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Unstable stratification effects on turbulent shear flow in the wall region

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Abstract—Measurements of the longitudinal and vertical velocities and temperature fluctuations in the wall region of fully-developed unstably-stratified flow between horizontal parallel plates were made. The unstable stratification effects on turbulent intensities, skewness and flatness factors and bursting period are discussed. The different dependences of these turbulent quantities and structure on unstable stratification in the wall region and outer region are made clear.

1. INTRODUCTION

THERE have been a number of theoretical and experimental studies on the stratified turbulent flow in the atmospheric surface layer or the wall region, over the last two decades. Recently, Gibson and Launder [1], Ueda *et al.* [2] and Fukui *et al.* [3] pointed out that the stratification effects on turbulent flow in the wall region were significantly different from ones in the outer region. Since the organized-structure motion, i.e. the so-called bursting process, arising under strong fluid shear in the wall region causes production of turbulence (see the papers of Kim *et al.* [4] and Corino and Brodkey [5]), the stratification effects on turbulent structure in this region are of great interest for the meteorological and engineering fields.

Although many field observations on the atmospheric surface layer (for example, Webb [6], Businger *et al.* [7], Pruitt *et al.* [8], Wyngaard *et al.* [9] and Haugen *et al.* [10]) have been presented, their data lack detailed information about the interaction between organized-structure motion near the wall and stratification because it is very difficult to obtain reliable data due to the inhomogeneity of topographic and thermal characteristics of the ground surface and also unsteadiness of air flow.

From the measurements in a special wind tunnel, Arya and Plate [11] showed that the similarity between the stably-stratified atmospheric boundary layer and the developing boundary layer in the wind tunnel existed. Arya [12] performed the experiments on stably and unstably-stratified flows and obtained the result that in the outer region the velocity and temperature profiles normalized by the wall parameters were strongly dependent on the stratification. Nicholl [13] studied the dynamical effects of a heated horizontal floor on the turbulent boundary layer. His investigation drew attention to the developing transition layer caused by a large temperature discontinuity. Townsend [14] also measured the fluctuations of velocity and temperature in the turbulent boundary layer over a strongly heated horizontal plane. He evaluated the thickness of the viscous-condition layer from the measurements of temperature fluctuations near the wall, which was the length scale in the fully turbulent region.

In order to discuss in more detail the stratification effects on the turbulent transport and its structure in the wall region, it is necessary to make measurements of turbulent quantities for stratified flows under thermally fully-developed condition. Fukui *et al.* [3] established a fully-developed stratified flow, by using a long rectangular duct with horizontal parallel plates which could be heated or cooled, and gave conclusive data of velocity and temperature profiles in the wall region of stably and unstably-stratified turbulent flows.

In the present paper, a new set of measurements for fluctuations of longitudinal and vertical velocity components and temperature in the fully-developed unstably-stratified flow is provided. The distributions of flatness and skewness factors and bursting period in the wall region are also given. In addition, we focused special attention on the differences of unstable stratification dependences of turbulent quantities and structure in both the wall region and the outer region.

2. EXPERIMENT

The experimental apparatus used in the present study is the same as the one described in a previous paper [3]. The main feature of the apparatus is described here.

The experiments were performed with a rectangular duct which was 8.0 m in length with 0.5×0.065 m cross-section and set horizontally. The heat transfer surfaces, made of polished brass plates, can be maintained at uniform but different temperatures by flowing cold and hot water (or steam) through jackets attached behind the heat transfer surfaces. The measurements were made at 7.5 m downstream from the entrance. This long entrance length was sufficient to establish fully-developed flow and temperature fields at the measuring section. From the preliminary experiments, it was

NOMENCLATURE

c_p	specific heat at constant pressure [J kg^{-1} K^{-1}]
F	flatness factor
g	gravitational acceleration [m s^{-2}]
H	threshold
k	von Karman constant
L	Monin–Obukhov length, $-u^{*3}/(kg\beta\overline{v\theta})$ [m]
q	heat flux [J m^{-2} s^{-1}]
Re	Reynolds number, $4\delta\langle U\rangle/\nu$
$\overline{Ri}$	bulk Richardson number, $g\beta\Delta T\delta/2\langle u\rangle^2$
S	skewness factor
S_i	sorting function
T	time-averaged temperature [K]
T_w	temperature at cooled wall [K]
T^+	dimensionless temperature, $(T-T_w)/T^*$
T^*	friction temperature, $\|q\|/(\rho c_p u^*)$ [K]
ΔT	temperature difference at heated and cooled walls [K]
t	time [s]
U	time-averaged longitudinal velocity [m s^{-1}]
U^+	dimensionless velocity, U/u^*
U_δ	time-averaged velocity at the centre of the duct [m s^{-1}]
u	longitudinal velocity fluctuation [m s^{-1}]
u^*	friction velocity, $\sqrt{\|\tau_w\|/\rho}$ [m s^{-1}]
$\langle U\rangle$	velocity averaged over the fluid layer [m s^{-1}]
u'	intensity of u, $\sqrt{\overline{u^2}}$ [m s^{-1}]
v	vertical velocity fluctuation [m s^{-1}]
v',	intensity of v, $\sqrt{\overline{v^2}}$ [m s^{-1}]
y	distance from the wall [m]
y^+	dimensionless distance, yu^*/ν.

Greek symbols

β	thermal expansion coefficient [K^{-1}]
δ	half-distance between the walls [m]
θ	temperature fluctuation [K]
θ'	intensity of θ, $\sqrt{\overline{\theta^2}}$ [K]
ν	kinematic viscosity [m^2 s^{-1}]
ρ	density [kg m^{-3}]
τ_b	mean bursting period [s]
τ_w	shear stress at the wall [Pa m^{-2}].

confirmed that temperature profile exhibited a point symmetry about the centre of the duct because the temperature and velocity profiles were fully developed. Hence, the heat flux was constant throughout the fluid layer. The cooled upper plate was used as a heat transfer surface.

