Experimental study of a turbulent jet in a linearly stratified flow

Joël Sommeria
Sanjay Singh
Pierre Augier

LEGI, Grenoble
Motivations

Find a ‘natural’ way to force stratified turbulence:
homogeneous not boundary controlled

Jets common in atmosphere ocean

Jet stream as seen from outer space (NASA)

Engineering

• Pumped-storage power plants in stratified reservoirs.
• Sewage discharge into lake or oceans.

Sewage discharge
Turbulent jet (homogeneous fluid)

- No pressure force
- Entrainment
- Energy dissipation

Turbulent cascade locally forced by shear
Stratified case:

- Vertical expansion is blocked when $\text{Ri} = \frac{N^2 b^2}{U^2} > 1/4$
Equation for turbulent kinetic energy (TKE)

\[
\frac{\partial}{\partial t} K + \frac{\partial}{\partial x_k} U_k K = -\frac{\partial}{\partial x_k} \left( \overline{p' u'_k} \right) + \nu \frac{\partial}{\partial x_k} \frac{\partial}{\partial x_k} K + 2\nu \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k} - 2\frac{\partial u'_i}{\partial x_k} \frac{\partial u'_i}{\partial x_k} \delta_{i3} \frac{\rho'}{\rho_0} \frac{\overline{\rho' u'_3}}{KU/b}.
\]

Advection \(\approx u_x \partial K/\partial x \sim \alpha KU/b\), production \(\sim KU/b\).
previous experiments

- \( \frac{x_m}{b_N} \approx 2.8, \frac{w_L}{b_N} \approx 0.95 \) (Roberts and Matthews 1987)
- \( \frac{x_m}{b_N} \approx 2.9 \) and \( \frac{w_L}{b_N} \approx 0.93 \) (Webster and Liu 2001)
- Webster and Liu (2001) compared the self-similarity of stratified case to that of unstratified case using digital particle tracking velocimetry (DPTV)

Flow visualization for stratified case (Webster and Liu 2001)

No data on horizontal expansion
Objective of our study:

- Perform the experiment on the Coriolis platform at Reynolds no. scaled up by a factor of 10.
- Use conductivity probes to measure the density profile.
- Calculate collapse parameters and compare with previous work.
- Perform horizontal plane measurements of the velocity field post-collapse using multi-level PIV.
- Study some of the jet characteristics like mean parameters, jet half-width, flow rates, etc.
Set-up

Top view of the experimental schematics
Experimental description

Instrumentation:
Multi-level PIV system
3 CCD cameras
2 CW solid-state lasers
3 conductivity probes

Experimental conditions:
Diameter of nozzle, $D = 5$ cm
Rotation, $\Omega = 0$
Flow rate, $Q = 0.5$-1.73 l/s
Stratification = 1%
Buoyancy freq., $N = 0.34$ rad/s
Reynolds no., $13696 < Re_D < 43878$

*Top view of the set up (as seen from the platform)*
(1) Density profiles

Relative density profile before and after all experiments (left). Brunt-Väisälä frequency, $N$ versus $Z$ (right). Last experiment
(2) PIV measurements from the vertical plane

Unstratified case calculated from fit data and using,

\[ U_c = \frac{S}{(x-x_0)} \]

where \( S = 0.097 \),

\[ x_0 = -7.97 \text{ cm} \]
(3) Jet collapse observation and its calculated parameters

Jet collapse observation using the thickness at half jet-radius

Calculated parameters for experiment Bb7 (Q= 1.33 l/s)

\[ \frac{x_m}{l_N} \approx 3.8, \frac{w_l}{l_N} \approx 0.80 \]

Roberts and Matthews (1987):

\[ \frac{x_m}{l_N} \approx 2.8, \frac{w_l}{l_N} \approx 0.95 \]

Webster and Liu (2001):

\[ \frac{x_m}{l_N} \approx 2.9, \frac{w_l}{l_N} \approx 0.93 \]
(4) Gradient Richardson number

\( \text{Gradient Richardson number (x= 120 cm) against corresponding vertical profiles} \)

\( Ri_g \) indicates the response of a turbulent field to the effect of stratification.

At \( Ri_g \geq 0.25 \), marginal stability is reached, and turbulence is suppressed.

\( Ri_g \) indicates the response of a turbulent field to the effect of stratification.
Top view of the horizontal plane

Time averaged mean velocity component $\langle U \rangle$ at the jet level

Horizontal mean velocity component shown with computed data from Dalsa 1 and Dalsa 2, merged and projected on same grid.
Multi-level horizontal plane PIV measurements

Vertical cross-sections of the mean velocity component $\langle U \rangle$
Jet-thickness and width at half-radius for Experiment Dd9
Computed from data acquired from Dalsa 1, Dalsa 2 and Miro

Jet thickness from the vertical plane over the entire domain of measurement along x-axis

Jet width from the horizontal plane over the entire domain of measurement along x-axis
Flow rates for Experiment Dd9
Computed from data acquired from Dalsa 1, Dalsa 2 and Miro

Flow rates over the entire domain of measurement along x-axis

Initial flow rate for Dd9: \( Q = 0.90 \, \text{l/s} \)
Multi-level horizontal plane PIV measurements (Dd9)

Vertical cross-sections of the mean velocity component \( \langle V \rangle \)

**Dalsa 1**

**Dalsa 2**
Multi-level horizontal plane PIV measurements (Dd9)

Vertical cross-sections of the mean Reynolds stress $\langle uv \rangle$

**Dalsa 1**

- $x = 138$ cm
- $x = 198$ cm
- $x = 258$ cm

**Dalsa 2**

- $x = 433$ cm
- $x = 533$ cm
- $x = 633$ cm
Conclusion

• Jet collapse distance and the width at collapse calculated and matched.

• Three regimes of the jet radius are observed. Isotropic expansion, vertical confinement and horizontal confinement.

• The growth of the jet thickness in the vertical plane and that of the width in the horizontal plane is inhibited.