Sixth International Symposium on Turbulence and Shear Flow Phenomena
Seoul, Korea, 22-24 June 2009

EFFECTS OF A PERIODIC SURFACE TEMPERATURE OSCILLATION ON STRATIFIED TURBULENCE IN A CHANNEL FLOW

Yu-Hong Dong
Shanghai Institute of Applied Mathematics and Mechanics,
Shanghai University, Yanchang Road
Shanghai 200072, China
dongyh@staff.shu.edu.cn

Xi-Yun Lu
Department of Mechanics and Mechanical Engineering,
University of Science and Technology of China
Hefei, Anhui 230026, China
xlu@ustc.edu.cn

ABSTRACT

Thermally stratified shear turbulent channel flow with temperature oscillation on the bottom wall has been investigated by large eddy simulation (LES) approach coupled with dynamic subgrid-scale (SGS) models. The objective of this study is to deal with the influence of the temperature oscillation on characteristics of thermally stratified turbulent flow and to examine the effectiveness of the LES technique on predicting unsteady turbulent flow driven by time-varying buoyancy force. The phase-averaged velocities and temperature, and some typical instantaneous flow structures at different Richardson numbers and periods of the oscillation are analyzed.

INTRODUCTION

Inherent unsteadiness of the driving conditions (e.g., time-varying pressure gradient, buoyancy force, and boundary motion) characterizes a variety of turbulent flows in both natural phenomena and engineering applications. The thermally stratified shear turbulence is a kind of complex flow driven by both shear and buoyancy forces, which occurs in a wide range of nature and engineering circumstances. The turbulent flow coupled with unsteady heat transfer is significant in the fundamental research of the turbulent heat transfer and turbulence control.

Although a variety of turbulent flows have been calculated by LES, little work has been done for the LES of thermally stratified turbulence. Garg et al. [1] investigated stably stratified turbulent channel flows to deal with turbulence suppression mechanism. Armenio et al. [2] performed the LES investigation of stably stratified turbulent channel flow to exhibit internal wave activity in the core of the channel. In the authors' group, new dynamic SGS models, including subgrid turbulent stress and heat flux models, for thermally stratified shear flow were proposed [3]. Sameen and Govindarajan [4] conducted a study of the effect of wall heating or cooling on the linear, transient and secondary growth of instability in channel flow. Dong et al. [5] employed the LES to calculate turbulent channel flow with passive scalar transfer.

In this study, the LES approach is employed to investigate the effect of a periodic surface temperature oscillation on stratified turbulence in a channel flow. Dynamic SGS models of turbulent stress and heat flux are used. The three-dimensional resolved incompressible Navier–Stokes and energy equations are solved by the fractional-step method proposed by Verzicco and Orlandi [6]. Dynamic SGS models of turbulent stress and turbulent heat flux are used.

MATHEMATICAL FORMULATIONS

A thermally stratified turbulent channel flow with temperature oscillation on the bottom wall of the channel is considered. In this study, the governing equations are the three-dimensional filtered incompressible Navier-Stokes equations and energy equation under the Boussinesq approximation. The formulations of the governing equations, dynamic SGS models for turbulent stress and heat flux are given in detail by Dong et al. [5]. The non-dimensional governing equations are then given as,

$$\frac{\partial \bar{u}_i}{\partial x_i}=0 \quad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t}+\frac{\partial}{\partial x_j}(\bar{u}_i\bar{u}_j)=-\frac{\partial \bar{p}}{\partial x_i}+\frac{1}{\mathrm{Re}_\tau}\frac{\partial^2 \bar{u}_i}{\partial x_j\partial x_j}-\frac{\partial \tau_{ij}}{\partial x_j}+\delta_{i1}+\mathrm{Ri}_\tau\tilde{T}\delta_{i2} \quad (2)$$

$$\frac{\partial \bar{T}}{\partial t}+\frac{\partial(\bar{T}\bar{u}_j)}{\partial x_j}=\frac{1}{\mathrm{Re}_\tau \mathrm{Pr}}\frac{\partial^2 \bar{T}}{\partial x_j\partial x_j}-\frac{\partial q_j}{\partial x_j} \quad (3)$$