Since the measurements in this study were carried out under the thermally fully-developed condition, the turbulence throughout the fluid layer was strongly affected by stratification. It is expected that reliable data may be obtained so that the different dependences of turbulent structure and quantities on unstable stratification in both the wall region and the outer region can be discussed in more detail.

Instantaneous velocity was measured with a ×-wire probe which consisted of platinum-coated tungsten wires (5 μm in diameter and about 1.2 mm long). The wires were operated with constant temperature anemometers. The temperature was measured with a Wollaston wire (1 μm in diameter and 1.3 mm long). The cold wire operated with a constant current (0.1 mA) was set 0.7 mm upstream from the centre of the hot ×-wire probe and in a direction perpendicular to the plane of the probe.

The output signals from the instruments were directly digitized using a 12 bits A/D converter and stored on magnetic tape. The sampling interval was 0.00125 s and the sample size 50,000. The time-averaged values and the fluctuations of velocity and temperature were calculated and the statistical processing of the digitized data were made with the FACOM M360 computer system in the Data Processing Center of Himeji Institute of Technology.

The cross-sectional mean velocity, $\langle u\rangle$, ranged from 0.94 to 1.75 m s^{-1} and the temperature difference between heat transfer surfaces was between 35.4 and 81.0 K. Thus, the Reynolds number, Re ($\equiv 4\delta\langle u\rangle/\nu$), based on the hydraulic equivalent diameter ranged from 6500 to 13,900 and the overall Richardson number, $\overline{Ri}$ ($\equiv g\beta\Delta T\delta/2\langle u\rangle^2$), from -0.0059 to -0.0451.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. *Mean velocity and temperature profiles*

The time-averaged values of velocity and temperature normalized by the wall parameters, U^+ ($\equiv U/u^*$) and T^+ ($\equiv (T-T_w)/T^*$), are presented in Figs. 1 and 2 against the dimensionless distance from the wall, y^+ ($\equiv yu^*/\nu$), where u^* is the friction velocity and T^* the friction temperature. The bulk Richardson number, $\overline{Ri}$, is the parameter which represents the degree of stratification.

The velocity profile for the slightly unstable run ($\overline{Ri} = -0.0059$) is in good agreement with the logarithmic law of the wall. In this study, the temperature gradient near the wall is very large so that the dependencies of velocity and temperature profiles on the Richardson number are significant even in the wall

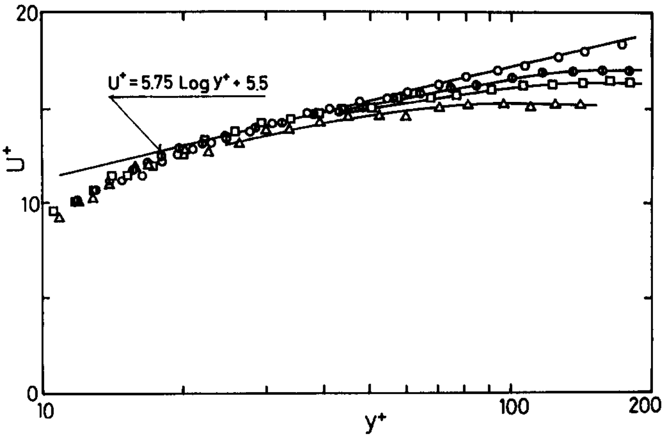

FIG. 1. Distributions of time-averaged velocity. ○, $\overline{Ri} = -0.0059$, $Re = 13900$; ◐, $\overline{Ri} = -0.0189$, $Re = 10400$; □, $\overline{Ri} = -0.0241$, $Re = 9100$; ●, $\overline{Ri} = -0.0321$, $Re = 7700$; △, $\overline{Ri} = -0.0451$, $Re = 6500$.

region. The temperature profile depends more remarkably on unstable stratification as compared with the velocity profile. This is anticipated from our results [3] that turbulent Prandtl number decreases with increasing degree of unstable stratification.

Fukui *et al.* [3] proposed the local gradient model which is useful for estimating the profiles of velocity and temperature and eddy diffusivities for momentum and heat transfer for both unstably and stably-stratified flows in the wall region. The present results agree well with the predictions from this model.

3.2. *Effects of unstable stratification on turbulent intensities*

Measurements of turbulent intensities of longitudinal and vertical velocity fluctuations, u' and v', in unstably-stratified flows are presented against y^+ in Figs. 3 and 4 where the intensities are normalized by the friction velocity. In Fig. 5, the intensity of temperature fluctuation normalized by the friction temperature are presented.

In slightly-stratified flow of $\overline{Ri} = -0.0059$, the distribution of u'/u^* shows the maximum at $y^+ \simeq 15$ and decreases with y^+, and the values of v'/u^* increase with y^+ near the wall and reach the maximum value of about unity. These trends of the present results agree with the measurements of Kreplin and Eckelmann [15] and Laufer [16].

Since the heat flux is constant over the fluid layer in this study, θ'/T^* is approximately constant in the region of $y^+ > 20$ and its profile for $\overline{Ri} = -0.0059$ is in good agreement with the previous results [17] obtained in the fully-developed vertical flow between parallel plates.

As seen in these figures, increasing instability in stratification has significant effects on the dimensionless intensities of u', v' and θ'. The values of u'/u^* in the region of $y^+ < 50$ increase with increasing instability and have a maximum in the region of $15 < y^+ < 20$, the same region as ones for weakly-stratified flow. In the outer region of $y^+ > 100$, however, there is almost no effect of stratification. The measurements of u' in the

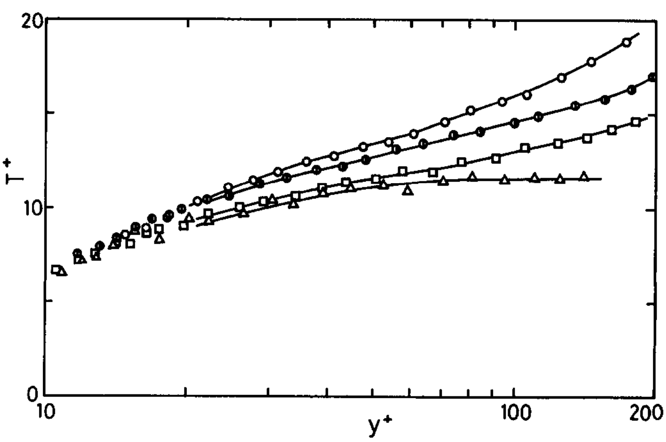

FIG. 2. Distributions of time-averaged tempeature. Legend as Fig. 1.

