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# Effect of stable-density stratification on counter gradient flux of a homogeneous shear flow

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**Abstract**

We performed direct numerical simulations of homogeneous shear flow under stable-density stratification to study the buoyancy effects on the heat and momentum transfer. These numerical data were compared with those of a turbulent channel flow to investigate the similarity between the near-wall turbulence and the homogeneous shear flow. We also investigated the generation mechanism of the persistent CGFs (counter gradient fluxes) appearing at the higher wavenumbers of the cospectrum, and lasting over a long time without oscillation. Spatially, the persistent CGFs are associated with the longitudinal vortical structure, which is elongated in the streamwise direction and typically observed in both homogeneous shear flow and near-wall turbulence. The CGFs appear at both the top and bottom of this longitudinal vortical structure, and expand horizontally with an increase in the Richardson number. It was found that the production and turbulent-diffusion terms are responsible for the distribution of the Reynolds shear stress including the persistent CGFs. The buoyancy term, combined with the swirling motion of the vortex, contributes to expand the persistent CGF regions and decrease the down gradient fluxes.


*Keywords:* Counter gradient flux; Stable-density stratification; Vortical structure; DNS

## 1. Introduction

The stratified flow is defined as a flow primarily in the horizontal direction that is affected by a vertical variation of the density [1]. Such flows are very important in geophysics as well as engineering. Not only in many important engineering flows, but also in geophysical flows, turbulent momentum and heat transports occur in the near-wall region under the presence of stable-density stratification. That region's longitudinal streamwise vortical structure makes a significant contribution to the momentum and heat transfer [2,3]. This longitudinal vortical structure is elongated in the streamwise direction and characterized by the streamwise vortical motion and intense streamwise vorticity.

Recently, that same vortical structure was observed in the homogeneous shear flow as well in the wall turbulence [4]; similar strain rates, which affect the redistribution and energy transfer of the Reynolds stresses as well as their production, were found to be imposed on the vortical structure of both the homogeneous shear flow and wall turbulence. Hence, similar buoyancy effects may be observed on the heat and momentum transfer associated with the vortical structure, although no quantitative comparison has been made between the homogeneous shear flow and near-wall turbulence under stable-density stratification.

As far as stable-density stratification is concerned, many numerical and experimental studies have been performed on homogeneous shear flow, and counter-gradient fluxes (CGFs) have been investigated there in detail [4–10].

The CGFs represent the Reynolds shear stresses which transfer the momentum to enhance the imposed mean shear and contribute to the negative production of turbulent kinetic energy $k$, and hence they are local phenomena in time or space [12]. Under stable density stratification, however, the CGFs may become quantitatively more important

