TEMPERATURE AND VELOCITY FLUCTUATIONS IN FORCED STABLY STRATIFIED AND CONVECTIVE TURBULENT FLOWS: EXPERIMENTS AND THEORY

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Abstract We study experimentally and analytically temperature and velocity fluctuations in forced stably stratified and convective turbulent flows. In the experiments with an imposed vertical temperature gradient we use an external source of turbulence produced by two oscillating grids located nearby the side walls of the chamber. Particle Image Velocimetry is used to determine the turbulent and mean velocity fields, and a specially designed temperature probe with sensitive thermocouples is employed to measure the temperature field. In unstably stratified flows (turbulent convection) we study transition phenomena caused by the external forcing from Rayleigh-Bénard convection with the large-scale circulation (LSC) to the limiting regime of unstably stratified turbulent flow without LSC whereby the temperature field behaves like a passive scalar. We found that the ratio $\left[(\ell_x \nabla_x \overline{T})^2 + (\ell_y \nabla_y \overline{T})^2 + (\ell_z \nabla_z \overline{T})^2\right] / \langle \theta^2 \rangle$ is nearly constant, is independent of the frequency of the grid oscillations and has the same magnitude for both, stably and unstably (convective) stratified turbulent flows, where ℓ_i are the integral scales of turbulence along x, y, z directions, $\overline{T}$ and θ are the mean and turbulent fluctuations components of the fluid temperature. At all frequencies of the grid oscillations we have detected the long-term nonlinear oscillations of the mean temperature for stably and unstably stratified flows. We demonstrated that for large frequencies of the grid oscillations, the temperature field in stably and unstably stratified turbulent flows can be considered as a passive scalar, while for smaller frequencies the temperature field behaves as an active field. We found in our experiments that for very small frequencies of the grid oscillations the turbulent kinetic energy in large Rayleigh number turbulent convection with LSC is produced by shear, rather than by buoyancy. The theoretical predictions based on the budget equations for turbulent kinetic energy, turbulent potential energy (determined by the temperature fluctuations) and turbulent heat flux, are in a good agreement with the obtained experimental results.

1. Experimental set-up

The goal of this paper is to review our theoretical and experimental study [1, 2] of forced stably and unstably (convective) temperature stratified turbulent flows. The experiments in temperature stratified turbulence have been conducted in rectangular chamber with dimensions $26 \times 58 \times 26$ cm^3 in air flow with the Prandtl number Pr $= 0.71$. In the experiments we use the external source of turbulence produced by two oscillating grids. Pairs of vertically oriented grids with bars arranged in a square array (with a mesh size 5 cm) are attached to the right and left horizontal rods. The grids are positioned at a distance of two grid meshes from the chamber walls and are parallel to the side walls. Both grids are operated at the same amplitude of 61 mm, at a random phase and at the same frequency which is varied in the range from 0.5 Hz to 16.5 Hz. To create stably or unstably temperature stratified turbulent flows a vertical mean temperature gradient was formed by attaching two aluminium heat exchangers to the bottom and top walls of the test section. The velocity fields were measured using a Stereoscopic Particle Image Velocimetry (PIV). We determined the mean and the r.m.s. velocities, two-point correlation functions and an integral scale of turbulence from the measured velocity fields. We also determined the mean and the r.m.s. temperatures from the measured temperature fields.

2. Unstably stratified turbulence

In unstably temperature stratified turbulence, the characteristic turbulence time in the experiments $\tau_z = 0.28 - 0.62$ seconds, while the characteristic time period for the large-scale circulatory flow ($\sim$ 10 s). These two characteristic times are much smaller than the time during which the velocity fields are measured ($\sim$ 600 s). The temperature difference between the top and bottom plates, ΔT, in all experiments was 50 K (i.e., the global Rayleigh number based on molecular transport coefficients, was $\mathrm{Ra} = 0.73 \times 10^8$). The temperature was measured at 144 locations in a flow.

When the frequency of the grid oscillations is larger than 2 Hz, the large-scale circulation (LSC) in the yz-plane in turbulent convection is destroyed. Here z is the vertical axis, the y-axis is perpendicular to the grids and the xz-plane is parallel to the grids. On the other hand, a complicated mean flow of the spiral form in the xz-plane with a non-zero mean vorticity in the y direction exists when the frequencies of the grid oscillations $2 < f < 7$ Hz. The destruction of the LSC is accompanied by a strong change of the mean temperature distribution. In particular, for the very low frequency f the thermal structure inside the LSC in turbulent convection is inhomogeneous and anisotropic. The hot thermal plumes concentrate at one side of LSC, and cold plumes accumulate at the opposite side of LSC. In the central part of the flow the vertical mean temperature gradient changes its direction depending on the frequency of the grid oscillations. For high frequency of the grid oscillations the mean temperature in turbulence without LSC is changed nearly linearly with hight in the central part of the flow.