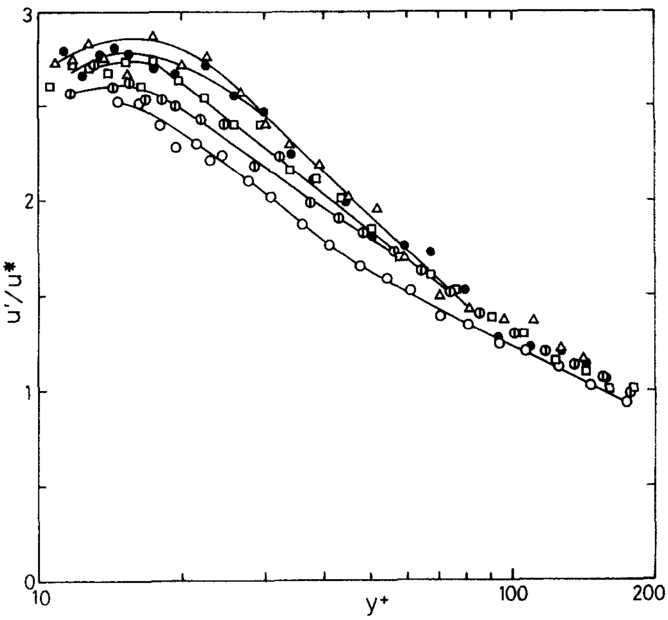

FIG. 3. Intensity of longitudinal velocity fluctuation. Legend as Fig. 1.

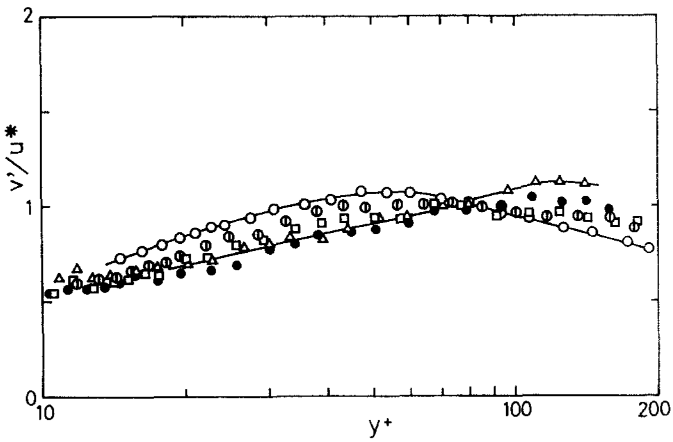

FIG. 4. Intensity of vertical velocity fluctuation. Legend as Fig. 1.

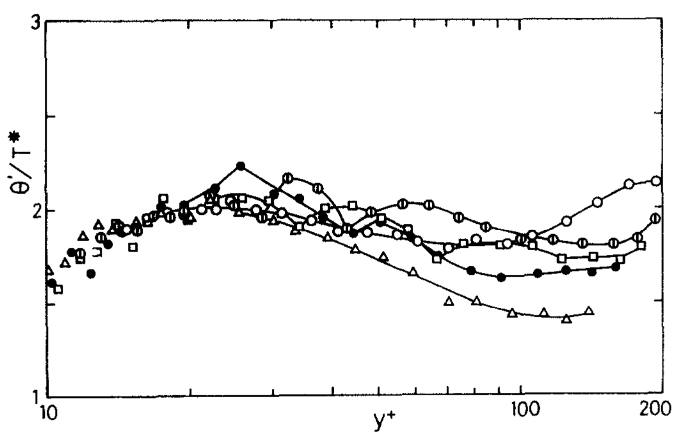

FIG. 5. Intensity of temperature fluctuation. Legend as Fig. 1.

wall region of the turbulent boundary layer over the heated horizontal plane (Nicholl [13] and Townsend [14]) showed the remarkable increase in intensity. In this case there was a large temperature gradient near the wall. Komori [18] studied the turbulent structure in the strongly-stratified flow in the open channel and showed that the value of u'/u^* near the free surface, that is, in the outer region, hardly changed even under the most strongly stratified condition. Thus, the different dependences of turbulent intensities of u on unstable stratification in the wall region and outer region agree with their results.

As seen in Fig. 4, v'/u^* decreases in the region of $y^+ < 75$, i.e. in the wall region but increases slightly in the outer region of $y^+ > 75$. Although the maximum occurs at the position of $y^+ \simeq 50$ in the case of weakly-stratified flow, the maximum vanishes for strongly-stratified flow and v'/u^* monotonously increases with y^+. Wyngaard *et al.* [9] showed that v'/u^* increased in proportion to $(-y/L)^{1/3}$ where L was the Monin–Obukhov length. But the dependence of v'/u^* in the region of $10 < y^+ < 70$ on unstable stratification can not be explained from their correlation because the values of v'/u^* in this region decrease with increasing instability.

The intensities of temperature fluctuation, θ'/T^*, decrease remarkably in the region of $y^+ > 100$ with increasing instability. A similar trend was shown by Wyngaard *et al.* [9]. The value of θ'/T^* at $y^+ < 25$, however, remained constant as reported in the previous paper [3]. In the region of $25 < y^+ < 100$ the measurements of the intensities scatter and the stratification effect on them is not distinguished clearly.

The stratification effects on turbulent structure in the outer region, that is, in the free turbulence, can be evaluated by local Richardson number, as shown by Komori [18]. As to the stratification effects on turbulence in the wall region, Fukui *et al.* [3] showed the similarity that the ratios of u'/u^* and θ'/T^* in the stably and unstably-stratified flows to those in neutral flow at the same y^+ position were well correlated with only one parameter y/L in the region of $y^+ < 50$. The dependency of the present data, u'/u^*, v'/u^* and θ'/T^* in this region, on unstable stratification also confirms the reliability of the similarity.

