TURBULENT STRATIFIED SHEAR FLOW EXPERIMENTS: LENGTH SCALE COMPARISON

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Abstract Stratified shear flows are ubiquitous in geophysical systems such as oceanic overflows, wind-driven thermoclines, and atmospheric inversion layers. The stability of such flows is governed by the Richardson Number Ri which represents a balance between the stabilizing influence of stratification and the destabilizing influence of shear. For a shear flow with velocity difference U, density difference $\Delta\rho$ and characteristic length H, one has $Ri = g(\Delta\rho/\rho)H/U^2$ which is often used when detailed information about the flow is not available. A more precise definition is the gradient Richardson Number $Ri_g = N^2/S^2$ where the buoyancy frequency $N = \sqrt{(g/\rho)\partial\rho/\partial z}$, the mean strain $S = \partial U/\partial z$ in which z is parallel to gravity and suitable ensemble or time averages define the gradients. We explore the stability and mixing properties of a wall-bounded shear flow over a range $0.1 < Ri_g < 1$ using simultaneous planar measurements of density and velocity fields using Planar Laser-Induced Fluorescence (PLIF) and Particle Image Velocimetry (PIV), respectively. The flow, confined from the top by glass horizontal boundary, is a lighter alcohol-water mixture injected from a nozzle into quiescent heavier salt-water fluid with velocity between 5 and 10 cm/s and with a relative fractional density difference of 0.0026 or 0.0052. The injected flow is turbulent with Taylor Reynolds number between 50 and 100. We compare a set of length scales that characterize the mixing properties of our turbulent stratified shear flow including the Thorpe Length L_T, the Ozmidov Length L_O, the Ellison Length L_E, and turbulent mixing lengths L_m and L_ρ.

INTRODUCTION

The stability and mixing of stratified shear flows are of fundamental [2] and geophysical interest [3]. For small Ri, the dominant instability is of Kelvin-Helmholtz type whereas at larger Ri, the velocity gradient can be wider than the extent of density changes and a Holmboe instability arises. A major challenge for laboratory experiments is to relate different measurable quantities so that they can be useful diagnostics for real geophysical situations. Here we describe a turbulent wall-bounded shear flow injected into quiescent fluid along a horizontal boundary where the injected flow is stably stratified with respect to the fluid initially at rest. The injection nozzle is 5 cm high and 48 cm wide with mean output flow velocity between 4 and 10 cm/s and fractional density difference of either 0.0026 or 0.0052. Using PIV and PLIF, we extract velocity and density fields, respectively (details are available in [1]). The velocity data consist of components $\{u(x,z), w(x,z)\}$ from a two-dimensional plane with coordinates $\{x, z\}$ where the x direction is the downstream and z is perpendicular to gravity; no information is available about the cross-stream y direction. Similarly, the density field

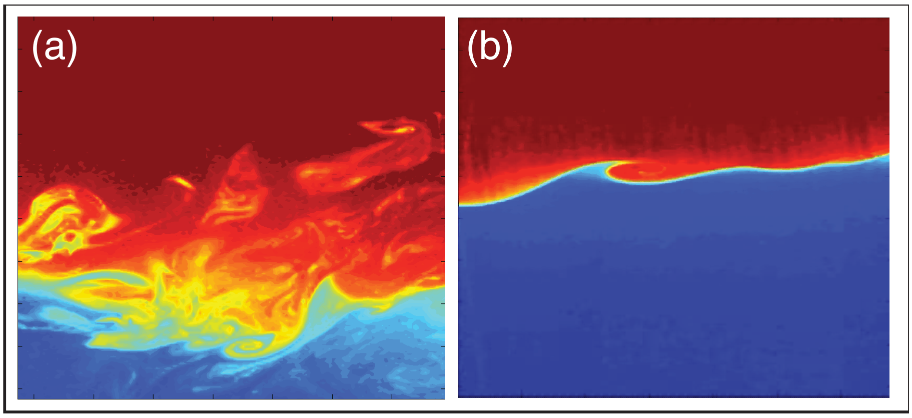

Figure 1. Density field with light (red) and heavy (blue) for (a) unstable Kelvin-Helmholtz conditions with $Ri_g \approx 0.1$ and (b) more stable Holmboe conditions with $Ri_g \approx 0.7$. The distance downstream from the injection nozzle is 11 cm at left side of image

is $\rho(x,z)$. From these fields, we can compute many diagnostics about the flow but here we concentrate on a number of length scales that parameterize the competition of turbulence and stable stratification. In particular, we compute

