GRAVITY CURRENTS:
From dust storms to volcano eruptions

LABORATORY EXPERIMENTS

FLUID DYNAMICS OF SUSTAINABILITY AND THE ENVIRONMENT

LOÏC TADRIST[1] , ALEXANDRE STEGNER, PASCALE BOURUET-AUBERTOT

ÉCOLE POLYTECHNIQUE, PALAISEAU, FRANCE
9-20 SEPTEMBER 2013

[1]CONTACT : *loic.tadrist@ladhyx.polytechnique.fr*

1 Introduction

Who has never chilled because of doorway flows ? Who has never felt on his face the freezing air flowing down the hallways of the métro in Paris (the tube in London)? These are two examples of gravity currents that you encounter daily. Gravity currents are flows between two fluids of different density driven by gravity. They are highly common in Nature: snow avalanches, submarine rock slides, dust storms, explosive volcano eruption, lava flows, mud flows (see [1]). Since these flows are harmful for humans, they have been highly studied [2, 3]. The purpose of the experiments is to get insights on the variation of the flow as a function of the parameters involved in the fluid dynamics. This experimental study focuses on two types of gravity currents. The first experiment is a model for classic forms of gravity currents (avalanches, lava flows, mud flows or dust storms)(80% of the time). You will have to discover what are the scaling laws which controls the flow dynamics. To this aim, you will realize different experiments varying some of the parameters. The second experiment models the strait of Gibraltar (20% of the time). Here the work is to understand some of the caracteristics of a gravity current flowing over a bump.

2 Material and methods

For time use efficiency I have prepared a detailed protocol of the experiment. Each test takes about 30 minutes. Nevertheless, feel free to discuss with me if you want to try something you just thought about.

2.1 Materials

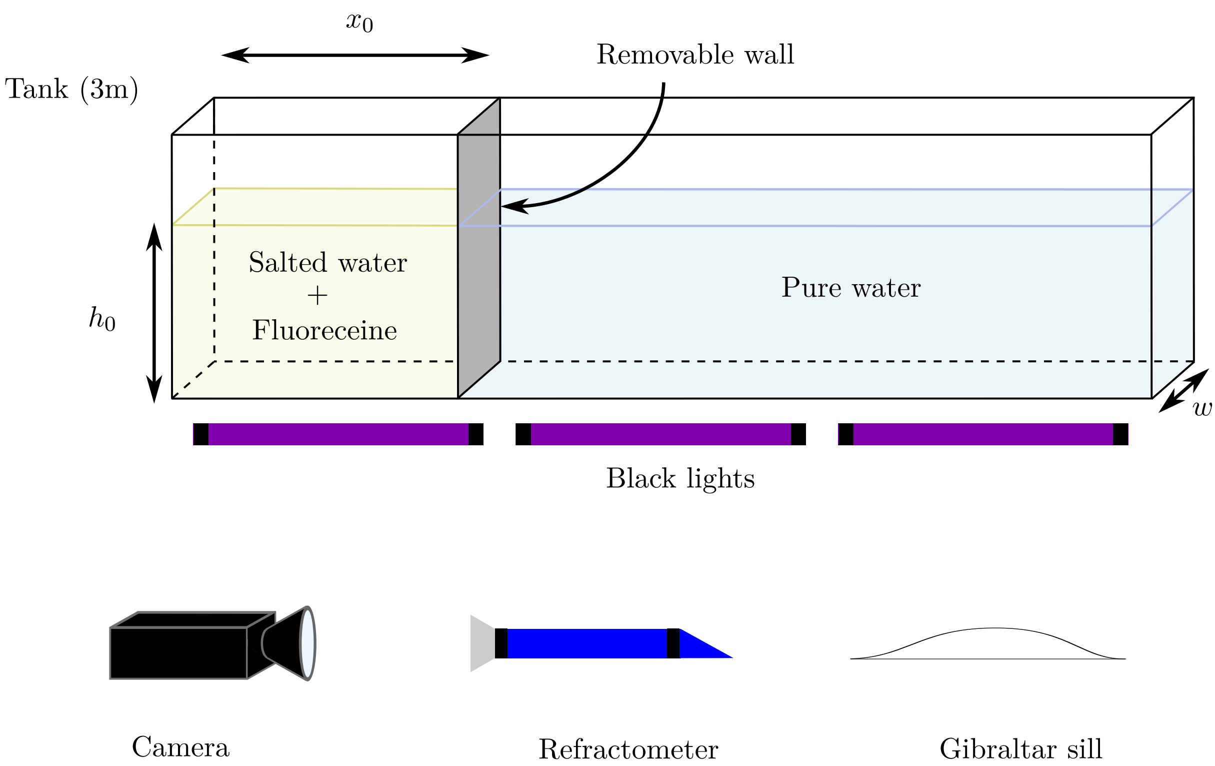

Figure 1: Given material to do the experiment.

