.3	3.75
300	0	4.13	4.09	0.091–11.7	0.091–11.7	4.95	4.9
	0.01	4.13	2.9	0.091–11.7	0.064–8.55	4.95	3.49
	0.02	4.13	2.8	0.091–11.7	0.062–7.97	4.95	3.35
	0.04	4.13	2.76	0.091–11.7	0.061–7.88	4.95	3.32