$$\tau_{ij}=R_{ij}-\delta_{ij}R_{kk}/3,\; R_{ij}=\overline{u_iu_j}-\bar{u}_i\bar{u}_j,\; q_j=\overline{Tu_j}-\bar{T}\bar{u}_j \quad (4)$$

where the "overbar" denotes the filtered variables, $\bar{u}_i$ represents the velocity components in the streamwise, wall-normal and spanwise directions, respectively. $\tilde{T}=\bar{T}-<\bar{T}>$. $\mathrm{Re}_\tau=u_\tau\delta/\upsilon$ represents the Reynolds number and $\mathrm{Pr}=\upsilon/k$ is the molecular Prandtl number with υ being the kinematic viscosity of the fluid and k the thermal diffusivity. Ri_τ is the Richardson number $\mathrm{Ri}_\tau=\beta g\Delta T\delta/u_\tau^2$, where β is the thermal expansion coefficient which assumed small enough so that the Boussinesq approximation is applicable.

In Eqs. (2) and (3), τ_{ij} and q_j represent SGS turbulent stress and heat flux, respectively, which need to be modeled by SGS models. The overall expressions of the SGS stresses and turbulent heat flux are read as

$$\tau_{ij} = -2C\overline{\Delta}^2 \left|\overline{S}\right| \overline{S}_{ij}, \quad q_j = -\frac{C\overline{\Delta}^2}{\mathrm{Pr}_T} \left|\overline{S}\right| \frac{\partial \overline{T}}{\partial x_j} \qquad (5)$$

where $\overline{S}_{ij} = (\partial \overline{u}_i / \partial x_j + \partial \overline{u}_j / \partial x_i)/2$, $\left|\overline{S}\right| = \left[2\overline{S}_{ij}\overline{S}_{ij}\right]^{\frac{1}{2}}$. $\overline{\Delta}$ is the filter width , as proposed by Germano et al. [7], and Pr_T represents the turbulent Prandtl number.

After a fully developed turbulent flow is established, a fixed temperature on the upper wall and an oscillating temperature on the bottom wall are imposed. Here, the non-dimensional temperature on the upper wall of the channel is $T_U = 0$, and the non-dimensional temperature on the bottom wall represents $T_B = -\sin(2\pi t / t_P)$, where t_P is the period of temperature oscillation. Usually, the Richardson number is used to characterize buoyancy effect in stably or unstably stratified flow. Here, it also represents a reference parameter with maximum temperature difference between walls when the temperature on the bottom wall varies with time.

NUMERICAL METHODS AND VALIDATION

To perform LES calculation, a fractional-step method is employed to solve the governing equations. Spatial derivatives are discretized by a second order central difference. Time advancement is carried out by the semi-implicit scheme using the Crank-Nicolson scheme for the viscous terms and the three-stage Runge-Kutta scheme for the convective terms.

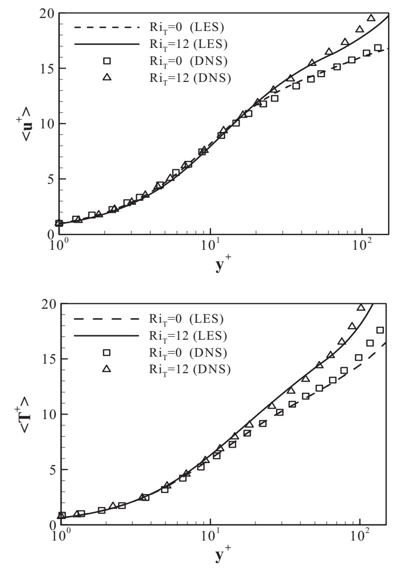

Figure 1. Profiles of the mean streamwise velocity and the mean temperature for different Richardson numbers

To validate the present calculation procedure, some typical DNS results for stably and unstably stratified turbulent channel flow performed by Iida et al. [8] are used to compare with our results. Here, two typical cases for and $\mathrm{Ri}_\tau = 0$ and 12 are employed to validate the present calculation. The distributions of the mean velocity and the mean temperature are shown in Figure 1. It is seen that the LES results agree well with the DNS data [8]. Moreover, we have compared other turbulent quantities with some previous DNS results (not shown here) and can confirm that our calculation code enables the LES results to be satisfactory.