$$L_O = \sqrt{\epsilon/N^3}; L_S = \sqrt{\epsilon/S^3}; L_E = \rho_{rms}/\langle\partial\rho/\partial z\rangle; L_m = \sqrt{\langle u'w'\rangle/S^2}; L_\rho = \sqrt{\langle w'\rho'\rangle/\langle S\partial\rho/\partial z\rangle}. \quad (1)$$

where ϵ is the turbulent energy dissipation. We also compute the Thorpe length L_T [3, 4] which involves a reordering of vertical density profiles such that $\rho(z)$ is monotonic in z and which is a measure of overturning that does not require direct measurement of ϵ.

RESULTS

For small $Ri_g \approx 0.1$, similar to the extensive study for an angled upper boundary [1], the interface between the two fluids is highly mixing as illustrated in Fig. 1 (a) where the density field is imaged using PLIF and the downstream distance is about 15 cm from the exit nozzle. For higher $Ri_g \approx 0.7$, see Fig. 1 (b), the flow is much more stable although large scale wave-like distortions of the interface are often observed. As a consequence of the wave-like motions, a simple Reynolds averaging conflates the turbulent disturbances with the wave motion. Instead, we use a local approach to evaluate the stability and mixing properties of the stratified shear flows. In particular, we define the interface location $z_i(x)$ at the maximum value of $\partial\rho/\partial z$ along the Thorpe reordered density profile $\rho_T(x, z)$. For unperturbed sections of the interface with $L_T = 0$, i.e., when the density profile is monotonic without reordering, this identification is consistent with a profile one would pick in, for example, most locations in Fig. 1 (b). Once we obtain the interface position $z_i(x)$, we perform averages with respect to that vertical position so that we have, for example, the average characteristics of the unperturbed sections with $L_T = 0$ and the perturbed sections with $L_T \neq 0$. We also can use information about the perturbed section to confine the vertical region of interest over which to compute, for example, ϵ. Thus, we will discuss the systematic

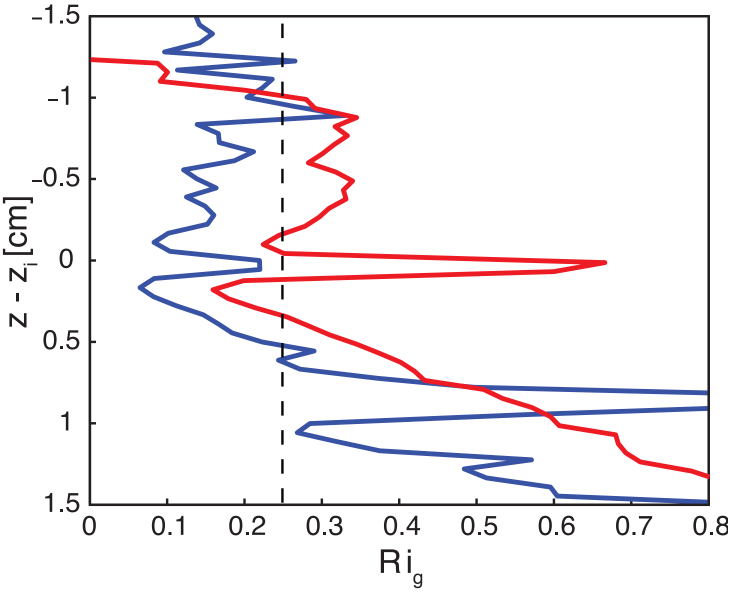

Figure 2. Vertical position relative to the interface $z - z_i$ (interface is at 0) vs Ri_g for an unstable case with $Ri_g(0) \approx 0.2$ (blue) and a weakly unstable situation (red) with $Ri_g(0) \approx 0.7$. Dashed vertical line corresponds to $Ri_g = 1/4$.

behavior of the length scales in Eq. 1 for unperturbed and perturbed sections of interface. As an example, we show in Fig. 2, average values of $\langle Ri_g(z - z_i)\rangle$ for a highly unstable case (blue) with more than 90% overturning and for a corresponding case (red) with small overturning for the unperturbed part of the interface. For the overturning case, the minimum is uniformly below the canonical threshold value for instability $Ri = 1/4$ (the vertical dashed line) whereas for the weakly unstable case, the interface itself is highly stable whereas the nearby regions are weakly unstable with $Ri_g \approx 1/4$, conditions conducive to Holmboe instability which has the cusp-like form seen in Fig. 1(b).

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