We have also found that the vertical component of the turbulent velocity field is $\sqrt{\langle u_z^2 \rangle} = [\langle (u_z^*)^2 \rangle \pm 4\ell_z \, \beta \, \sqrt{\langle \theta^2 \rangle}]^{1/2}$, where the positive (negative) sign is for the unstably (stably) stratified turbulent flow, $\sqrt{\langle (u_z^*)^2 \rangle}$ is the vertical component of the turbulent velocity field in isothermal flow, $\beta = g/T_*$ is the buoyancy parameter, T_* is a reference value of the mean absolute temperature and $\mathbf{g}$ is the acceleration of gravity. The latter equation is derived from the budget equation for the vertical turbulent kinetic energy. This implies that the buoyancy heat flux contributes to the production of the turbulent kinetic energy in turbulent convection in the absence of the LSC. However, as follows from the measurements in our experiments (see [3]) the turbulent kinetic energy in turbulent convection with coherent structures (LSC) is produced by shear, rather than by buoyancy.

At all frequencies of the grid oscillations we have observed the long-term nonlinear oscillations of the mean temperature with the period that is of the order of 10 s. There are two possible mechanisms for such oscillations. One mechanism could be related to the large-scale Tollmien-Schlichting waves in sheared turbulent flows, which can cause the nonlinear oscillations of the mean temperature field. Another mechanism of the nonlinear oscillations could be related to the generation of small-scale kinetic helicity due to large-scale shear flows in the system. The large-scale shear generates large-scale helicity, and since the total helicity is conserved, a non-zero small-scale helicity is produced.

Our measurements showed that the turbulent length scales are weakly dependent on the frequency f of the grid oscillations in the unstably stratified turbulent flow for $f > 3$ Hz, while the turbulent velocities and turbulent time scales vary strongly with the frequency f. Note that $\tau_y\, f$ and $\tau_z\, f$ tend to a constant for higher frequencies ($f > 5$ Hz) of the forcing, where $\tau_{y,z}$ are the characteristic turbulent times in horizontal and vertical directions.

3. Stably stratified turbulence

In our experiments with the stably stratified turbulence, we determined the dependence of the r.m.s. of the temperature fluctuations $\sqrt{\langle\theta^2\rangle}$ versus the frequency f of the grid oscillations. The temperature fluctuations monotonically increase with the increase of the frequency f of the grid oscillations due to the monotonic increase of the mean temperature gradients. In the case of the unstably stratified turbulent flow the dependence $\sqrt{\langle\theta^2\rangle}$ versus frequency is more involved.

We also determined the frequency dependencies of the following measured turbulence parameters: the r.m.s. velocity fluctuations, $u_{\rm rms} = \sqrt{\langle\mathbf{u}^2\rangle}$, the vertical anisotropy $A_z = \langle u_z^2\rangle/u_{\rm rms}^2$, and the integral scales of turbulence along horizontal and vertical directions. Except for the small frequencies of the grid oscillations, the horizontal integral scale of turbulence behaves similarly for both, the stably and unstably stratified turbulent flows, while the vertical integral scale of turbulence is systematically higher for the unstably stratified turbulent flow. On the other hand, the vertical anisotropy A_z only slightly increases with the frequency of the grid oscillations.

In our experiments we found that the non-dimensional ratio $\ell_*\, \nabla_* \overline{T}/\sqrt{\langle\theta^2\rangle}$ versus the frequency f of the grid oscillations, is nearly independent of the frequency of the grid oscillations and has the same magnitude for both, stably and unstably stratified turbulent flows, in agreement with the theoretical predictions based on the budget equations for turbulent potential energy (determined by the temperature fluctuations) and turbulent heat flux, where $[\ell_*\, \nabla_* \overline{T}]^2 = \big[(\ell_x \nabla_x \overline{T})^2 + (\ell_y \nabla_y \overline{T})^2 + (\ell_z \nabla_z \overline{T})^2\big] / \big[1 + \beta\tau_0^2 (\nabla_z \overline{T})\big]$ and τ_0 is the characteristic turbulent time.

To characterize the stably stratified flows, we determined the turbulent Richardson number $Ri_T = N^2 \tau_0^2$ versus frequency f of the grid oscillations for the stably stratified turbulent flow, where $N^2 = \beta \nabla_z \overline{T}$. The turbulent Richardson number Ri_T strongly decreases with the increase of the frequency of the grid oscillations due to the strong decrease of the turbulent correlation time τ_0 with increase of the frequency f. For large frequencies of the grid oscillations whereby $Ri_T \ll 1$, the temperature field can be considered as a passive scalar. On the other hand, for smaller frequencies of the grid oscillations, $Ri_T > 1$, and the temperature field behaves as an active field. Note that the passive-like scalar behaviour of the temperature field can be understood in the kinematic sense. In particular, when the temperature fluctuations $\langle\theta^2\rangle$ do not affect the turbulent kinetic energy, the temperature field can be considered as a passive scalar. This implies that the evolution of the temperature field in a given turbulent velocity field is a kinematic problem, whereby there is no dynamic coupling between the temperature fluctuations, $\langle\theta^2\rangle$, and the turbulent kinetic energy. When the effect of the temperature fluctuations on the turbulent kinetic energy cannot be neglected, the temperature is considered as an active field. This definition of the passive or active behavior of the temperature field is different from that based on the scaling behaviour of the temperature structure function. [4]

References

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