RESULTS AND DISCUSSION

Some typical calculations have been performed for the different cases with their parameters given in Tables.1.

Table.1 The parameters of the cases

case	Re_τ	Pr	Ri_τ	T_P	$(\triangle y)/\delta$
1 (LES)	180	0.71	50	3.2	0.0018-0.051
2 (LES)	180	0.71	128	3.2	〃
3 (LES)	180	0.71	50	6.4	〃
4 (LES)	180	0.71	0	3.2	〃
5 (DNS)	180	0.71	50	3.2	0.0004-0.0183

Based on some typical results, we will briefly analyze thermally stratified turbulent flow behaviors. To reveal global character and statistically unsteady behavior of thermally stratified turbulent channel flow in9duced by the temperature oscillation on the bottom wall, the volume-integrated turbulent kinetic energy is defined as

$$E_k = \frac{1}{2}\int_{-1}^{1} < (\overline{u}')^2 + (\overline{v}')^2 + (\overline{w}')^2 >_S^2 dy \qquad (6)$$

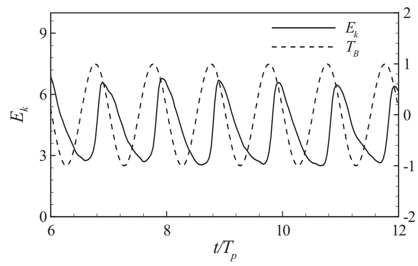

Figure 2. Time evolution of the volume-integrated turbulent kinetic energy

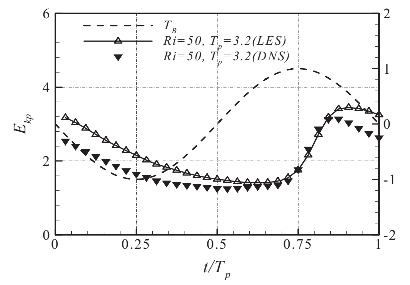

Figure 3. Time evolution of the phase-averaged turbulent kinetic energy.

Figure 2 and 3 show the time evolution of E_k and its phase-average E_{kp} by LES and DNS, respectively. The distribution of turbulent kinetic energy for $\mathrm{Ri}_\tau = 50$ and $t_P = 3.2$ and the corresponding sinusoidal curve of the temperature variation are shown in Figure 2 and 3. It is reasonably predicted that E_k varies quasi-periodically with time. By comparing with the phases corresponding to the lowest peaks of E_k and T_B, it is found that E_k changes with a phase lag about $t_P/4$ with respect to T_B. This behavior implies that the turbulent flow needs time to reflect the temperature variation on the wall.

(a)
(b)

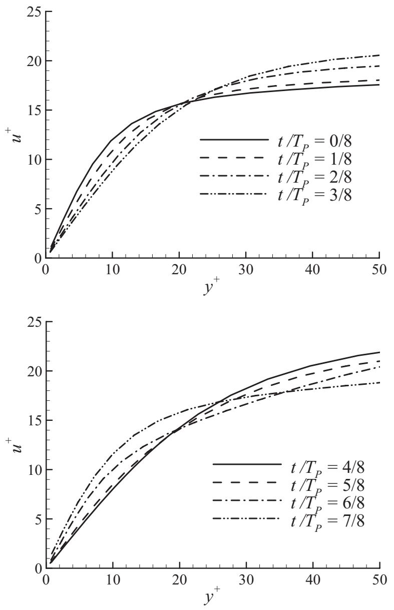

Figure 4 The phase-averaged velocity normalized by the friction velocity of purely shear channel flow at $\mathrm{Ri}_\tau = 50$ and $t_P = 3.2$.