3.3. *Flatness and skewness factors*

To investigate the shape of the probability density distributions of fluctuations, the flatness and skewness factors which are defined as follows are introduced.

$$F(\alpha) = \overline{\alpha^4}/\alpha'^4,\ S(\alpha) = \overline{\alpha^3}/\alpha'^3 \qquad (1)$$

where $\alpha = u, v, \theta$ and α' is their intensity of fluctuation. The two factors are plotted against y^+ in Figs. 6 and 7. Kreplin and Eckelmann [15] measured the skewness and flatness factors of the u and v components in an isothermal flow. Their experiments gave the following results. At $y^+ \simeq 13$, $F(u)$ has the minimum value of 2.2 and $F(v)$ reaches the maximum of 4.9, and at $y^+ > 40$, $F(u) \simeq 3$ and $F(v) \simeq 3.5$. As to the skewness factors, $S(u)$ becomes zero at $y^+ \simeq 13$ and reaches the constant value of -0.54 with increasing y^+, and $S(v)$ C.1 $\sim$ 0.2 in the region of $10 < y^+ < 100$. Recently, Johnson and Eckelman [19] also showed that $S(v)$ had the maximum value of 3 at $y^+ \simeq 110$. Considering the difficulties of measuring these quantities, the present results agree well with theirs.

The dependency of the flatness factors of u, v and θ on unstable stratification is not so significant, but for strongly-stratified flow $F(u)$ increases slightly in the region of $40 < y^+ < 100$ and $F(v)$ decreases in the region of $y^+ < 30$. However, the skewness factors depend strongly on stratification. In the range of y^+ less than about 100 both $S(u)$ and $S(\theta)$ decrease remarkably

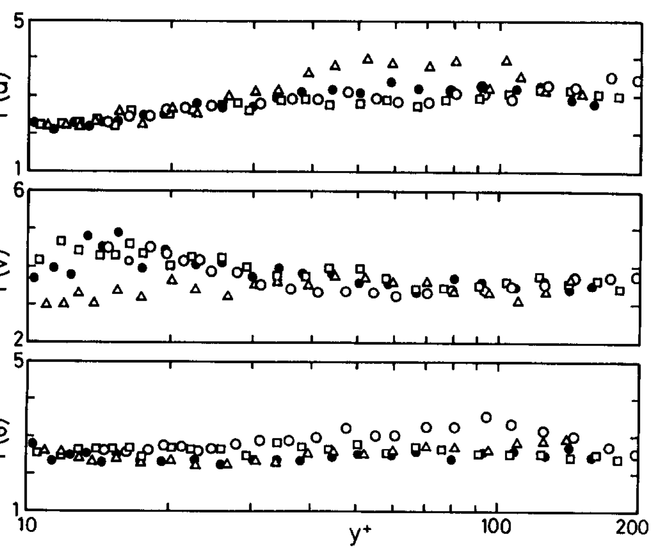

FIG. 6. Flatness factors of velocity and temperature fluctuations. Legend as Fig. 1.

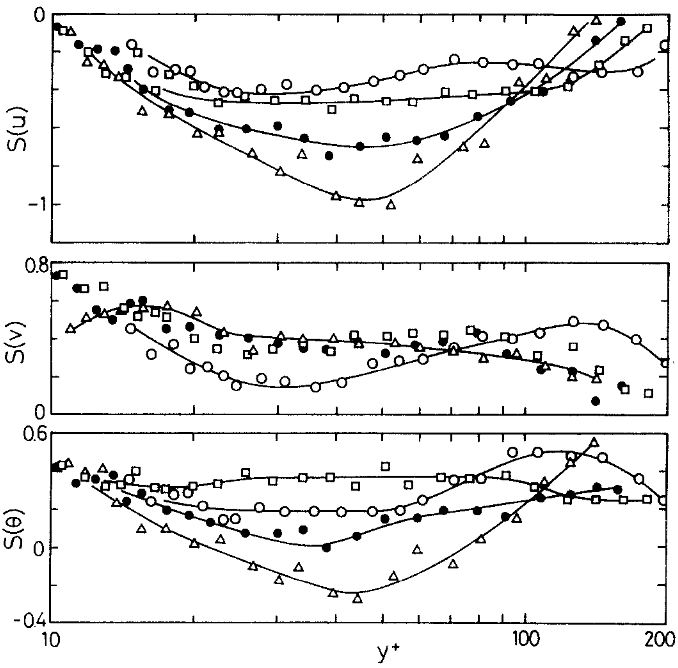

FIG. 7. Skewness factors of velocity and temperature fluctuations. Legend as Fig. 1.

and $S(v)$ increases with increasing instability. But in the region of $y^+ > 100$ the different dependencies of skewness factor on stratification are seen. For both $S(u)$ and $S(\theta)$ the minimum occurs at the same position of $y^+ \simeq 45$. At the same position, $S(\theta)$ becomes negative under strongly unstable conditions. In the present work the wall was cooled and then heat is transferred from another heated wall to this cooled wall. Therefore, we can expect that unstable stratification promote the ejection motion and the fluid cooled near the wall is transferred violently to the position of $y^+ \simeq 45$.

3.4. *Stratification effects on instantaneous turbulent flux of momentum and heat*

It is very important to understand more precisely the effects of unstable stratification on the turbulent momentum flux, namely, Reynolds stress and heat flux. To make clear the coherent structure of turbulence near the wall, Lu and Willmarth [20] proposed the conditional analysis technique which the instantaneous Reynolds stress was divided into four different events in the u–v plane. That is,

$$\frac{\widetilde{uv}_i(H)}{\overline{uv}} = \frac{1}{\overline{uv}} \lim_{\tau\to\infty} \frac{1}{\tau}\int_0^\tau uv(t)\,S_i(t,H)\,\mathrm{d}t \quad (2)$$

where the sorting function S_i is defined as

$$S_i(t,H) = \begin{cases} 1 \text{ if } |uv(t)| > H\cdot u'\cdot v' \\ 0 \text{ otherwise.}\end{cases} \quad (3)$$

The subscript i refers to the ith quadrant in the u–v plane. τ denotes the sampling time and H the hole size. So $\widetilde{uv}_i/\overline{uv}$ express the contributions to total Reynolds stress from the different events and are dependent on the hole size. The second ($u < 0$, $v > 0$) and fourth ($u > 0$, $v < 0$) quadrants represent the ejection and sweep motions, respectively. The first ($u > 0$, $v > 0$) and third ($u < 0$, $v < 0$) quadrants represent the outward and inward interaction motions. Their technique was applied to analyse the statistical behaviours of turbulent motions in the unstably-stratified flow.

