Laminar-turbulent cycles in inclined stratified shear flows under strong confinement

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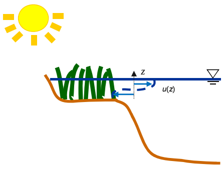
1. Motivation

Stably stratified shear flows are ubiquitous in the environment:

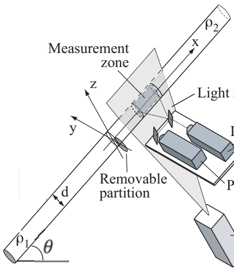
- Atmosphere: sea breeze, clear air turbulence
- Lakes: convective circulation due to differential heating and cooling
- Locks in canals: salinity driven


[NOAA / Forecast Systems Laboratory, http://www-frd.fsl.noaa.gov/mab/scatcat/]



Here, we consider stably-stratified shear flows under strong confinement at an incline.

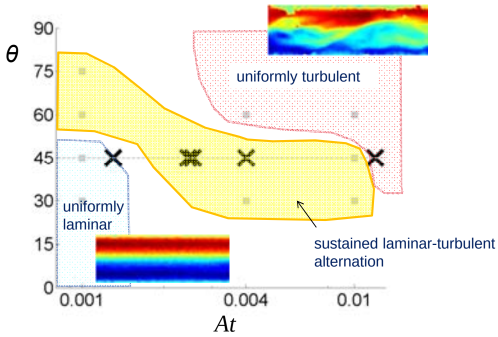
2. Strongly-confined, stably-stratified shear flows generated as a lock exchange in an inclined tube

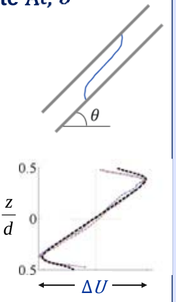


- $d = 20$mm
- $L = 167.0$cm × 2
- simultaneous PIV-PLIF measurements
  - 6.5cm window $20d$ from partition
- $Sc \sim 3000$.
- θ
- $At = (\rho_2-\rho_1)/(\rho_2+\rho_1)$

3. Laminar-turbulent cycles

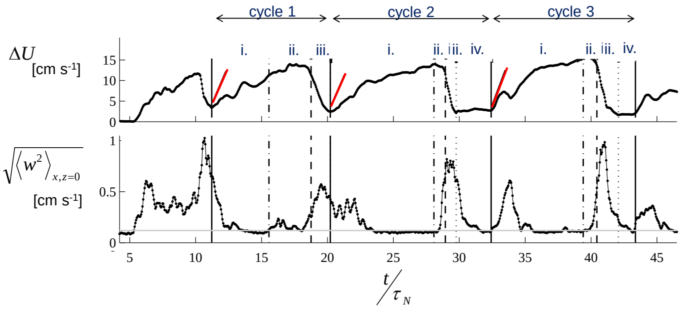
a. Laminar-turbulent alternation occurs at intermediate At, θ





[Modified from Znaien *et al*. 2011]

b. Mean axial velocity (hence shear) displays a ramp-cliff pattern



- Brunt-Väisälä frequency $\tau_N = \dfrac{2\pi}{\sqrt{2g\mathrm{At}\sin\theta/d}} \sim 5s$

- ΔU (top) exhibits a sustained ramp-cliff pattern.
- RMS velocity (bottom) alternately decays gradually, then rises sharply.
- Flow accelerates as it relaminarizes and as the first signatures of the onset of instability appear, then decelerates rapidly as the K-H billows break down.
- Four phases in a cycle:
  i. Flow relaminarization and acceleration (‘ramp’)
  ii. Growth of K-H instability
  iii. Breakdown of K-H billows and flow deceleration (‘cliff’)
  iv. Decay of residual turbulence

4. Characteristic scales of the ramp-cliff cycle

i. Flow relaminarization (‘ramp’)

- Approximate upper (lower) current as a “free rise” (“free fall”).

$$\underbrace{\frac{\mathrm{d}\Delta U}{\mathrm{d}t}}_{\text{acceleration}} \cong 2g\sin\theta\,\underbrace{\frac{\langle\rho\rangle_x^- - \langle\rho\rangle_x^+}{\langle\rho\rangle_x^- + \langle\rho\rangle_x^+}}_{\text{local density contrast}}$$