(a)
(b)

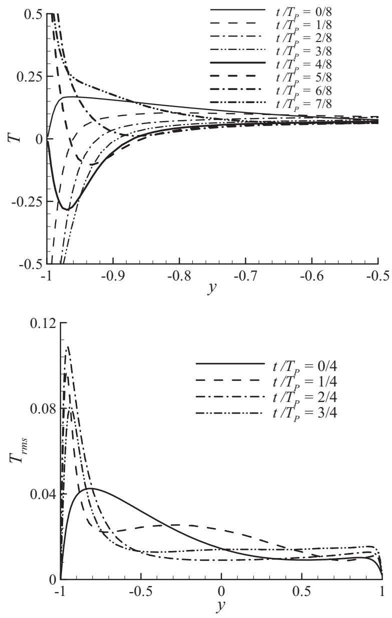

Figure 5 The phase-averaged temperature and its fluctuation at different phases: (a) temperature; (b) temperature fluctuation for $\mathrm{Ri}_\tau = 50$ and $t_P = 3.2$.

Figure 4 shows the sequence of the phase-averaged velocity normalized by the friction velocity of purely shear channel flow. When the temperature of the bottom wall of the channel is sinusoidally oscillating, the channel flow is undergone by stable and unstable stratification effect during one cycle. It can be found that the velocity profile evolution appears the tendency of re-laminarization due to the stable stratification effect in view of the mean velocity profiles from $t/T_P =$ 0/8 to 3/8. The mean velocity profile develops gradually to blunt distribution due to the unstable stratification effect for the mean velocity profiles from $t/T_P =$ 4/8 to 7/8.

The behaviors of the phase-averaged temperature and temperature fluctuation are analyzed as shown Figure 5. The temperature varies notably in the region of $-1 < y \le -0.5$ shown in Figure 5a, because the temperature oscillation is set on the bottom wall and the corresponding buoyancy force effect has a significant influence on the flow near the bottom wall region. In Fig.5b, the distribution of the temperature fluctuation has a small peak near the bottom wall at $t/T_P =$ 0/4 and a high peak at $t/T_P =$ 2/4 due to the stratification effect during one cycle. The mechanism can be explained by internal energy conversion between the turbulent kinetic energy and the potential energy.

(a)
(b)

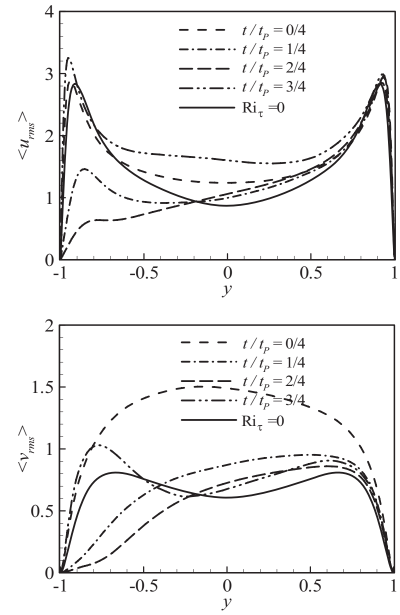

Figure 6. Distributions of the phase-averaged turbulent intensities for $\mathrm{Ri}_\tau = 50$ and $t_P = 6.4$: (a) u_{rms}, (b) v_{rms}.

As turbulent flow is influenced by stable or unstable stratification, turbulence intensity is reduced and strengthened alternately in one cycle. Figure 6 shows the profiles of the phase-averaged turbulent intensities for $\mathrm{Ri}_\tau = 50$ and $t_P = 6.4$ at several phases. The corresponding turbulent intensities of unstratified turbulent channel flow at the same Reynolds number (referred to as $\mathrm{Ri}_\tau = 0$) are also plotted in Figure 6. The evolution of the streamwise turbulent intensity u_{rms} in one cycle is similar to that of turbulent kinetic energy in Figure 2. The profile of u_{rms} near the bottom wall decreases gradually from $t/T_P = 0/4$ to 2/4, and changes quickly to high level distribution at $t/T_P = 3/4$. According to the distributions of v_{rms} in Figure 6b, it can be concluded that the increase of E_{kP} from $t/T_P = 0.7$ to 0.8 in