As seen in Fig. 7, the skewness factors of u and θ for strongly-stratified flow have a minimum at $y^+ \simeq 45$. So we selected three points, i.e. $y^+ \simeq 15$, 45 and 125, as the specified ones.

Figure 8(a) shows the measured results for the slightly-stratified flow. At $y^+ = 14.7$ contributions of ejection ($\widetilde{uv}_2$) and sweep ($\widetilde{uv}_4$) motions to the total Reynolds stress are nearly equal to each other. The ratio of $\widetilde{uv}_2/\widetilde{uv}_4$ increases in the range of $15 < y^+ < 20$ but is approximately constant in the range of $20 < y^+ < 100$. And it increases slightly at $y^+ = 126$. As compared to these two intense motions the contributions of interaction motions are weaker and almost constant in the whole wall region. These behaviours of four motions in the wall region are in good agreement with those of Wallace *et al.* [21].

The results of strongly-stratified unstable flow are shown in Fig. 8(b). In the outer region of $y^+ = 125$, the stratification effects on all four events are found evidently. Above all the ejection motion is affected remarkably and makes the largest contribution to the total turbulent momentum flux. These effects of unstable stratification are similar to those in the open channel flow with cooled free surface (Mizushina *et al.* [22]). At the positions of $y^+ = 15.5$ and 52.1, however,

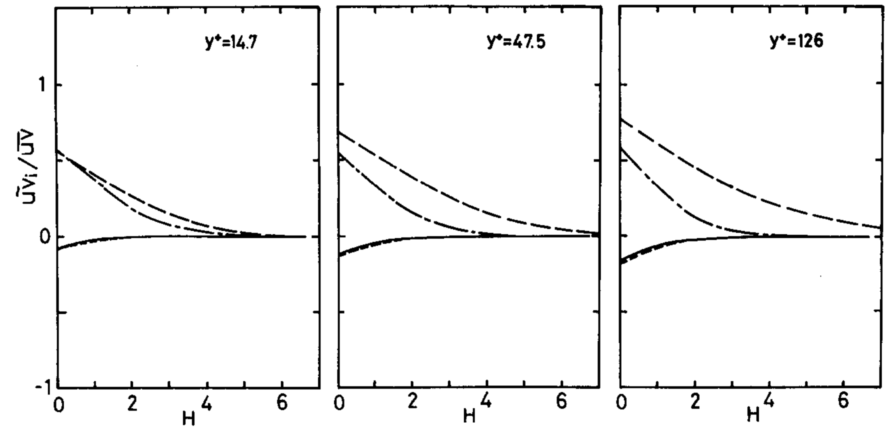

FIG. 8(a). Contributions to total turbulent momentum flux from different events in slightly-stratified flow $(\overline{Ri} = -0.0059)$. -----, $u > 0, v > 0$; — — —, $u < 0, v > 0$; ———, $u < 0, v < 0$; —·—, $u > 0, v < 0$.

the contributions of sweep motion and interaction motions are not so dominant but only the ejection contribution increases with instability.

Consequently, the following results are obtained from the experiments over the range of $y^+ > 10$ for strongly-stratified flow. Since only the ejection motion is promoted in the region of $y^+ < 15$, its contribution to the total momentum flux increases. The contribution of the intense ejection motion in the range of $15 < y^+ < 80$, however, remains almost constant. On the contrary, the contributions of the other three events, that is, sweep and interaction motions, were not very much affected even with increasing instability. In the region of $y^+ > 90$, all four motions are remarkably promoted so that the contributions of large-amplitude motions increase with y^+.

In the next instance, the unstable stratification effects on instantaneous turbulent heat flux were examined with the use of the conditional averaging technique. The contributions to total turbulent heat flux from the four events are expressed by

$$\frac{\widetilde{v\theta}_i(H)}{\overline{v\theta}} = \frac{1}{\overline{v\theta}} \lim_{\tau \to \infty} \frac{1}{\tau} \int_0^\tau v\theta(t) S_i(t, H)\, \mathrm{d}t \qquad (4)$$

where S_i is defined by equation (3).

The experimental results for the slightly-stratified unstable flow are shown in Fig. 9(a). Since all four contributions of $\widetilde{v\theta}_i/\overline{v\theta}$ and the dependences of hole size are similar to ones of $\widetilde{uv}_i/\overline{uv}$ as shown in Fig. 8(a), the turbulent transport mechanism of heat is found to be correlated adequately with one of momentum so that both the ejection and sweep motions mainly contribute to the turbulent heat transfer.

