

Characterization of gravity current formation for the use in detonation refraction experiments

M.L. Wolf, D.H. Lieberman and J.E. Shepherd

Graduate Aeronautical Laboratories
California Institute of Technology
Pasadena, CA 91125
USA

GALCIT Report FM2005-006
August 30, 2005

Abstract

Detonation propagation through an interface is being studied at Caltech. In these experiments, the interface shape is determined by the gravity currents. This report presents an experimental study of the formation and the development of these gravity currents by an analog system in a water channel using water and salt water to simulate the density differences in detonation experiments. The major parameters such as the Reynolds number and the density difference were matched in both experiments to be able to compare the gravity current in the water channel and the gravity current in the Galcit detonation tube. In the present study, the gravity current was generated by the removal of a plate, and was visualized by adding food dye. The results confirm previous studies; Keulegan demonstrated in 1957 that the velocity of the gravity current is a function of the square root of the density difference. The interface is affected by the retracting of the plate which creates the wake effects. The Kelvin-Helmholtz instabilities on the upstream side of the gravity current create the visualized mixing zones. Finally, this study revealed how the gravity current interface into the Galcit detonation tube should develop and where the mixing zones should occur.

Table of contents

Introduction	p1
1) Theory and calculation	p2
2) Experimental setup	p3
2.1) The water channel	p3
a) Water channel setup	p3
b) The salt water solution	p4
c) Experiments	p5
2.2) Particle image velocimetry (PIV)	p5
a) Principle of PIV	p5
b) PIV setup and experiments	p6
3) Analysis and results	p7
3.1) General results	p7
a) Measurement of the velocity of the plate	p7
b) The gravity current	p8
3.2) Gravity currents profile and velocity	p9
3.3) Boundary layer	p10
a) Definition	p10
b) Estimation of the boundary layer thickness	p11
3.4) Experimental validation	p13
3.5) Characterization of the gravity current	p17
a) Addition of a top on the water channel	p17
b) Variation of the density of the salt solution	p17
c) Velocity of the gravity current determine by PIV	p18
3.6) Comparison with the GDT experiment	p19
a) Velocity of the GDT plate	p19
b) Gravity currents in the test section	p20
4) Conclusion	p22
1) References	p23

Appendix

Appendix 1: Graph of the velocity of the plate	p24
---	------------

Appendix 2: Image of the GC	p25
------------------------------------	------------

A) Water/blue salt water (channel 1)	p25
B) Water/blue salt water (channel 1-bottom)	p26
C) Water/blue salt water (channel 2-bottom)	p26
D) Water/blue salt water zoom (channel 2-bottom)	p29
E) Water/blue water (channel 2-bottom)	p31
F) Water/blue water zoom (channel 2-bottom)	p32
G) Blue water/salt water zoom (channel 2-bottom)	p33
H) Blue water/salt water (channel 2-bottom)	p34
I) Water/blue salt water (channel 2-bottom-top)	p34
J) Water/blue water (channel 2-bottom-top)	p36
K) Water/blue salt water $\rho=1033 \text{ kg/m}^3$ (channel 2_bottom-top)	p37

Appendix 3: Graphs of the velocity of the GC	p39
---	------------

a) exp33: Blue water/salt water (bottom)	p39
b) exp42: Water/blue salt water (bottom-top)	p40
c) exp49: Water/ blue salt water $\rho=1033 \text{ kg/m}^3$	p41

Appendix 4: PIV pictures	p42
---------------------------------	------------

Appendix 5: Data summary	p43
---------------------------------	------------

Data of the velocity of the plate-channel1	p43
Data of the velocity of the plate-channel2	p44
Data of the velocity of the plate-GDT	p44
Data of the velocity of the GC	p45

Introduction

A gravity current or density current is the flow of one fluid over another caused by a density difference between the fluids subject to the force of gravity. The difference in specific weight which provides the driving force may be due to dissolved or suspended material or to temperature differences. Gravity currents are formed in many different natural situations and many scientific disciplines, for example in the atmosphere, thunderstorm outflows and sea breeze fronts are gravity currents of relatively cold air. Gravity currents have important application in aircraft safety, atmospheric pollution, entomology, and pest control and especially in dense-gas technology (Simpson 1982). In the ocean, gravity currents are driven by salinity and temperature inhomogeneities, or as turbidity currents whose density derives from suspended mud or silt (Simpson 1987). The important problem of oil spillage on the sea is also connected to gravity currents.

