Flow structure and air entrainment mechanism in a turbulent stationary bore

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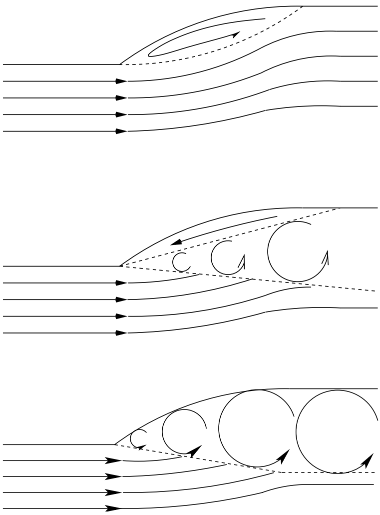
Introduction

Flow structure in a stationary bore. A review.

Longuett-Higgins & Turner (1974): the bore is a recirculating bubble, the roller, that rides on a high-speed flow where streamlines smoothly open. Based on this model, Cointe & Tulin (1994) developed a simple mechanical theory to calculate the main features of the flow.

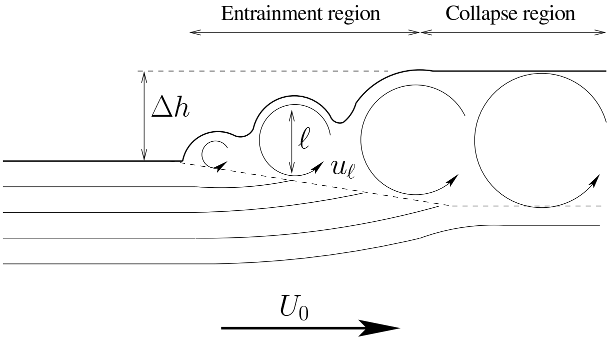
Peregrine & Svendsen (1978): A high-speed stream impinges into a region of slowly moving fluid, giving birth to a 2D mixing layer. Lin & Rockwell (1990) experimentally proved the existence of this mixing layer in a weak spilling breaker.

Hoyt & Sellin (1989): In a strong bore, the mixing layer extends vertically up to the free surface. There is no a permanent region of slow-moving spilling fluid. They proposed that the structured can be described as a mixing layer separating the air and water streams.



Introduction

Flow structure in a stationary bore. Proposed model.



Two regions can be differenciated:

- Entrainment region: A mixing layer between the high-speed stream and the spilling fluid developes. However, in the instantaneous flow picture, there is not such a steady mass of spilling fluid.
- Collapse region: Large coherent structures are not strong enough any more to produce the collapse of the free surface.

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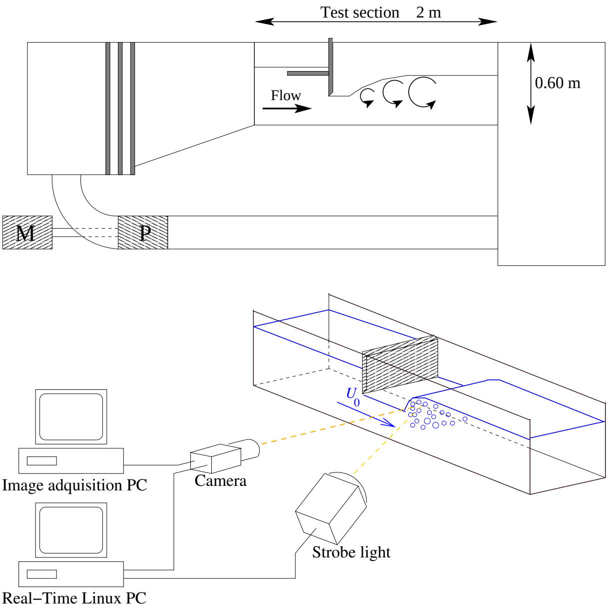
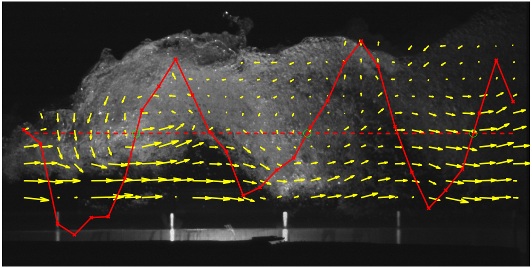


Test section 2 m
0.60 m
Flow
M
P
U_0
Image adquisition PC
Camera
Strobe light
Real–Time Linux PC

- One pair of images is taken every $T = 1/15$ s.
- The images in the pair are separated $\Delta t = 1$ ms apart.
- A correlation algorithm similar to the one used in PIV is applied to correlate every image pair.
- The interrogation window was 64×64 pixels with 50% overlap, corresponding to about 2.5 cm resolution.
- A gaussian filter was applied to every velocity field to filter out the high-frequency noise. This is consistent with the fact that we are only interested in the large scale flow features.

