# **Combined PIV-LIF measurements of two layer flows: analysis of mixing processes over different bottom macro-roughness.**

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#### Abstract

This study presents preliminary results on the application of combined Particle Image Velocimetry – Laser Induced Fluorescence measurements to characterize flow and mixing processes of stratified flows at laboratory scale. Laboratory experiments were conducted with two different bottom configuration and two hydraulic submergences showing the influence of these aspects in the exchange flows.

#### Keywords

Stratified flows; mixing process; bottom roughness; PIV; LIF

#### **INTRODUCTION**

Two-layer density flows are characterized by two different fluids that can be clearly distinguished one on top of the other. This phenomenon can occur naturally in estuaries or straits (e.g., Strait of Gibraltar) and it is considered as a highly important environmental exchange system. Hydrodynamic instabilities have been observed at the interface of the stratified flows, such as small-scale Kelvin-Helmontz and Holmboe instabilities, as well as large-scale instabilities such as billow-like structures (e.g. Zhu y Lawrence, 2001, Negretti et al., 2008).

Stratified flow exchanges are primarily due to the interaction between baroclinic effects (density differences) and interfacial instabilities. Nevertheless, additional barotropic components (due to the external pressure forcing mechanism) are also responsible for the flow and the characteristics of the mixing processes. (Negretti et al., 2007). Armi (1986) and Farmer and Armi (1986) systematized the analysis of two-layer bidirectional flows, establishing the framework for internal hydraulics. Further developments of this theory include theoretical and experimental works such as the ones developed by Zhu and Lawrence (1998, 2000) or Morin et al. (2004).

In comparison with the progress of the internal hydraulics theory, the number of studies analyzing the interactions between the geometry of the bottom floor and the flow patterns and development of the shear interface is much smaller. Some relevant experimental works are those developed by Thorpe (1983) or Negretti et al. (2008), as well as the recent application of numerical LES modelling to the analysis of density currents over an array of dunes conducted by Tokyay et al. (2011). The current study examines the influence of the bottom macro-roughness on the development of the shear interface and the mixing processes over a rough bed made up of one isolated dune and a series of continuous dunes. For this purpose, a series of flume tests were carried out at the R+D Centre of Technological Innovation in Building and Civil Engineering (CITEEC) of the University of A Coruña (Spain). Preliminary results of the study can be consulted in Anta et al. (in press).

## MATERIAL AND METHODS

The tests were conducted over a bottom bed with an isolated submarine dune and a series of continuous dunes. The different dune configurations were set up in a 20 m long and 0.6 m wide closed flume. In the centre of the flume, a narrower channel, 0.15 cm wide and 2 m long, connected the two water bodies. The tested dune was L=40 cm long,  $\Delta$ =6 cm high and with a 5:1 slope along

the first 30 cm starting on the left end, connecting with a cosine slope along the last 10 cm defined as  $z = \Delta \cos^2(\pi \cdot x/20)$ , where z is the height of the dune in cm at a distance of x from its crest, measured towards the right. A total of four tests were carried out combining two types of bottom macro roughness (1 dune and 5 dunes, see Table 1), and two total water depths ( $H=2\Delta$ ,  $H=4\Delta$ , with  $\Delta$  as the height of the dune). The tank was then filled up to the considered height and a Plexiglas barrier was placed over the sill crest. The difference in density,  $\Delta \rho / \rho = 1.07\%$ , was reproduced by adding salt to the right reservoir. Combined PIV-LIF measurements were used to study in detail the behaviour of two-layer flows and the influence of the bed morphology. A scheme of this setup can be found in Anta et al. (in press).

able 1. Summary of the experimental conditions tested in the experiments	

	High submergence		Low submergence	
	Isolated	Continuous	Isolated	Continuous
	dune	dunes	dune	dunes
Experiment	(a)	(b)	(c)	(d)
Submergence $H/\Delta$	4		2	
$q/H\sqrt{g'H}$	0.105	0.099	0.053	0.043

## **RESULTS AND DISCUSSION**

In pure baroclinic exchange flows, as reported by Farmer and Armi (1986), the net flow across a vertical plane should be zero. Nevertheless, and as described in Negretti et al. (2007), we found an unsteady barotropic flow component superimposed to the baroclinic exchange flow. Net flow oscillations normalized per unit width are clearly shown in Figure 1.