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**Nomenclature**

| | |
|---|---|
| $D_\kappa$ | spectrum of dissipation rate $\varepsilon$ |
| $E_\kappa$ | energy spectrum of turbulent kinetic energy $k$ |
| $E_{12}$ | cospectrum of velocity fluctuations $u_1$ and $u_2$ |
| $E_{12}^*$ | $E_{12}$ normalized by the spatial average of the Reynolds shear stress |
| $g$ | gravitational acceleration |
| $II$ | second invariant of deformation tensor |
| $II_{\mathrm{r.m.s.}}$ | root-mean-square value of $II$ |
| $k$ | turbulent kinetic energy, $\overline{u_i u_i}/2$ |
| $k_0$ | initial turbulent kinetic energy |
| $L_i$ | side of computational region in the $i$th direction |
| $L_{ij,k}$ | integral scale of $k$th direction, $\int_0^{L_k/2}\overline{u_i(x_k)u_j(x_k+r_k)}/\sqrt{\overline{u_i^2}}\sqrt{\overline{u_j^2}}dr_k$ |
| $N$ | buoyancy frequency, $\sqrt{g\beta S_\theta}$ |
| $Pr$ | the Prandtl number |
| $p$ | pressure (see Eq. (10) for detail definition) |
| $p_{\mathrm{r}}$ | rapid pressure (see Eq. (11) for detail definition) |
| $p_{\mathrm{s}}$ | slow pressure (see Eq. (12) for detail definition) |
| $q$ | reference turbulent velocity, $\sqrt{\overline{u_i u_i}}$ |
| $Re_{\mathrm{t}}$ | turbulent Reynolds number |
| $Ri$ | gradient Richardson number |
| $R_{12}$ | cross correlation between $u_1$ and $u_2$, $R_{12} = -\overline{u_1u_2}/\sqrt{\overline{u_1^2}}\sqrt{\overline{u_2^2}}$ |
| $R_{2\theta}$ | cross correlation between $\theta$ and $u_2$, $R_{2\theta} = -\overline{u_2\theta}/\sqrt{\overline{u_2^2}}\sqrt{\overline{\theta^2}}$ |
| $r_{\mathrm{e}}$ | radius of vortex |
| $S$ | mean velocity gradient |
| $S_{\mathrm{r}}$ | reference mean velocity gradient |
| $S_\rho$ | mean density gradient |
| $S_\theta$ | mean temperature gradient |
| $S^*$ | shear rate number |
| $s_{ij}$ | strain rate tensor |
| $t$ | time |
| $\widetilde{U}_i$ | instantaneous velocity in $x_i$-direction |
| $\overline{U}_i$ | mean velocity in $x_i$-direction |
| $u_i$ | fluctuating velocity in $x_i$-direction |
| $x_1$, $x_2$, $x_3$ | streamwise, vertical and spanwise directions |
| $\beta$ | volumetric expansion coefficient |
| $\gamma$ | diffusivity of density and temperature |
| $\varepsilon$ | dissipation rate of turbulent kinetic energy |
| $\eta$ | Kolmogorov scale |
| $\tau$ | tilting angle of longitudinal vortical structure (see Fig. 8 for detail) |
| $\kappa$ | three-dimensional wavenumber, $\sqrt{\kappa_i\kappa_i}$ |
| $\kappa_i$ | wavenumber of $i$th direction |
| $\kappa_\eta$ | Kolomogorov wavenumber, $2\pi/\eta$ |
| $\theta$ | temperature fluctuation |
| $\nu$ | kinematic viscosity |
| $\rho$ | density |
| $\tilde{\rho}$ | instantaneous density |
| $\rho_0$ | reference density |
| $\omega_i$ | $i$th component of vorticity vector |
| $\langle\ \rangle$ | conditionally averaged value |
| $\overline{(\ )}$ | volume averaged value |

in comparison to the case without it because of a significant decrease in the down gradient fluxes (DGFs).

Webster [5] measured the data of stationary homogeneous shear flow under stable stratification. His data have subsequently often been used for a comparison to check the validity of numerical and experimental data. Gerz et al. [6] performed numerical simulations on stratified homogeneous shear flow, and studied the generation mechanism of the CGFs appearing in a high-Prandtl-number flow, though this is mostly explained by the linear process. The linearly generated CGFs were confirmed in the experimental study of a homogeneous shear flow [7].

Recently, the rapid distortion theory, RDT, was found to predict the CGFs in a homogeneous shear flow as well as a homogeneous decaying turbulence [8]. The RDT can predict the oscillation motion of both the turbulent heat flux and the Reynolds shear stress at the large Richardson number.

There are some studies, however, indicating that the contribution of nonlinear terms to the CGFs cannot be negligible. Holt et al. [9], presenting the close association between CGFs and hairpin vortices, reported that the swirling motion of the vortex contributed to generating the CGFs, and that the nonlinear convective process was responsible for CGF generation. They also showed that these nonlinear CGFs persistently appear at high wavenumbers even without buoyancy. They found, however, that at the very large Richardson number, the nonlinear effects became negligible, and that the CGFs appeared over all the wavenumbers of the cospectrum, which is predictable by the RDT.

In [10], the CGFs appearing at high wavenumbers were named as the persistent CGFs, and they conjectured that such persistent CGFs were generated because the Reynolds shear stress produced by the vortical swirling motion rapidly cascaded into the higher wavenumbers; the molecular diffusion could not dissipate the Reynolds shear stress before emergence of the CGFs. However, their assumption has been confirmed by neither the experimental nor the numerical results.

Persistent CGFs are generated not only in a homogeneous shear flow [9–11], but also in a boundary layer [13] and mixing layer [14], indicating that these CGFs appear in almost all the turbulent shear flows. Hence, we should pay closer attention to persistent CGFs, and their association with the vortical structure.