- viscosity negligible.
- density uniform in each layer
- two-layered, laminar, parallel flow

- During early stages of relaminarization $\mathrm{d}\Delta U/\mathrm{d}t$ ~ measured density contrast
- Persistent overestimation attributed to viscous effects.

ii. K-H billow growth

$$\tau_s = \left(\left.\frac{\partial\langle u\rangle_x}{\partial z}\right|_{z=0}\right)^{-1}$$

- Growth rate of K-H billows is governed by the shear that gives rise to the instability.
- Characteristic time of shear given by τ_s
- Measured $\tau_s = (0.01\text{-}0.02)\,\tau_N$
- Duration of billow growth $= (0.9\text{-}3.2)\,\tau_N$
  → stabilizing effect of viscosity and confinement?

iii. K-H billow breakdown (‘cliff’)

$$\tau_m = \frac{d}{\sqrt{\langle w^2\rangle_{x,z=0}}}$$

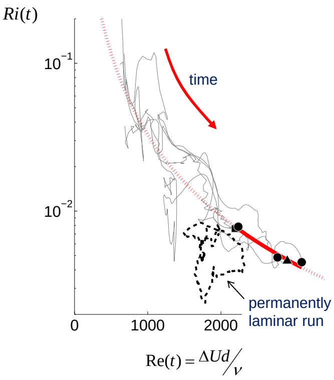
- Duration of billow breakdown governed by turbulent mixing.
- Characteristic time of turbulent mixing given by τ_m
- Measured $\tau_m = (0.6\text{-}0.7)\,\tau_N$
- Duration of ‘cliff’ phase $= (0.8\text{-}1.6)\,\tau_N$
  → good agreement!

iv. Decay of residual turbulence

$$\tau_g(t) = \frac{V_f t}{u_g}$$

- Decay of residual turbulence is terminated by the arrival of pockets of relatively unmixed fluid.
- We think that these pockets of fluid originate in the undisturbed regions beyond the gravity current fronts, then propagate upstream.
  - path length of pocket = front velocity $V_f \times t$
  - time required for pocket to travel this distance is given by τ_g
- Measured $\tau_g = (8 - 12)\,\tau_N$.
- Duration of turbulent decay phase $= (1\text{-}3)\,\tau_N$

5. Richardson and Reynolds numbers at the onset of instability



- $$\mathrm{Ri}(t) = \underbrace{\frac{-g\cos\theta}{\langle\rho\rangle_{x,z=0}}\left.\frac{\partial\langle\rho\rangle_x}{\partial z}\right|_0}_{\text{stratification}}\underbrace{\left(\left.\frac{\partial\langle u\rangle_x}{\partial z}\right|_0\right)^{-2}}_{\text{shear}}$$
- Re increases and Ri decreases during each relaminarization phase (thin grey line).
- Flow remains laminar to Ri « 0.25.
- Ri does not segregate flows that remain laminar (dashed) from those that develop K-H billows.
- Necessary criterion for the onset of instability is for Re to exceed 2200 (cf. uniform pipe flow!).

Conclusions

- Strongly-confined stratified shear flows were generated as a lock exchange in an inclined tube.
- Laminar-turbulent alternation at $2.5 \times 10^{-3} < \mathrm{At} < 4.0 \times 10^{-3}$.
- Laminar-turbulent cycle characterized by a distinctive ramp-cliff variation in axial velocity.
- Necessary criterion for the onset of instability is for local Re to exceed 2200.
- Transverse stratification does not directly control the onset of instability.

References

Tanino Y, Moisy F, Hulin J-P. 2012. Laminar-turbulent cycles in inclined lock-exchange flows, *Physical Review E* 85, 066308.
Znaien J, Moisy F, Hulin J.-P. 2011. Flow structure and momentum transport for buoyancy driven mixing flows in long tubes at different tilt angles, *Physics of Fluids* 23, 035105.

Acknowledgements

This material is based on work supported by Agence Nationale pour la Recherche grant ANR-07-BLAN-0181.