Figure 2b is mainly contributed by u_{rms}. The vertical turbulent intensity v_{rms} is shown in Figure 6b. At $t/T_P = 1/4$ and 2/4, the distributions of v_{rms} for $\mathrm{Ri}_\tau = 50$ are lower than that for $\mathrm{Ri}_\tau = 0$ near the bottom wall due to stable stratification effect. This character is consistent with the previous work for stably stratified turbulent channel flows [1, 2]. Then, the profiles of v_{rms} for $\mathrm{Ri}_\tau = 50$ at $t/T_P = 3/4$ and 0/4 (or 4/4) are higher than the distributions of $\mathrm{Ri}_\tau = 0$ due to unstable stratification effect.

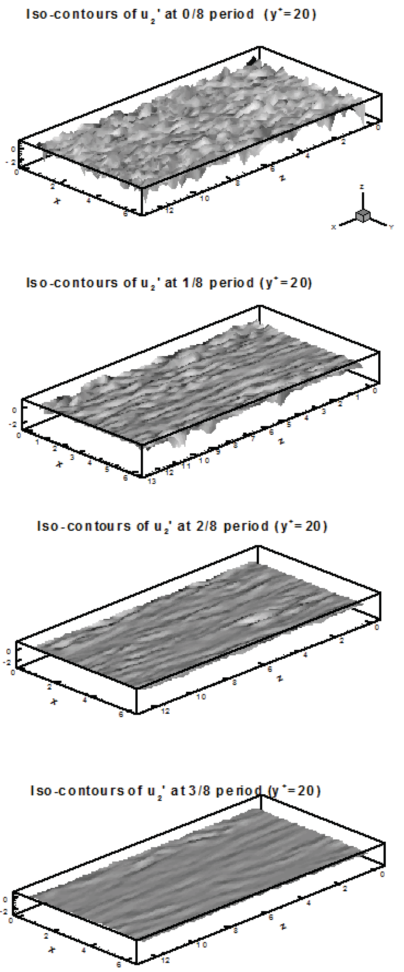

Figure 7. Instantaneous contours of the wall-normal velocity fluctuation in a $x-z$ plane at $y^+ = 20$. (a) $t/T_P = 0/8$, (b) 1/8, (c) 2/8, and (d) 3/8.

To get better insight into the flow structures, some typical instantaneous flow patterns are visualized. Figure 7 shows the instantaneous contours of the wall-normal velocity fluctuation at several phases, in a plane parallel to the wall at $y^+ = 20$. The patterns clearly illustrate the evolution of turbulent intensities with absent and healthy streaky structures at different phases. At $t/T_P = 0/8$ and 1/8, fairly healthy streaky structures can be observed, corresponding to the strengthened vertical turbulent intensity, very long streaks generate with respect to $t/T_P = 1/8$. This phenomenon is related to the energy transfer between the wall-normal and horizontal directions based on the analysis of the Reynolds-stress budgets. As stable stratification effect plays as a dominating factor from $t/T_P = 2/8$ to 3/8, turbulence is significantly suppressed and the absent streaky structures appear.

CONCLUDING REMARKS

Based on the calculated results, the behaviors of the phase-averaged velocities and temperature are mainly analyzed. When the temperature of the bottom wall is oscillating, the channel flow is undergone by stable and unstable stratification effect during one cycle. The phase-averaged velocity profile evolution appears the tendency of re-laminarization due to the stable stratification effect and varies gradually to blunt distribution due to the unstable stratification influence. The turbulence intensities are suppressed and the temperature fluctuation increases when stable stratification effect plays as a domination factor, and the turbulence intensities are strengthened and the temperature fluctuation decreases when unstable stratification effect is dominated. The instantaneous flow patterns clearly illustrate that the unsteady buoyancy force due to the temperature oscillation has a significant effect on the flow structures near the bottom wall of the channel.

ACKNOWLEDGEMENTS

This work was supported by the Natural Science Foundation of China (No. 10772109), the Shanghai Municipality Education Committee (No.09YZ03), the Key Project Science Foundation of Shanghai Sci. & Tech. Committee (No. 08JC1409800) and the Shanghai Leading Academic Discipline Project (No. Y0103).

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