**Figure 1**. Normalized net flow at the sill crest. Total depth of H=24 cm - (a) isolated dune and (b) continuous dunes – and H=12 cm - (c) isolated dune and (d) continuous dunes.

As it can be observed, the amplitude of the net flow is larger for the isolated dune bottom configuration experiments. The period of the barotropic oscillations (~30-40 sec) is much smaller than the characteristic period of the interfacial internal seiche propagated in a closed two-dimensional basin given by  $T_s = 2L_{tot} / c$  (Morin et al. 2004). The total length of the channel is  $L_{tot}=18$  m and the celerity of the interfacial wave can be determined as  $c = \sqrt{g' z_1 z_2 / (z_1 + z_2)}$ , with  $z_1$  and  $z_2$  being the water depth in the upper and lower layer respectively. Assuming the interface at the center depth of the flume, the obtained periods are 432 s and 193 s for high and low submergence experiments respectively. Again, similar findings were reported by Negretti et al. (2007).



**Figure 2**. Series of instantaneous LIF images for a total depth H=24 cm - (a) isolated dune and (b) continuous dunes – and H=12 cm - (c) isolated dune and (d) continuous dunes. The dye was added to the fresh water. The time lag between images is 1 s.

Figure 2 shows the development of the flow during the experiments recorded by a series of instantaneous LIF images taken 150 s after the beginning of the experiment (at the beginning of maximal exchange flow). The barotropic features of the exchange flow are clearly visible in the isolated dune experiments where two-dimensional pulsating billows structures are formed over the

dune. Downstream of the sill crest, the interface position is firstly shifted upwards and then advected downstream -see dashed lines in Figure 2-a and -c). Sometimes the interfacial waves grow from KH instabilities which are propagated within the interface upstream and downstream the sill crest. The advection and growth of the billow-structures enhances the mixing from the lower salty layer to the upper freshwater layer. In the lower depth trial (Fig. 2–c), the entrainment of fresh water can eventually block the lower layer flow, shifting the position of the interface to bed bottom. In the continuous dunes experiments, the interface position taken by the LIF images is quasi-horizontal, and only small instabilities can be observed (Fig 2-b and –d). Thus, this configuration with the array of dunes is more effective in damping the formation of the two-dimensional structures at the interface. Similar findings were reported by Negretti et al. (2008) when analyzing the effect of different roughness placed along the down-slope of an isolated dune. Nevertheless, we must notice the differences in the bottom roughness which can be considered as a micro-roughness effect which clearly contrasts with our macro-roughness analysis.



**Figure 3**. Velocity record over the sill crest for a time series of 300 s: (a) isolated dune and (b) continuous dunes for a total depth of H=24 cm and (c) isolated dune and (d) continuous dunes for H=12 cm. Heights are normalized with the water height above the crest  $h_s$  18 and 6cm, respectively.

This qualitative flow description is consistent with the net flow measurements shown in Figure 1 and the velocity records presented in Figure 3. The latter figure shows the maximal exchange flows in a vertical plane over the dune crest. Fluctuating flow pulsations due to barotropic effects are visible for isolated dune experiments in the lower layer (Fig. 3-a and -c) while for the array of dunes, flow accelerations and decelerations associated with the billows-like structures are damped.

As expected, the exchange discharges are higher for the high submergence experiments and decrease for continuous dunes bottom roughness (see also Table 1). The latter is due to the lower equivalent depth of the exchange flows which induces a friction loss due to the presence of the array of dunes.

