Mixing mechanisms across a density interface in a Taylor-Couette flow

Diana PETROLO[1], Sandro LONGO[1]

[1] Dipartimento di Ingegneria e Archiettura (DIA), Università degli Studi di Parma, Parco Area delle Scienze 181/A, 43124 Parma, I
email: diana.petrolo@studenti.unipr.it
email: sandro.longo@unipr.it

ABSTRACT

Density interfaces are very frequent in the natural environment, and they usually form where the local level of turbulence is not intense enough to do work against the buoyancy forces and overturn the density interface. The thermocline, which divides the upper mixed layer from the stratified ocean interior, is perhaps the greatest example of a very sharp and stable density interface in the oceanic environment.

Although several experimental and theoretical studies have devoted their attention to the vertical flux across a density interface in a two-layer fluid, mixed mechanically by grids or rods along the horizontal or vertical direction (Linden, 1979; Whitehead & Stevenson, 2007), little is known about how the buoyancy transport occurs and which is the principle mechanism responsible for mixing.

In this paper we attempt to increase the overall understanding of turbulent mixing across a two-layer stratification in a Taylor-Couette flow. We experimentally observe that a single periodic wake-like perturbation develops at the density interface, and travels with an amplitude that increases with the rotation rate of the inner cylinder, Ω, and a period that decreases with Ω. Our model says the vertical buoyancy flux per unit area, f, is a constant fraction of $\Delta\rho\, c$, where $\Delta\rho$ is the density difference between the two layers in steady state and c is the celerity of the coherent structures, and the ratio $f/(\Delta\rho\, c)$ is independent on Ω.

1. Experimental set-up and observations

Our experimental set-up consists of a Taylor-Couette (TC) tank with a steady outer cylinder, of radius R_2 = 17.2 cm, and a rotating inner cylinder, of radius R_1 = 8.5 cm. The gap of the tank, $\Delta R = R_2 - R_1$, is filled with two layers of fluid of equal depth but of different density. We conduct a series of experiments where we vary the rotation of the inner cylinder, Ω, in the range Ω = 1.00 – 2.75 rad s^{-1}. Because turbulence would lead to a decrease in the density difference between the layers and a well-mixed steady state (Woods et al. 2010; Oglethorpe et al. 2013; Petrolo & Woods, 2019), we supply a continuous source of fresh fluid in the top layer and a continuous source of salty water (with a salinity of 25%, the maximum concentration of NaCl in water at ambient temperature). At the same time, we withdraw the same fluid as supplied by two sinks positioned at the same depths of the respective sources, in order to keep a constant volume in the tank. The steady state is attained when the density difference $\Delta\rho$ between the two layers does not vary in time. In steady state, we use a home-made two-wire conductivity probe (CP) to measure the equivalent level of the density interface in time. This is possible upon calibration of the probe at different depths above and below the density interface, by which we associate the conductivity of the fluid to the distance between the interface and the centre of mass of the two electrodes. The conductivity probe proves extremely stable, with an overall accuracy < 0.1 mm, as a very small change in density level causes a significant change in the recorded conductivity of the fluid. We also use Ultrasound Velocity Profiles (UVP) to measure the velocity of the fluid in the vertical direction.

1.1. Dynamics at the interface

Figure 1a shows a time window of the level of the density interface measured by the CP, at a distance r = 4 cm from R_1. The rotation rate is Ω = 2.75 rad s^{-1}. Grey dots represent the raw signal, while the red solid line represents the moving average with a time window of ≈ 2.5 s. The interface appears to oscillate periodically around a mean value, with a peak period T_p that decreases with Ω according to the interpolating function $T_p = 12\pi/\Omega$, as shown in Fig.1b. T_p has been estimated both by a zero-(up)crossing analysis and the energy spectrum. The results do not vary substantially and seem to not depend on the radial position, at least for $r > 4$ cm. If r = 2 cm and $\Omega < 2.00$ rad s^{-1}, T_p attains half the interpolated value, probably as a consequence of nonlinear interactions that characterize the region close to the inner cylinder, where turbulence is generated, similarly to the "fetch" in the context of wind gravity waves. When the waves coalesce and propagate outward, they double their period and achieve the regime configuration.