To prepare the salted water,you will use a precise weighing scales to weight the salt and a graduated seal for the amount of water. You will check the concentration using the refractometer. At the end of the experiment, to empty the water tank, you will pour the used water into the white container. At last, you will use a computer to process the data.

2.2 Methods

Measuring salt concentration

You will measure salt concentration with a refractometer. The refractometer measures the index of salted water, hopefully it is directly graduated in salt concentration. To use it, you just have to drop off some salted water on the blue prism. The mobile piece of the refractometer has to be turned to spread the water drop. You just have to read the water salinity and water density on the refractometer.

Measuring gravity currents Quantitative analysis of the experiments is based on image processing of the signal recorded by the camera. It requires only two things : to put a scale into the camera field and to note the speed of acquisition (the number of frames per second). Then all the data treatment will be done thanks to a Matlab program, which is already written.

3 Gravity Currents

3.1 The experiment

First of all, you need to see what is a gravity current. The experimental apparatus consists of a large water tank that is initially divided into two parts by a removable wall. Fill the largest part of the tank with tap water and fill the other part with salted water (1 $g.L^{-1}$). You will prepare 4 liters of salted water and place the removable wall so that h=15 cm. To make the experiment visible, you will have to add some fluoreceine, a fluorescent chemical product, into the salted water (10 drops per liter). To enhance contrast, you have to turn off the light and to turn on the black lights. Remove quickly but carefully the wall, a gravity current takes place.

When the current reaches the other edge of the tank, the experiment is done. You need to empty the tank with the pipes provided. This is the longest part of the experiment, do not loose time to empty the tank.

What are your first observations? What could be interesting to measure ?

3.2 Measurements

What is the speed of the flow ? Repeat the experiment but now focusing on the time evolution of the flow. With the camera you can record the flow front positions in time.(Do not forget to put a scale in the camera field and to note the speed of acquisition. You have to choose the good acquisition speed from the first experiment you did, 2.7 or 5.4 fps.) For recording the flow evolution, you will use Matlab. This software is efficient for both controlling the camera and processing the data.

Recording the data

1. First turn on the computer and the camera, make sure the camera is linked to the computer (USB 2).

2. Create your own directory on the Desk.

3. Open Matlab and launch the command *imaqtool*. This will open a user interface.

4. Choose on the left the camera resolution (Lumenera USB2, default). Start preview.

5. Adjust the camera in such a way that you obtain the best image (the whole tank must appear in the camera field, the image must be clear and the a good contrast for the fluoreceine must be found).

6. In the *imaqtool* user interface in **acquisition parameters**, **General**, set frame per triger to infinite.

7. **acquisition parameters**, **Device properties**, set the frame rate. You can play on the parameters to obtain a better image.
8. **acquisition parameters**, **logging**, log to Disk and give a name to the film. Make sure the name of your file is not confusing.
9. **acquisition parameters**, **Trigger**, Trigger type must be manual.
10. **acquisition parameters**, **Region of interest**, first Reset then Select or Edit and clic on the preview to select the region of interest. This region must contain the fluoreceine flow and the scale. Note that it is important to focus on the region of interest in order to avoid memory saturation.
11. Start the acquisition and wait before triggering. Remowe the wall and trigger acquisition when the fluoresceine flow is in the camera field. At the end of the experiment, stop the acquisition.
12. Note in your notebook the caracteristics of the experiment (height, salinity, volume) and its name.

Using the data :

1. Launch the program thanks to the command: " *fen_test();* "
2. Give the directory and the name of the film. (ex: "C:\desk\your folder\your film.avi")
3. First, set the scale: click **Scale , Start**,then point both end of the scale on the image. Enter the real length (mm)to the program. Set the fps used during the experiment.
4. Second, select the region of interest by choosing the appropriate rectangle: click **Region of interest, Start** then select the rectangle on the figure and double click. Do not select the scale into the ROI.
5. Set the level threshold(<256).The only white part must be the fluoreceine.
6. Here process the analysis.
7. The program plots $x(t)$ and $v(t)$ the position and speed of the front at time t. you can play on the matlab plot tool (window of the plot).
8. You can save x, v and t.

Here you just have used a matlab program that detects the front of salted water on each frame of the film. You have to plot the front position and the front speed in time. With the matlab window tool, you can choose the plotting method (linear-log or loglog) to show a trend.