Another key factor which affects the flow structure is the roughness separation ratio  $\lambda/\Delta$  combined with the flow submergence  $H/\Delta$ . To highlight this behavior, mean velocity maps are presented in Figure 4. Both the flow and the position of the shear interface over the isolated dunes adapt to the bottom shape. However, in the continuous dunes experiments, a different flow pattern is observed depending on the flow submergence. In the high submergence experiment, quasi-stable separated clockwise vortices occupy the entire cavity between the dunes, exhibiting characteristics of –d type skimming flows (Anta et al., in press). However, in the array of dunes with H=12 cm and due to the low exchange discharge, the lower layer flow adapts to bottom shape and the upper layer remains quasi-horizontal. In this test, a near zero velocity area appears downstream the sill between the two layers (i.e. Fig 4-d, x/L~0.3 and z/H~0.1). Thus, the bottom roughness can be considered as a type in between –d and –k type roughness.



**Figure 4**. Mean velocity maps for (a) isolated dune and (b) continuous dunes - total depth of H=24 cm- and (c) isolated dune and (d) continuous dunes -H=12 cm. The x and y axes are normalized with the length of the left side of dune (L=30cm) and the total depth respectively.



**Figure 5**. Time-averaged quantities for shear-layer thickness  $\delta$  (left) and bulk Richardson number *J* (right). The x and y axes are normalized with the length of the left side of dune (L=30cm) and the total depth respectively.

The effect of the flow submergence and the roughness characteristic length on the shear layer thickness  $\delta$  and the bulk Richardson number is presented in Figure 5. Here, the mean shear layer thickness is defined as the vertical distance in which the velocity profile covers from 15% to 85% of the maximum velocity in that profile,  $\delta = h|_{\overline{u}=0.15} - h|_{\overline{u}=0.85}$ , and the bulk Richardson is defined using this parameter as  $J = g' \delta / \Delta U^2$  (see Negretti et al., 2007). Upstream of the sill crest, the dimensionless time-averaged shear layer thickness remains almost constant for all the experiments. Differences due to submergence appear downstream the sill with remarkably thicker shear layers in the lower water depth tests. It is also worth noticing that an increase of the depth downstream the dune increases the shear layer thickness, especially in the isolated dune bottom configurations. The bulk Richardson number measures the stabilizing effect of buoyancy relative to the interfacial shear destabilizating effect. In high submergence experiments, the Richardson number remains nearly constant with a mean value of 0.3. A slight increasing trend is visible downstream the sill. Larger values have been found in the low submergence tests of roughly one order of magnitude. This is due to the smaller velocity difference found between the two layers for low-depth experiments and therefore, the smaller importance of shear forces in the development of the exchange flows.

Lastly, an example of the averaged horizontal (left) and vertical (right) Reynolds transports, u'c' and  $\overline{w'c'}$  respectively, for the high submergence test is plotted in Figure 6. Positive values represent mass transport from the lower salty layer into the upper fresh water layer, while negative values correspond to the transport into the lower layer. Larger values for both horizontal and vertical buoyant transport are recorded for the isolated dune test, highlighting the effect of the large barotropic structures in the mixing processes. Furthermore, horizontal mixing tends to add fresh water into the salty layer while vertical transport is bidirectional. Similar findings were reported by Negretti et al. (2008). In the array of dune tests, the mixing patterns follow the velocity structure shown in Figure 4. It also can be noticed as the buoyant transport rates are one order smaller than the values found for the isolated dune case.



**Figure 6**. Buoyant transport  $\overline{u'c'}$  (left) and  $\overline{w'c'}$  (right) for (a) isolated dune and (b) continuous dunes - total depth of H=24 cm. The x- and y- axes are normalized with the length of the left side of dune (L=30cm) and the total depth respectively.

## CONCLUSIONS

We have presented some preliminary results on gravimetric exchange flow over two different bottom configurations and two submergences. The main objective of the paper was to show the capabilities of combined PIV-LIF measurements in analyzing such types of flows. Both techniques were used to study in detail the behaviour of two-layer flows and the influence of the bed morphology. The Particle Image Velocimetry method (PIV) allows us to obtain quantitative data such as velocity fields and discharges while the Laser Induced Fluorescence (LIF) was used to determine density maps and identify the formation, growth and development of shear layer instabilities, such as Kelvin-Helmholtz instabilities. In addition to this, different dimensionless ratios such as the bulk Richardson number, and spatial evolutions of the shear–layer thickness have been presented.

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