The purpose of this project is to characterize the interface created between two different gas mixtures during a combustion experiment. The combustion experiment involves propagating a detonation in a stoichiometrically rich ethylene-oxygen mixture into an oxidizer or a diluent such as oxygen or nitrogen. It has been observed (see Pintgen and Shepherd 2003) that a secondary pressure peak arises when combusting fuel rich mixtures. The secondary pressure peak is attributed to a secondary combustion. Experiments by Lieberman's (2005) are being performed on the interaction of a shock wave and interface between air or oxygen and partially oxidized detonation products (Figure 1). The goal of these experiments is to study the mixing and the subsequent chemical reaction of a turbulent mixing zone from the interface. However it is difficult to visualize the interface in this experimental setup so the goal of the present study is to recreate the properties and the experimental conditions of the interfaces in Galcit detonation tube (GDT) by using liquids to visualize the gravity currents.

The first step was to study the GDT experimental setup and to determine the non-dimensional parameters that describe the system. The second step involved matching these parameters with a water channel design to ensure that the gravity currents would be similar. The water channel was built and experiments were run. In order to characterize the shape and the velocity of the gravity current different parameters were tested. Finally a comparison between the GDT experiments and the water channel experiments has been done.

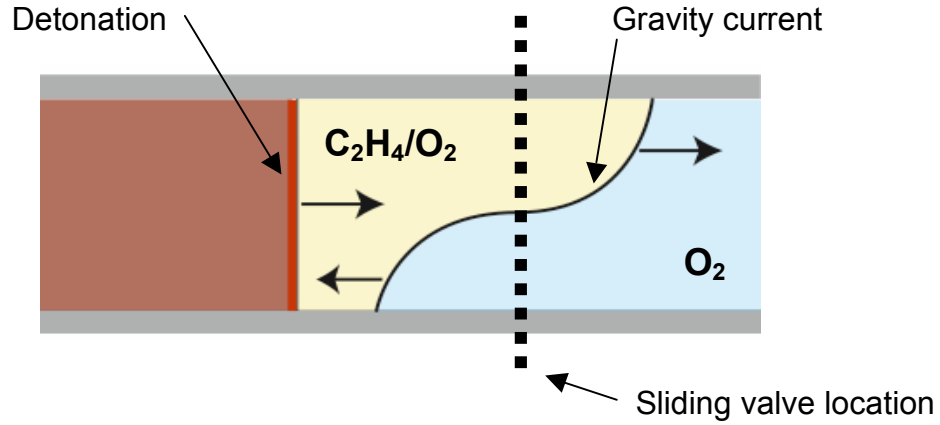


Figure 1: The gravity current occurring in the GDT.

3) Theory and calculation

Two parameters characterize the speed and the shape of gravity currents: the velocity of the plate v_{plate} , and the difference in density between the two fluids: $\Delta\rho$. $\Delta\rho$ is important because the velocity of the gravity current is a strong function of the density difference. The purpose is to determine these two parameters for the Galcit Detonation Tube (GDT) and to match them for the water channel.

There are three parameters to match. The first one is the Reynolds number. The Reynolds Number gives a measure of the flow regime created by the motion of the plate initially separating the two fluids. The definition of the Reynolds number is

$$Re = \frac{V_{plate}d}{\nu} \quad \text{non dimensional number}$$

where d is the height of the GDT in meter and ν is the kinematic viscosity of the fluid in m^2/s . the other parameter to match is the residence time. The residence time is the time it takes for the plate to be remove from the water channel.

$$t_{res} = \frac{d}{V_{plate}}$$

The last parameter which is important to match is the velocity of the gravity current. The initial velocity of the gravity current is defined in the following equation (Keulegan 1957):

$$U = C \sqrt{\frac{\Delta\rho h g}{\rho_2}}$$

U represents the velocity of the gravity current (m/s), C: is a constant dependent on fluids. The theoretical value is $C = \frac{1}{\sqrt{2}}$ (Benjamin 1968), $\Delta\rho$ represents density difference between the two fluids, ρ_2 is higher density of the flow, g is the acceleration of gravity ($g=9.81 \text{ m/s}^2$), and h is the depth of the following steady flow (height of the GDT or the water channel)

This table summarizes the parameters for each experiment

Conditions	GDT	water channel
temperature	298 K	298 K
pressure	15 kPa	1 atm
velocity of the plate	0.9 m/s	0.18 m/s
density fluid 1	$\rho_1 = 0.182 \text{ kg/m}^3$	1000 kg/m^3
density fluid 2	$\rho_2 = 0.194 \text{ kg/m}^3$	1066 kg/m^3
kinematic density	$\nu = 8.63 \text{ e-5 m}^2/\text{s}$	$1.00 \text{ e-5 m}^2/\text{s}$
Reynolds number	1569.5	1569.5
$\Delta\rho/\rho$	0.066	0.066
residence time	0.16s	0.20 s