Plotting the data in linear-log diagram allows to determine an exponential relationship if the data points collapse on a straight line.

$$y = ke^x \quad \text{with} \quad Y = \log(y) \quad \rightarrow \quad Y = \log(k) + \log(e) \cdot x \tag{1}$$

Plotting the data in log-log diagram allows to show a power law relationship if the data points collapse on a straight line..

$$y = A \cdot x^k \quad \text{with} \quad Y = \log(y) \quad \text{and} \quad X = log(x) \quad \rightarrow \quad Y = \log(A) + k \cdot X \tag{2}$$

Is there a trend? Can you isolate two regimes?

3.3 Dimensional analysis

After observing the phenomenon, it is of primary importance to perform the dimensional analysis. It allows to have quickly some trends on the system.

Vashy-Buckingham Theorem :
The number of dimensionless terms that can be formed, p, is equal to the nullity of the dimensional matrix. If a physical equation has n variables and if k is the rank of the dimensional matrix, one can build $p = n - k$ dimensionless numbers.

For simplicity, k is the rank of the matrix of the exponents of the dimensions (dimensional matrix). Draw the matrix.

Thus here one can build up n-k= dimensionless numbers. Give a set of dimensionless numbers:

Among them, you can have approximate values for usual dimensionless numbers which are characteristic of the flow :

Reynolds number	Froude number
$\mathcal{R}_e =$	$\mathcal{F}_r =$

What can you tell about viscous effects versus inertial effects ? What does the value of the Froude number show ? Give the first assumption in the form of the law.

4 Assessing the model

In order to assess the model, we may vary the different parameters, namely the salt concentration, the height of salted water and the initial volume of salted water.

4.1 Varying salt concentration

Redo the experiment varying the salt concentration (0.5 $g.L^{-1}$, 1 $g.L^{-1}$, 2 $g.L^{-1}$, 10 $g.L^{-1}$) at a fixed height (15 cm) and fixed volume (4 l). And process the data with the Matlab program.

How the maximum speed is varying ?

4.2 Varying height of salted water

Redo the experiment varying the height (5 cm, 15 cm, 30 cm) at a fixed volume (4 l) and fixed salt concentration (1 $g.L^{-1}$). Process the data with the Matlab program.

How the maximum speed is varying ?

4.3 Varying the volume of salted water

Redo the experiment varying the initial volume (1 l, 2 l and 8 l) with fixed height (15 cm) and fixed salt concentration (1 $g.L^{-1}$). Process the data with the Matlab program.

How the maximum speed is varying ?

Conclusion : The best way to conclude such a study is to plot all the points on the same curve: the master curve. You may rescale all the curves with the scaling factor.

Can you comment this plot ?

5 The Box model

The dimensional analysis does not allow to access to the scaling law of the speed of the spreading of the liquid. We propose here to build a simple model of forces equilibrium, see [4]. We model the high density liquid as a box which lays out, and gets thiner, see Fig. 2.

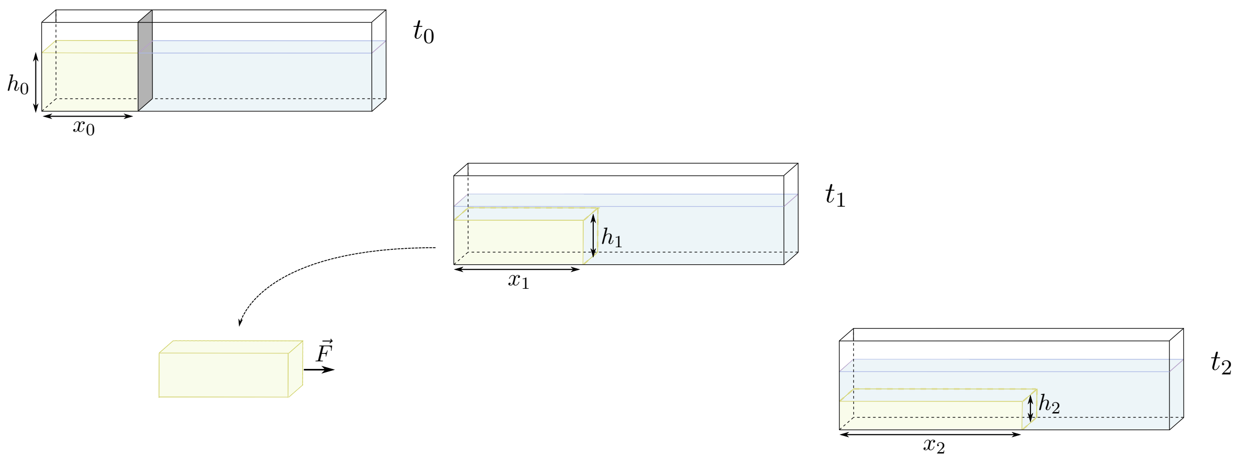

Figure 2: The box model kinematics

Here, we want to find the spreading velocity $\dot{x}$ of the salted liquid. We will simply use elementary hydrodynamics to find the scaling law.