PIV measurements

- Despite the filtering, measurements are still too noisy to employ any conventional technique to detect the vortices.
- Since vortex centers lay approximatelly on the horizontal axis, the average vertical velocity on every x station is employed to detect the vortices.
- Points where this average vertical velocity becomes negative are possible canditates to be vortex centers.
- Visual inspection is required to eliminate spurious vortices.



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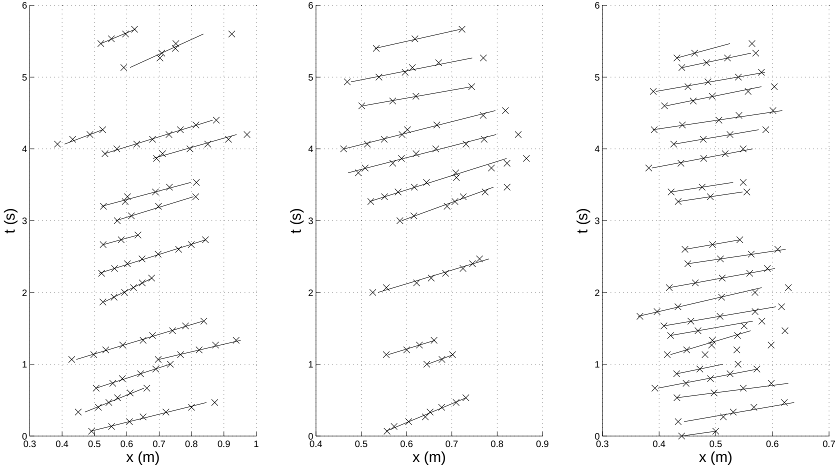
- Measurements have been performed for three different sets of experimental conditions

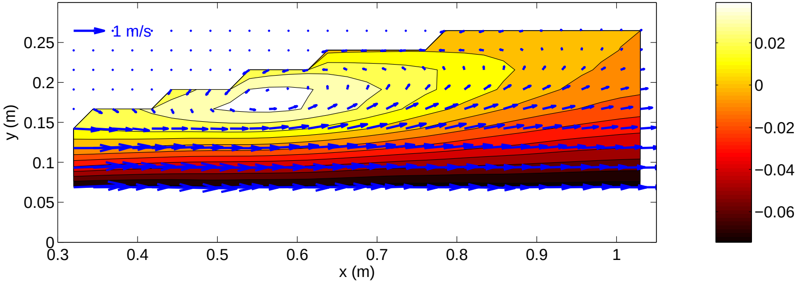
Set	1	2	3
Free stream velocity, U_0 (m/s)	2.48	2.21	2.07
Maximum height difference, Δh (m)	0.15	0.14	0.11
Upstream water depth, Δh_0 (m)	0.11	0.10	0.15
Froude number (Δh), $Fr_{\Delta h} = U_0^2/g\Delta h$	4.16	3.46	3.87
Froude number (h_0), $Fr_0 = U_0^2/gh_0$	5.70	4.98	2.91

Results
Convective velocity of the Large Coherent Structures

Set 1	Set 2	Set 3
$\overline{U}_c = 0.71$ m/s	$\overline{U}_c = 0.59$ m/s	$\overline{x}_c = 0.72$ m/s
$\sigma_{U_c} = 0.14$ m/s	$\sigma_{U_c} = 0.16$ m/s	$\sigma_{U_c} = 0.14$ m/s



- The roller described in previous works actually exists, but only in the average sense.



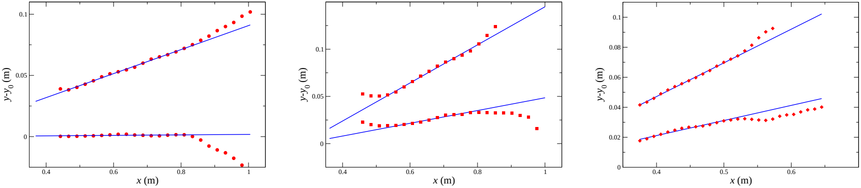
Results

Analysis of the mean velocity profiles. Growth rate of the mixing layer.

- A dimensionless horizontal velocity will be defined as

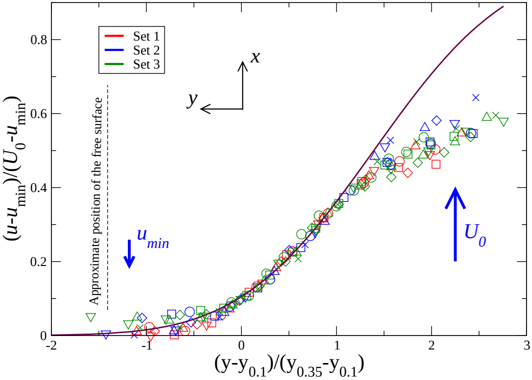
$$U = \frac{u - u_{\min}}{U_0 - u_{\min}}$$

  being $u_{\min}$ the velocity measured at the top of the roller in each set.
- The growth rate of the mixing layer will be characterized by separation rate between the iso-U lines $U = 0.1$ and $U = 0.35$.