Figure 9(b) shows the results for the strongly-stratified unstable flow. Although the contribution of ejection motion to the total turbulent momentum flux increased remarkably with instability, its contribution to the total turbulent heat flux is not so evidently

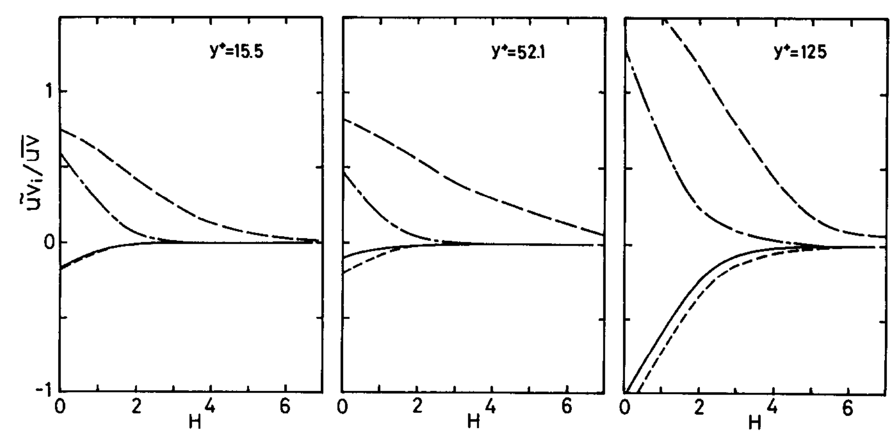

FIG. 8(b). Contributions to total turbulent momentum flux from different events in strongly-stratified flow $(\overline{Ri} = -0.0451)$. Legend as Fig. 8(a).

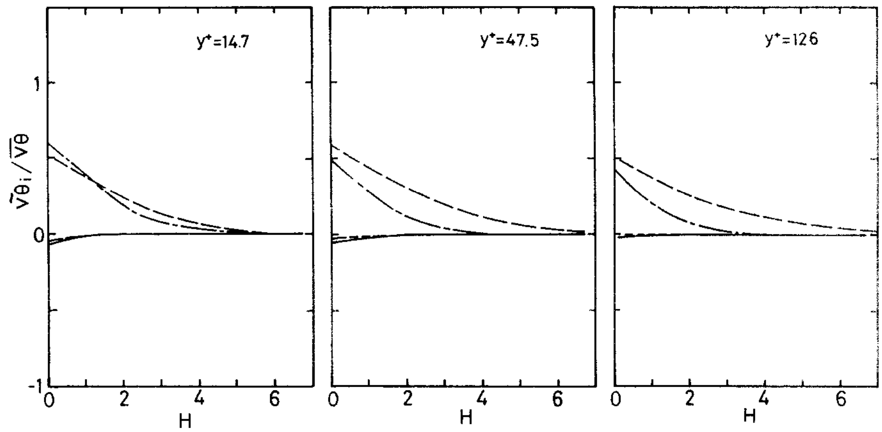

FIG. 9(a). Contributions to total turbulent heat flux from different events in slightly-stratified flow ($\overline{Ri} = -0.0059$). Legend as Fig. 8(a).

dependent on instability but slightly increased at $y^+ = 15.5$ and 52.1 as compared with the results of weakly-stratified flow.

It is noticed here that at $y^+ = 125$ the contribution of inward interaction motion to the total turbulent heat flux, $\widetilde{v\theta}_3/\overline{v\theta}$, represented by a solid curve in Fig. 9(b), is positive in the range of $H < 3$. Since the inward interaction motion ($u < 0, v < 0$) represents the motion upward to the cooled wall, the hot eddy is transferred by this motion so that $\widetilde{v\theta}_3/\overline{v\theta}$ must be negative as a general rule. Hence the positive value of $\widetilde{v\theta}_3/\overline{v\theta}$ implies that the cold eddy is transferred from hot fluid layer to cold fluid layer by the inward interaction motion and then by counter-gradient heat flux. The theoretical and experimental study on laminar longitudinal vortices generated in the horizontal fluid layer heated from below showed the counter-gradient heat flux in the centre region of the vortex by Fukui *et al.* [23]. Recently, authors [24] also found the large ordered motion of turbulent longitudinal vortices in the strongly-stratified unstable turbulent flow. Therefore, the counter-gradient heat flux, that is, the negative value of $\widetilde{v\theta}_3/\overline{v\theta}$ is expected to be caused by this turbulent longitudinal vortices.

3.5. *Stratification effects on bursting period*

It is very interesting to obtain the mean bursting period and to investigate its dependence on unstable stratification. Although several methods have been proposed to determine the bursting period, the technique of Lu and Willmarth [20] was adopted in this study. The mean bursting period is defined as follows:

$$\tau_b = \tau \Big/ \int_0^\tau S_2(t, H)\,dt \tag{5}$$

τ_b depends strongly on the hole size. For example, Lu and Willmarth obtained the bursting period by setting $H = 4 \sim 4.5$ and Nakagawa *et al.* [25] showed that the results of τ_b for $H = 2$ agreed with their visual data.

The results of τ_b with $H = 2$ and 3 for unstably-stratified flows are shown in Fig. 10. The dimensionless

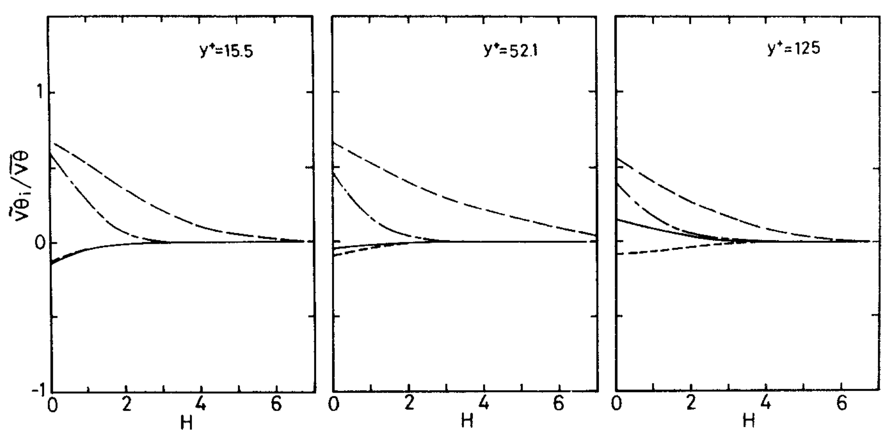

FIG. 9(b). Contributions to total turbulent heat flux from different events in strongly-stratified flow ($\overline{Ri} = -0.0451$). Legend as Fig. 8(a).