Table 1: Parameters for GDT and water channel

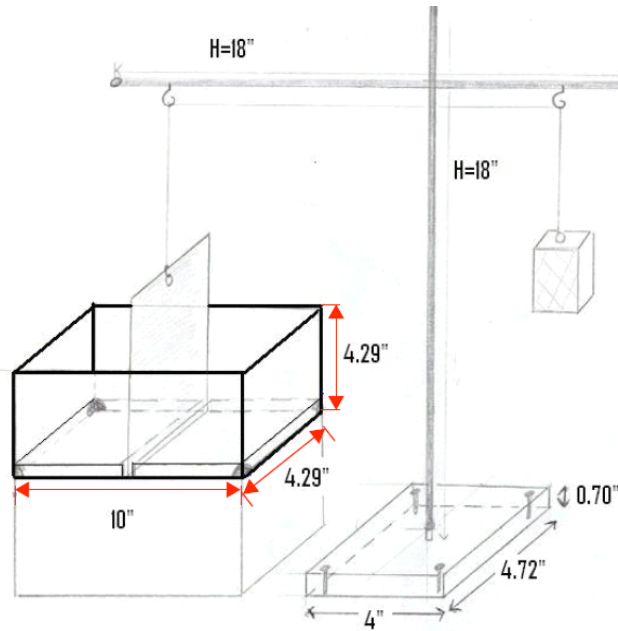
4) Experimental setup

2.1) The water channel

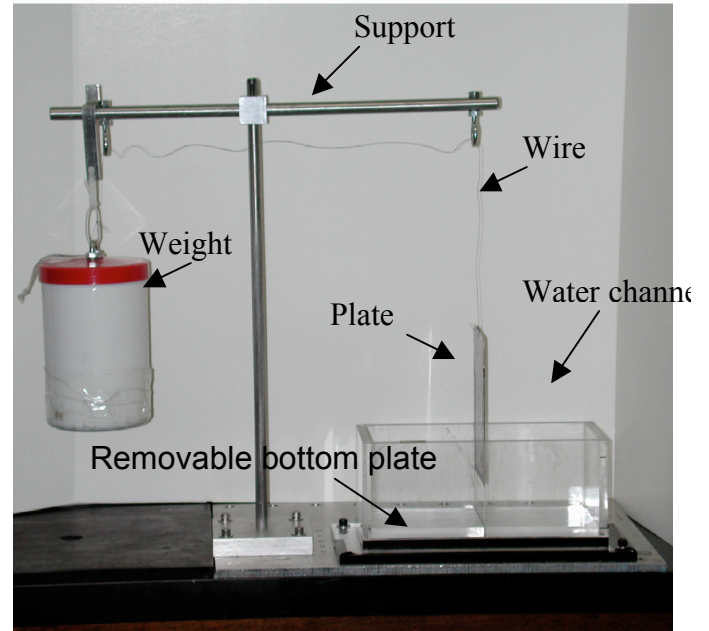
a) Water channel setup

A rectangular water channel was constructed with the dimensions determined from the scaling analysis in the previous section. The water channel is 25.4 cm long, has a height of 10.8 cm and a width of 10.8 cm. The plate is a piece of sheet metal 14.6 cm high, 9.6 cm wide and 0.16 cm in thickness. The water channel (figure 2) is made of acrylic to enable the visualization of the gravity currents.

The water channel is composed of 5 pieces of acrylic which are glued together with acrylic glue. The plate is attached with a wire to a weight (4.1 kg) and the weight is released by a metal latch which is disengaged by the operator.



a



b

Figure 2: Experimental setup: 1a is a schematic of the experimental setup and 1b is a picture of the experimental setup

The water channel was designed to hold water with no a leak across the sliding plate. For this reason, the glue chosen also creates a seal at the edges of the water channel. The sealing of the plate with the water channel is made possible by coating the interfaces with vacuum grease. A slit on the bottom of the channel was necessary to avoid a leak inside of the channel. Two water channel were built both of them have the same dimension, the water channel 1 was used to fixed the parameters, and all the following results were obtained with the water channel 2.

