Diapycnal mixing in Taylor-Couette flow

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Abstract

We consider the mixing of a two-layer fluid in a Taylor Couette flow. This flow allows establishing well-controlled flow regimes, i.e. Taylor vortices, wavy-vortex and turbulent flow regimes, for which the interfacial mixing is measured quantitatively using the LIF method. Even though flow conditions are different in each regime, the mixing efficiency represented by the flux Richardson number, Ri_f, as a function of the overall Richardson number, Ri_o, reveals a similar behaviour with an increase in mixing efficiency at small Ri_o up to a maximum value of $\approx$ 0.10 to 0.25 and then a decrease at large Ri_o. The maximum is reached at $Ri_o \approx 2$ to 10 depending on flow regime. The large spread in Ri_f - Ri_o values is typical of mixing efficiencies reported previously for different types of stirring , including grid stirring and bar stirring experiment. What is of interest here is that the spread is obtained in the same apparatus andis show to be dependent on Reynolds number. The other interesting observation is that for large Ri_o (here of order 10^2) the mixing efficiency increases again. Since shear instabilities are unlikely to occur for these Ri_o numbers other mixing processes should be responsible. Observations suggest trapping effects that lead to wave breaking at the interface.

The mixing of the upper ocean layer, such as due to internal wave breaking, shear instability, Langmuir vortices, as well as convection *e.g.* due to evaporation of salt water (see Thorpe, 2004), is a long standing issue in fluid mechanics. Former investigations motivated by this application report isotropic grid-generated turbulence or locally generated turbulence in a (non-rotating) stratified fluid to investigate the mixing efficiency. The Taylor-Couette flow we here consider is anisotropic, consist of annular ring-shaped vortex structures with horizontal axis, and, unlike most other experiments and simulations on mixing allows for the generation of inertial-gravity waves.

The caracteristics of the Taylor-Couette device employed are unconventional, with gap-width 5 cm of ratio 12.2 and inner diameter of 30 cm. Since the most unstable wavelength depend on gap-width and Reynolds number, the Taylor vortices in this device will have a larger diameter. Typically, the effect of a linear stratification is to increase the threshold value for instability, or transition to another regime, and to decrease the aspect ratio of the Taylor vortices (see Caton, Janiaud & Hopfinger, 2000). Under the influence of the buoyancy force, the Taylor vortices have a smaller aspect ratio, unlike the wavelength of the waves, generated by centrifugal instability near the inner cylinder wall, that is not affected by stratification. As a consequence, beyond the instability threshold, waves and Taylor vortices appear simultaneously at different spatial scales. In the two-layer fluid with vertically varying density-gradient inertial waves propagate away from the inner cylinder. These propagating waves (see Ermanyuk & Flor, 2005) encounter the shear between the Taylor vortices and the motion at the interface. While their frequency is affected by the local fluid velocity they encounter critical layers and break, are absorbed or reflect above and below the interface where the wave frequency approaches the local buoyancy frequency.

Figure 1 shows the mixing efficiency represented by the Richardson flux number, $Ri_f = D/L_h E Ri_o$ as a function of overall Richardson number $Ri_o = \Delta B L_H / U_H^2$, obtained for

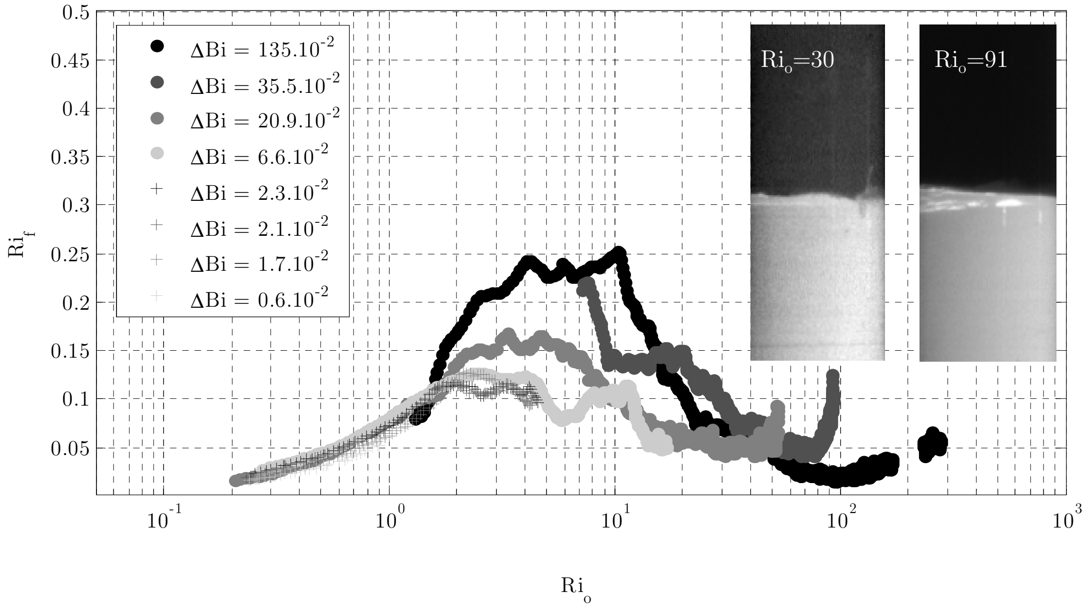

Figure 1: *Mixing efficiency Ri_f of the TC flow as a function of the overall Ri-number Ri_o, in the turbulent regime for a constant Reynolds number $Re = \Omega ad/\nu = 3409$ (Ω cylinder rotation frequency, d gapwidth and radius a) and various initial buoyancy jumps $\Delta B_i = g\Delta\rho/\overline{\rho}$ (see legend, in m/s^2). The temporal evolution of the flow goes from left to right with an initially strong interface (high Ri_o) at the right. Flow pictures for $\Delta B_i = 35.5\,10^{-2}\,m/s^2$). White: salted water, black: freshwater.*

the turbulent regime. D is the height of the upper layer, L_H is the vortex diameters, E is the adimensionnal entrainment rate, U_H is the maximum vortex velocity. The buyoancy jump is modelised by $\Delta B = g\Delta\rho/\overline{\rho}$. For larger Ri_o, the mixing efficiency systematically increases. Though former studies suggest the influence of waves interacting with the shear layer as a possible mechanism to increase the mixing efficiency (see Strang & Fernando 2001, Peltier & Caulfield, 2003), this has not been shown for such high Ri_o numbers. Observations reveal a mixing layer of approximately 5 mm thickness, with wave breaking fluid motions, while vortices above and below erase filaments of dense (light) fluid from the upward (downward) moving layer induced by wave motions. The flow represented by the monotonic decreasing part (for smaller Ri_o) of the curve also showed filamentation generated by the same process, but the waves do not break in the interior of the pycnocline. This suggests that the increase in mixing efficiency is a consequence of waves being trapped at the interface and break, thus contributing to the mixing efficiency.

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