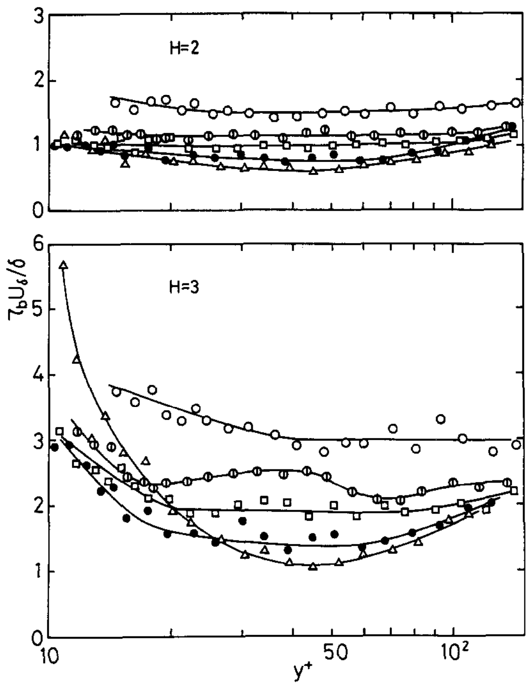

FIG. 10. Distributions of mean bursting period with $H = 2$ and 3. Legend as Fig. 1.

bursting period with $H = 3$ for slightly-stratified flow agrees well with those in neutral flows given by Laufer and Narayanan [26] ($\tau_b U_\delta/\delta \simeq 5$) and Nakagawa *et al.* [25] ($\tau_b U_\delta/\delta \simeq 1.5 \sim 3.0$). From this figure, τ_b evidently depends significantly on the hole size and stratification.

In both cases for $H = 2$ and 3, the bursting period decreases with $|\overline{Ri}|$. The bursting period for $H = 2$ distributed uniformly throughout the whole ranges of y^+, but ones for $H = 3$ depended significantly on y^+. In the case of $H = 3$, the profile of $\tau_b U_\delta/\delta$ for strongly-stratified flow have the minimum at $y^+ \simeq 45$. This position is equal to one where the skewness factors of longitudinal velocity and temperature fluctuations have the minimum (see Fig. 7) but the physical meaning of this is uncertain. By using the results for $H = 3$ the corrlation between $\tau_b U_\delta/\delta$ and $\overline{Ri}$ was obtained as follows:

$$\tau_b U_\delta/\delta = 3.6 - 31.3\,|\overline{Ri}|^{0.8} \quad (6)$$

where $\tau_b U_\delta/\delta$ was determined at $y^+ = 45$. It is thought, however, that the hole size to determine the bursting period depends significantly on instability and also the period for strongly-stratified flow depends remarkably on y^+.

Though it is thought that the bursting process and turbulent structure are affected significantly by the large-scale motion of turbulent longitudinal vortex under unstably-stratified condition and also by the bursts generated near the opposite wall (Sabot and Comte-Bellot [27]), these problems will be discussed in more detail in the near future.

4. CONCLUSIONS

The experimental results obtained in the wall region of the fully-developed unstably-stratified flow between the horizontal parallel plates are summarized as follows.

(1) The dependences of turbulent intensities of fluctuations on unstable stratification in the wall region are different from those of the outer region. The intensity of longitudinal velocity fluctuation increases with instability of stratification in the region of $y^+ < 50$ but in the outer region remains almost constant. The intensity of vertical velocity fluctuation decreases significantly in the region of $y^+ < 75$, and monotonously increases with y^+ in the case of strongly stratified flow although it increases in the outer region of $y^+ > 100$ with increasing instability. The unstable stratification has no effect on the intensity of temperature fluctuation in the region of $y^+ < 25$ but causes the intensity to increase slightly in the outer region.

(2) Although the flatness factors of two velocity components and temperature are almost independent on stratification degree except for strongly-stratified flow, the skewness factors of these three fluctuations are remarkably affected with stratification. The skewness factors of longitudinal velocity and temperature fluctuations for strongly-stratified flow have the minimum at $y^+ \simeq 45$. The skewness factor of vertical velocity fluctuation increases in the region of $15 < y^+ < 70$ with increasing instability of stratification but decreases in the region of $y^+ > 70$.

(3) In the wall region, the contribution of ejection motion to the total turbulent momentum flux increases but the contributions of sweep and interaction motions are almost independent of unstable stratification. In the outer region, all these motions are promoted. The contributions of the four motions to the total turbulent heat flux is not significantly dependent on unstable stratification. But, in the case of inward interaction motion under strongly-stratified condition, counter-gradient heat flux occurs in the outer region. It is thought that the counter-gradient heat flux is caused by the ordered large-scale motion of turbulent longitudinal vortex.

(4) The bursting period decreases with instability and the correlation with bulk Richardson number is proposed. The period for strongly-stratified flow has the minimum at $y^+ \simeq 45$ where the skewness factors of longitudinal velocity and temperature fluctuations also have the minimum. It is considered, however, that the conditional sampling method in order to determine the bursting period for stratified flows is necessary to be established in the future because the hole size and bursting process depend strongly on the stratification.

REFERENCES

1. M. M. Gibson and B. E. Launder, Ground effects on pressure fluctuations in the atmospheric boundary layer, *J. Fluid Mech.* **86**, 491–511 (1978).