b) The salt solution

The temperature measured during all the experiments is 22°C. The gravity currents are due to the forces created by the difference in density between two fluids which are suddenly mixed as we pull up the plate. In these experiments, the fluids are clear deionized water and salt water in which blue food dye is added to either one. The density of each solution is measured using a hydrometer to an accuracy of 1 kg/m³. The density of the water is 1000 kg/m³ and the density of the salt water and the dye is 1066 kg/m³. The salt water solution is made with deionized water and sodium chloride. To prepare 10 L of salt water solution, 1034 g of salt and 200 mL of food dye are required. To be sure that the solution is homogenized, the salt is added in small quantities and dissolved in the water using a magnetic stirrer. Between each addition of salt the density of the solution is measured with a hydrometer.

c) Experiments

To generate gravity currents, salt water and clear water are poured on each side of the plate in the water channel. The experiments in this study always have the salt solution on the right and the water on the left. The plate is pulled up by the falling weight. The gravity current is formed and propagates along the water channel. The experiment is recorded with a Vision Research V5 Phantom camera version 5 associated with a Nikon zoom lens (70-210 mm f4-f5.6b). This allows for analysis frame by frame of the gravity current and measurement of the speed of the plate. The Phantom camera has the following settings:

Exposure time	7000 μ s
Frame per second	100
Resolution	1024x1024
Aperture	5.6

Table 2: Phantom camera settings

2.2) Particle Image Velocimetry (PIV)

a) Principle of PIV

Particle Image Velocimetry (PIV) is a planar measurement technique wherein a pulsed laser light sheet, pulsed twice, is used to illuminate a flow field seeded with tracer particles small enough (on the order of micrometers) to accurately follow the flow. The positions of the particles are recorded on a digital CCD camera at each instant the light sheet is pulsed. The data processing consists of determining the average displacements of particles in the flow. The most common way of measuring the displacement is to divide the image plane into small subsections called interrogation areas and cross-correlate the interrogations of images from the two exposure time with each other pixel by pixel. The spatial displacement that produces the maximum cross correlation statistically approximates the average displacement of the particles in the interrogation cell. Knowledge of the time interval between light sheet pulses makes it possible to calculate the velocity of the flow associated with each interrogation area. The velocity is equal to the displacement divided by the time between the two laser pulses:

$$\bar{v} = \frac{\Delta \bar{x}}{\Delta t}$$

A velocity vector map over the entire target area is obtained by repeating the cross-correlation for each interrogation area over the two image frames captured by the CCD camera.

b) PIV setup and experiments

The water channel is used in the normal condition (figure 3), that is in the same operating mode that is explained in section 2.1c. To visualize the flow, hollow glass spheres with a diameter of 44 microns are added to both sides of the water channel. The number of particles in the flow is important to obtain a good signal and have an accurate cross correlation. Before pulling up the plate, the number of particles is verified qualitatively. In general, there should be 10 to 25 particles per interrogation area.

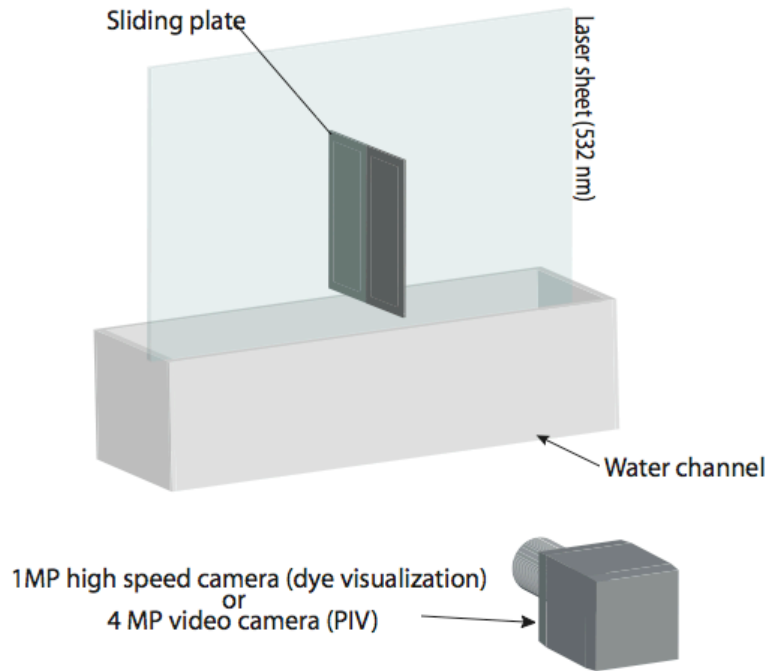


Figure 3: Schematic of the PIV setup

The two laser pulses that create the laser sheet are generated by a Nd:YAG laser which a wavelength of 532 nm. The gravity current flow is recorded by an ImperX 4 M15L CCD camera. The exposure time mode used is called "Triggered Double Exposure" (TDE) that means that there is one trigger pulse and the camera takes two images (frames). The first frame is very short ($20 \mu\text{s}$) and the second frame is full length (0.1 s). The CCD camera uses with a Nikon zoom lens (24-120mm f/8-f/11). The delay between two frames is called Δt and it is about 1.4 ms. The CCD camera has the following settings:

