Experimental study of forced stratified turbulence

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Recent results have shown that strongly stratified turbulence has a three dimensional dynamic instead of a quasi-two dimensional dynamic conjectured previously. The structures are strongly anisotropic with an aspect ratio scaling like the Froude number $l_v/l_h \sim F_h$ [1]. A direct cascade of energy from large scales to small scales associated with a ${k_h}^{-5/3}$ horizontal kinetic energy spectrum has been predicted and observed in DNS of forced stratified turbulence when the buoyancy Reynolds number $\mathcal{R}^t$ is sufficiently large [2]. In constrast, for small $\mathcal{R}^t$, the flow is dominated by vertical viscous effects even if the Reynolds number is large [3, 4].

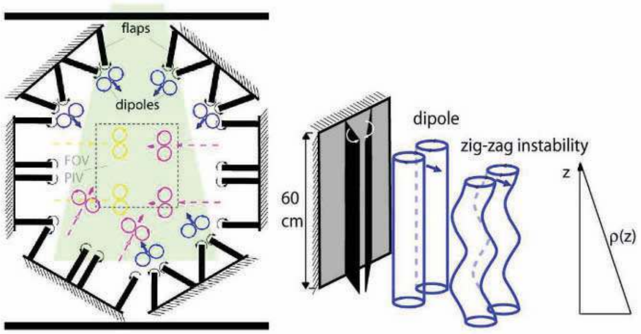

Fig. 1. Sketch of the experimental apparatus.

In order to investigate the turbulent regime experimentally with a sufficiently high buoyancy Reynolds number, we have set-up a new experiment where the flow is generated by 12 vortex generators (flaps) placed on the side of a large stratified tank (Fig. 1). Each generator produces periodically and independently a counter-rotating vertical columnar vortex pair which propagates toward the central part of the tank. The interactions between all the randomly produced vortex pairs give rise to a forced turbulent flow with a low Froude number F_h and a large Reynolds number Re. The buoyancy Reynolds number based on the characteristics of the vortices generated by the flaps is $\mathcal{R}^s \equiv ReF_h{}^2 \sim 100$ while the buoyancy Reynolds number based on the injection rate of energy ϵ : $\mathcal{R}^t \equiv \epsilon/(\nu N^2)$, is order unity. As seen on figure 2, the mean kinetic energy of the flow is statistically stationary but with high fluctuations typical of turbulent flows.

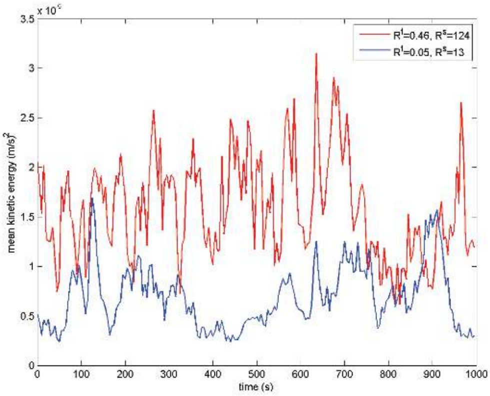

Fig. 2. Mean kinetic energy as a function of time.

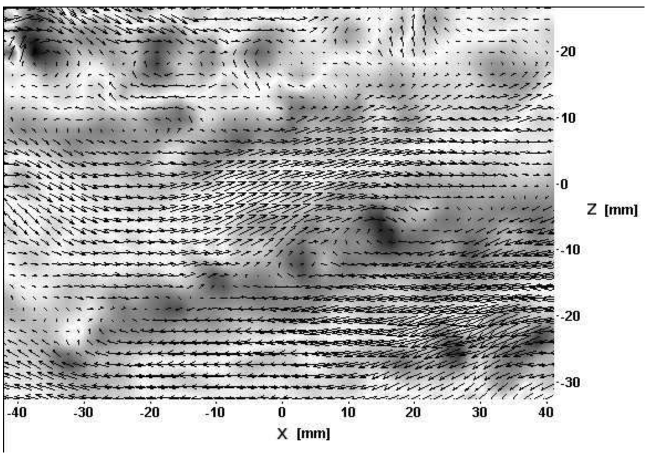

Fig. 3. Vertical cross-section of the velocity field. The background color represents the horizontal vorticity $|\omega_y|$ perpendicular to the cross-section. In heavy shaded regions, $|\omega_y| \sim N$.