2. H. Ueda, S. Mitsumoto and S. Komori, Buoyancy effects on the turbulent transport processes in the lower atmosphere, *Q. Jl R. met. Soc.* **107**, 561–578 (1981).
3. K. Fukui, M. Nakajima and H. Ueda, A laboratory experiment on momentum and heat transfer in the stratified surface layer, *Q. Jl R. met. Soc.* **109**, 661–676 (1983).
4. H. T. Kim, S. J. Kline and W. C. Reynolds, The production of turbulence near a smooth wall in a turbulent boundary layer, *J. Fluid Mech.* **50**, 133–160 (1971).
5. E. R. Corino and R. S. Brodkey, A visual investigation of the wall region in turbulent flow, *J. Fluid Mech.* **37**, 1–30 (1969).
6. E. K. Webb, Profile relationships: the log-linear range, and extension to strong stability, *Q. Jl R. met. Soc.* **96**, 67–90 (1970).
7. J. A. Businger, J. C. Wyngaard, Y. Izumi and E. F. Bradley, Flux-profile relationships in the atmospheric surface layer, *J. atmos. Sci.* **28**, 181–189 (1971).
8. W. O. Pruitt, D. L. Morgan and F. J. Lourence, Momentum and mass transfers in the surface boundary layer, *Q. Jl. R. met. Soc.* **99**, 370–386 (1973).
9. J. C. Wyngaard, O. R. Coté and Y. Izumi, Local free convection, similarity, and the budgets of shear stress and heat flux, *J. atmos. Sci.* **28**, 1171–1182 (1971).
10. D. A. Haugen, J. C. Kaimal and E. F. Brodkey, An experimental study of Reynolds stress and heat flux in the atmospheric surface layer, *Q. Jl R. met. Soc.* **97**, 168–180 (1971).
11. S. P. S. Arya and E. J. Plate, Modeling of the stably stratified atmospheric boundary layer, *J. atmos. Sci.* **26**, 656–665 (1969).
12. S. P. S. Arya, Buoyancy effects in a horizontal flat-plate boundary layer, *J. Fluid Mech.* **68**, 321–343 (1975).
13. C. I. H. Nicholl, Some dynamical effects of heat on a turbulent boundary layer, *J. Fluid Mech.* **40**, 361–384 (1970).
14. A. A. Townsend, Mixed convection over a heated horizontal plane, *J. Fluid Mech.* **55**, 209–227 (1972).
15. H.-P. Kreplin and H. Eckelmann, Behavior of the three fluctuating velocity components in the wall region of a turbulent channel flow, *Phys. Fluids* **22**, 1233–1239 (1979).
16. J. Laufer, The structure of turbulence in fully developed pipe flow, NACA Technical Report 1174 (1954).
17. M. Nakajima, K. Fukui, H. Ueda and T. Mizushina, Buoyancy effects on turbulent transport in combined free and forced convection between vertical parallel plates, *Int. J. Heat Mass Transfer* **23**, 1325–1336 (1980).
18. S. Komori, Turbulent structure in stratified flow. Doctoral dissertation, Kyoto University, Kyoto (1980).
19. F. D. Johnson and H. Eckelmann, A variable angle method of calibration for X-probes applied to wall-bounded turbulent shear flow, *Exp. Fluids* **2**, 121–130 (1984).
20. S. S. Lu and W. W. Willmarth, Measurements of the structure of the Reynolds stress in a turbulent boundary layer, *J. Fluid Mech.* **60**, 481–511 (1973).
21. J. M. Wallace, H. Eckelmann and R. S. Brodkey, The wall region in turbulent shear flow, *J. Fluid Mech.* **54**, 39–48 (1972).
22. T. Mizushina, F. Ogino and N. Katada, Ordered motion of turbulence in a thermally stratified flow under unstable conditions, *Int. J. Heat Mass Transfer* **25**, 1419–1425 (1982).
23. K. Fukui, M. Nakajima and H. Ueda, The longitudinal vortex and its effects on the transport processes in combined free and forced laminar convection between horizontal and inclined parallel plates, *Int. J. Heat Mass Transfer* **26**, 109–120 (1983).
24. K. Fukui, M. Nakajima and H. Ueda, Turbulent longitudinal vortices in unstably stratified turbulent flow between horizontal parallel plates, *22nd National Heat Transfer Symposium of Japan*, B217 (1985).
25. H. Nakagawa and I. Nezu, Bursting phenomena near the wall in open-channel flows and its simple mathematical model, *Mem. Fac. Engng Kyoto Univ.* **40**, 213–240 (1978).
26. J. Laufer and M. A. B. Narayanan, Mean period of the turbulent production mechanism in a boundary layer, *Phys. Fluids* **14**, 182–183 (1971).
27. J. Sabot and G. Comte-Bellot, Intermittency of coherent structures in the core region of fully developed turbulent pipe flow, *J. Fluid Mech.* **74**, 767–796 (1976).

EFFETS DE LA STRATIFICATION INSTABLE SUR L'ECOULEMENT TURBULENT DE CISAILLEMENT DANS LA REGION PARIETALE

Résumé—On mesure les fluctuations des vitesses longitudinale et verticale et de température dans la région de paroi d'un écoulement développé, stratifié de façon instable, entre des plans horizontaux parallèles. Les effets de la stratification instable sur les intensités turbulentes, les facteurs de dissymétrie et d'aplatissement et la période d'éclatement sont discutés. On clarifie les différentes dépendances de ces quantités turbulentes et de la structure sur la stratification instable dans la région pariétale et dans la région extérieure.

DIE FOLGEN INSTABILER SCHICHTUNG BEI TURBULENTER SCHERSTRÖMUNG IM WANDBEREICH

Zusammenfassung—Die Geschwindigkeiten längs und quer zur Hauptströmungsrichtung und die Temperaturschwankungen im Wandbereich einer voll ausgebildeten instabil geschichteten Strömung zwischen zwei horizontalen parallelen Platten wurden gemessen. Der Effekt instabiler Schichtung auf die turbulenten Intensitäten, Schwankungs- und Glättungsfaktoren und die Dauer des Auftretens werden erörtert. Die verschiedenen Abhängigkeiten dieser turbulenten Größen und der Aufbau der instabilen Schichtung im Wandbereich und außerhalb davon werden verständlich gemacht.

ВЛИЯНИЕ НЕУСТОЙЧИВОЙ СТРАТИФИКАЦИИ НА ТУРБУЛЕНТНОЕ СДВИГОВОЕ ТЕЧЕНИЕ В ПРИСТЕННОЙ ОБЛАСТИ

Аннотация—Проведены измерения продольной и вертикальной составляющих скорости и флуктуаций температуры в пристенной области полностью развитого неустойчиво стратифицированного течения между горизонтальными параллельными пластинами. Обсуждается влияние неустойчивой стратификации потока на интенсивность турбулентности, коэффициенты асимметрии и неоднородности, а также на период возмущений. Выясняются различные зависимости этих турбулентных величин и структуры потока от неустойчивой стратификации в пристенной и других областях.