First, through volume conservation of the spreading box, give a simple relationship between x(t) and h(t).

Now, can you determine what is creating the driving force $\vec{F}$? Express this force as a function of h(t).

At last, give the differential equation governing the evolution of $x(t)$.

Now, so far as you have a differential equation you can try to solve it. What is the power law of x in t ? (i. e.: what is α if you write $x \propto t^{\alpha}$?)

At the light of your first experiments and this power law, can you give the range of validity of the Box model ?

6 The strait of Gibraltar

Here, The strait of Gibraltar is modeled with a little bump placed on the bottom of the tank. Obviously, this stands for the undersea relief, not the rock of Gibraltar. The water of the Mediterranean sea is denser (Salinity of 38 $g.L^{-1}$) than this of the Atlantic Ocean (S=35 $g.L^{-1}$). Thus, it exists a strong gravity current which have some particularities.

6.1 Experiment

Place the little bump on the bottom of the tank as represented on the fig. 6.1. Place the gate over the little bump and fill the compartments with Atlantic and Mediterranean waters. Mediterranean water (Salted water) is denser and colored with fluoreceine. For the first experiment, use a 1 $g.L^{-1}$ concentration.

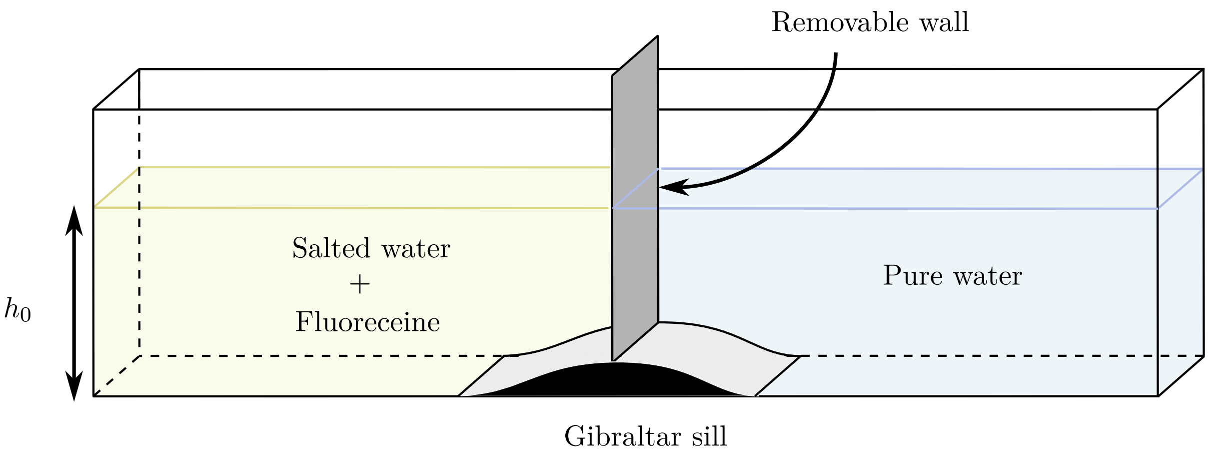

Figure 3: Gibraltar experiment

What do you observe ? Describe the flow behavior.

6.2 Is there a control parameter ?

Can you do a quick dimensional analysis ?

It is obvious that you can play easily on two parameters : The difference of density between the two fluids and the height of water above the bump. With the camera and the **imaqtool** program, you can record the flow speed and measure the surging wave.

Redo the experiment varying the height of water (7cm, 10 cm, 15 cm) at a fixed salinity (1 $g.L^{-1}$).

Redo the experiment varying the salinity (0.5 $g.L^{-1}$, 2 $g.L^{-1}$, 5 $g.L^{-1}$) at a fixed height of water (10 cm).

What is the relevant parameter, the total height of water or the height of water above the bump ?

6.3 Conclusion

Can you trace all the results as a function of the Froude number above the bump ? What is your conclusion ?

To go further, you can read *The motion of the front of a gravity current travelling down an incline* [5].

7 Bibliography

References

[1] H. Huppert & P. Linden, *Gravity currents: a personal perspective, Journal of Fluid Mechanics, (2006)* PDF

[2] John E. Simpson, *Gravity currents: In the environment and the laboratory, Cambridge University Press, 1999*

[3] Shin J. O.& S.B. Dalziel & P. F. Linden,*Gravity currents produced by lock exchange, Journal of Fluid Mechanics, (2004), vol. 521, p. 1-34* PDF

[4] M. Ungarish, *An introduction to gravity currents and intrusions, CRC Press.,(2010), chapter 4, p. 57-66* PDF

[5] R. Britter & P. Linden, *The motion of the front of a gravity current travelling down an incline, Journal of Fluid Mechanics, (1980)*