PIV measurements in vertical cross-sections show that the flow is organised into horizontal layers (Fig. 3). This layering arises spontaneously via the zigzag instability of individual vortex pairs [5]. When the buoyancy Reynolds number is increased, shear instabilities and intermittent overturning become more and more visible between layers in agreement with [3, 6].

Horizontal velocity spectra exhibit a narrow ${k_h}^{-5/3}$ inertial domain at intermediate scales (0.2 rad/mm $\lesssim k_h \lesssim$ 0.7 rad/mm) even for the lowest $\mathcal{R}^t$ investigated (Fig. 4). This inertial range becomes more and more flat as $\mathcal{R}^t$ increases as observed in DNS of forced stratified turbulence [3].

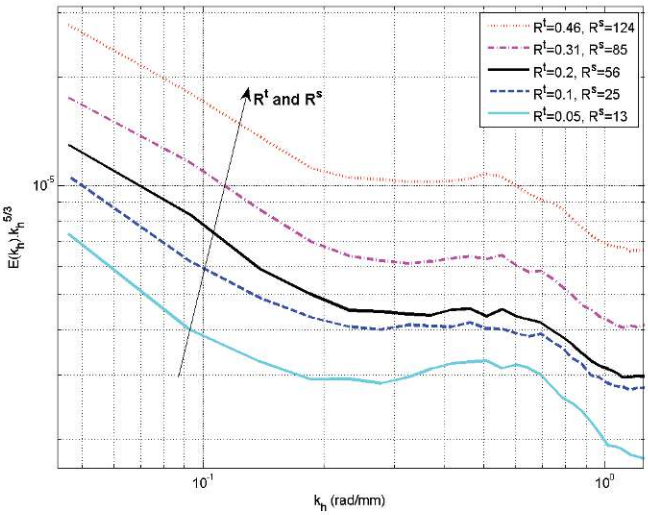

Fig. 4. Compensated 1D kinetic energy spectrum : $E(k_h){k_h}^{5/3}$ as function of the horizontal wave number k_h for different buoyancy Reynolds numbers.

As shown in figure 5, the rotational and divergent parts of the horizontal velocity are of the same order at all scales even if the forcing is purely vortical. This is consistent with the scaling law $l_v/l_h \sim F_h$ for which the dynamic of waves and vortices can not be separated [1, 3]

We have set-up a novel experiment on forced strongly stratified turbulence with buoyancy Reynolds number of order one. For the first time, a ${k_h}^{-5/3}$ inertial range has been observed experimentally in agreement with theoretical predictions, DNS and atmospheric measurements.

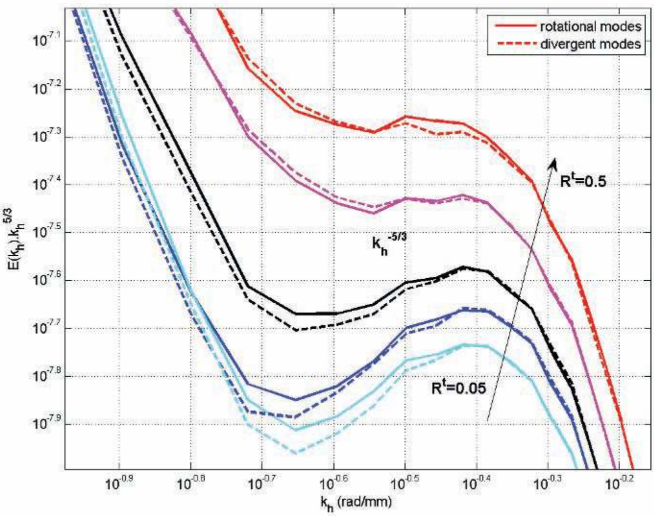

Fig. 5. Compensated 2D kinetic spectrum of the vortical and divergent parts of the horizontal velocity.

References

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