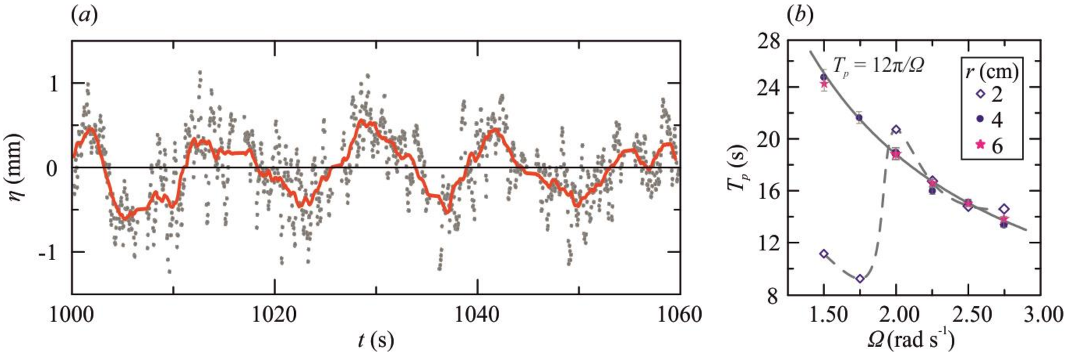

Fig. 1. (a) Equivalent level of the density interface, at $\Omega = 2.75$ rad s^{-1}. Grey dots refer to the raw signal, the red solid line to the time average with a time window of ≈ 2.5 s; (b) the peak period of the equivalent level of the interface as a function of Ω and distance r from R_1.

1.2. Single periodic wake-like perturbation

Another interesting insight of the mechanisms that occur at the density interface is given by the injection of dye at the interface. Videos from the top view of the TC tank are recorded by three video-cameras at 120° from each other. It can be observed that coloured parcels tend to accumulate and travel around the annulus until they self-adjust into a single wave of given size and angular velocity.

Similar information can be obtained by shadowgraphs. The tank is horizontally illuminated by a slide projector and any density change or other disturbances cause a change in the refractive index and project their shadows onto the surface of the inner cylinder. Figure 2 shows a time series of a vertical line of pixels taken from the video of an experiment run at $\Omega = 2.50$ rad s^{-1}. We can observe a wake-like perturbation with a nose, two linear propagating front in the top and bottom layer. We define α as the fraction of the T_p between the nose and the limit of the mixing region. This limit is when the density interface becomes sharp again after a wreak due to eddies and vortices carrying buoyancy from the bottom layer to the top. If we consider a linear density gradient, $(\rho_t - \rho_b)/\, l(t)$, inside the mixing region of thickness $l(t)$, we can model the time averaged correlation between the density fluctuations ρ' and vertical velocity fluctuations w' as $\langle\rho' w'\rangle = -D(\mathrm{t})\ \Delta\rho/l(t)$, where D(t) is the diffusivity. We can therefore express the vertical buoyancy flux per unit cross area over a cycle f as

$$f = \frac{1}{T_p}\int_{t_0}^{t_0+\alpha t} \frac{g\langle\rho' w'\rangle}{\rho_0}\mathrm{d}t = -\frac{1}{T_p}\int_{t_0}^{t_0+\alpha t} \frac{gD(t)}{\rho_0}\frac{\Delta\rho}{l(t)}. \qquad (1)$$

We then parametrize $D(\mathrm{t}) = k\, l(t)\, c$, where k is a non-dimensional coefficient that may take into account the geometrical parameters of the experimental set-up, and c is the celerity of the coherent structure, evaluated by cross-correlating the vertical velocity measured by two UVP. Solving Eq. (1) we find that $k\alpha = f/(\Delta\rho\, cg)$ is independent on Ω.

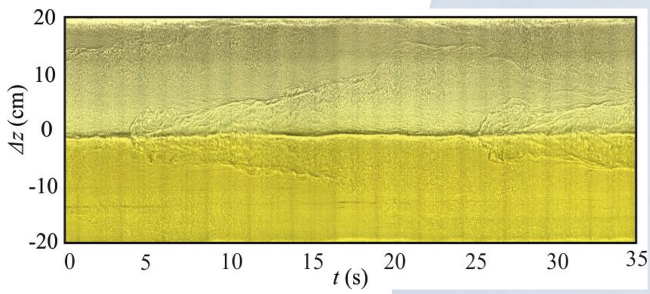

Fig. 2. Time series of a vertical line of pixels taken from the video of an experiment run at $\Omega = 2.50$ rad s^{-1}.

References

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