- There exists a region where isolines diverge almost linearly. This region coincides fairly well with that occupied by the roller in the three sets.

- If the adimensional velocity profiles are plotted against $\eta = (y - y_{0.1})/(y_{0.35} - y_{0.1})$ they exhibit self-similarity



- Close to the interface with the potential-flow region, the profiles departure from the profile proposed by Townsend (1976), $U = (1 + \mathrm{erf}((\eta - \eta_0)/C))/2$.

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- The advection velocity of the vortices in a mixing layer separating two streams moving at velocities U_0 and u_{min} is given by

$$u_{\mathrm{c}} = \frac{U_0 + u_{\mathrm{min}}}{2}$$

- In the present case, the measured advection velocity of the vortices is notably smaller than the value expected:

Set	1	2	3
Free stream velocity, U_0 (m/s)	2.48	2.21	2.07
Minimum measured velocity, u_{min} (m/s)	-0.20	-0.21	-0.04
$U_{c(m.l.)} = (U_0 + u_{\mathrm{min}})/2$ (m/s)	1.14	1.00	1.02
Measured, U_{c} (m/s)	0.71	0.59	0.72

- In all the three sets, the free stream velocity, U_0, is kept almost constant for the whole length of linear growth (or roller). Therefore, the finite depth of the channel is not expected to have any effect on the dynamics of the large vortices.

- In the classical mixing layer, the growth rate $\mathrm{d}\ell/\mathrm{d}x$ is given by:

$$\frac{U_0 + u_{\min}}{U_0 - u_{\min}} \frac{\mathrm{d}\ell}{\mathrm{d}x} = 2\beta = 0.028$$

being β the entrainment parameter (Townsend, 1976).

- In the present flow, assuming a velocity profile $U = (1 + \mathrm{erf}((\eta - \eta_0)/C))/2$, the growth rate is given by:

$$\frac{\mathrm{d}\ell}{\mathrm{d}x} = 1.11 \frac{\mathrm{d}(y_{0.1} - y_{0.35})}{\mathrm{d}x}$$

- The growth rates calculated for the three sets are:

Set	1	2	3
Growth rate, $\mathrm{d}\ell/\mathrm{d}x$	0.11	0.14	0.12
$(U_0 + u_{\min})/(U_0 - u_{\min})$	0.852	0.824	0.965
$(U_0 + u_{\min})/(U_0 - u_{\min})\,\mathrm{d}\ell/\mathrm{d}x$	0.095	0.113	0.118

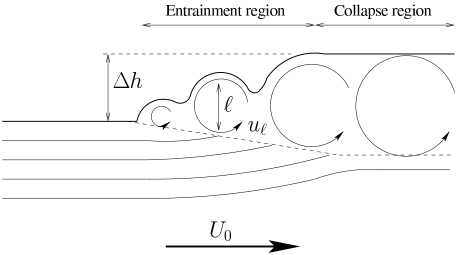
- The measured entrainment parameter is therefore:

$$\beta = 0.054 \pm 0.007$$

- This is 3.5 times larger than in the classical mixing layer ($\beta = 0.014$).
- The shear flow under consideration is therefore about 3.5 times more efficient entraining fluid.
- Very few pairing events were observed during the tracking of the vortices, so the main growth mechanism for the vortices is the entrainment of irrotational fluid from the free stream.

Discussion
Hypothesis: effect of the free surface.

- It has been seen that vortices move slower than predicted by the classical mixing layer theory.



- Since the free stream velocity is almost constant through the length of the bore, this difference has to be caused by the presence of the free surface.
- The kinetic energy present in the large structures is additionally dissipated in two ways:
  - Large vortices have to overcome an inverse pressure gradient due to the increasing depth.
  - The large deformation of the free surface and its subsequent breakup into very small air bubbles.
- Work is currently ongoing to model these two effects and try to predict the observed velocities.

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Conclusions

- The region close to the toe of a bore has been estudied experimentally using statistical correlation techniques on images of the flow. The two-dimensional nature of the flow has allowed us to study the dynamics of the flow by imaging just one plane close to the wall.
- Accurate measurements have been performed of the advection velocities of the large scale eddies observed in the flow. They have been observed to move significantly slower than what would be expected in a classical mixing layer.
- The roller described in the literature emerges as an structure in the mean velocity field even though no recirculating motion exists at any particular time.
- The shear layer grows linearly in a region that coincides fairly well with that occupied by the roller.
- Velocity profiles within this region exhibit a self-similar behavior. However, the self-similar velocity profile does not follow the one proposed by Townsend.
- The growth rate of the shear layer is about 3.5 larger than that expected for a classical mixing layer. This is consistent with the slower advection velocity of the large scale features.