Exposure time:	
first frame	$20 \mu\text{s}$
second frame	0.1 s
Frame per second	15
Resolution	2048x2048

Table 3: CCD camera settings

5) Analysis and Results

3.1) General results

a) Measurement of the velocity of the plate

It is important to know the velocity with which the plate is retracting; in fact, we suppose that the sliding of the plate will create some turbulence that could affect the development of the gravity current. If the plate is always retracting with the same velocity, then the plate always affect the gravity current in the same way. The velocity of the plate can be determined by tracking a point on the sliding plate using the tracking software of the Phantom camera. The position and the time of a point are obtained for each frame. With this data and using Excel, the velocity history of this point can be drawn. Figure 4 is a position versus time plot for experiments 26, 27, 28 and 29; the weight used in those experiments was 4.1 kg.

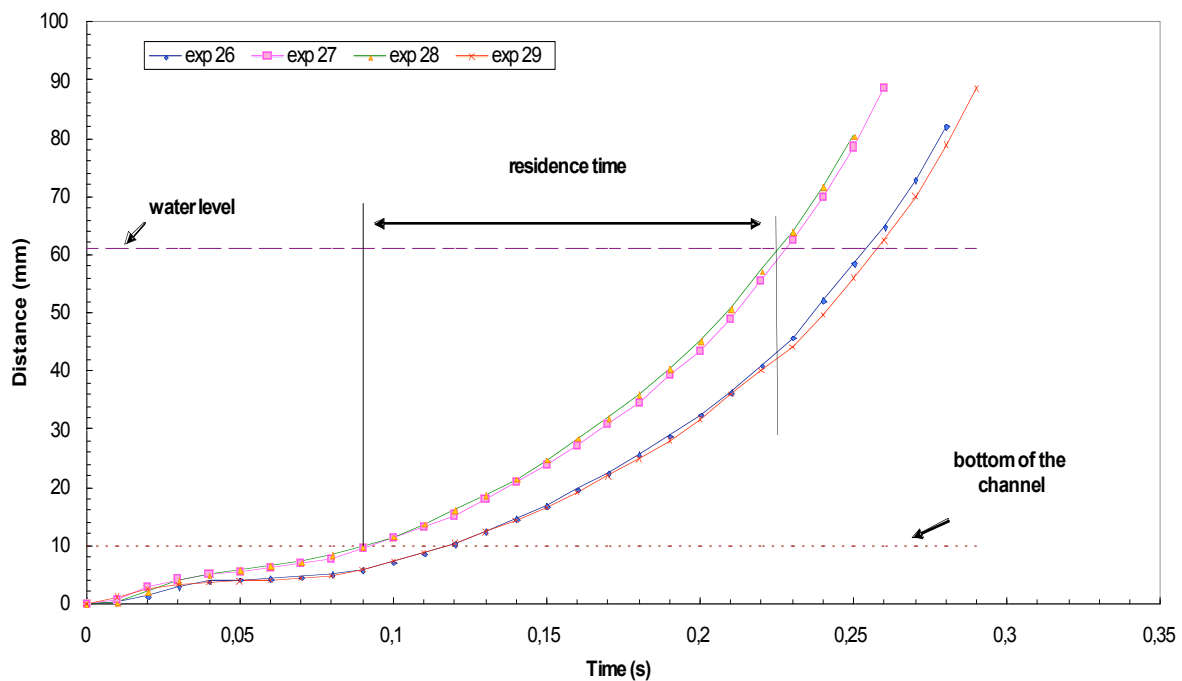


Figure 4: Velocity of the plate for the experiments 26, 27, 28 and 29.

The horizontal line at a distance of 10 mm represents the location of the bottom of the channel. To reproduce the conditions in the GDT experiment, two pieces of acrylic have been added to the bottom. The average residence time of the plate is 0.15 s. The time scale of these experiments corresponds to the time scale of the GDT experiments which is 0.17 s. The average velocity of the plate determined by these experiments is: $V_{\text{plate}} = 0.20 \text{ m/s}$; The experiments are reproducible, in fact the residence times are similar (see fig 3), so we can suppose that the plate always exits the water channel with the same velocity.

In other words the turbulence caused by the opening of the plate always affects the gravity current in a similar way. The horizontal line at 60 mm represents the free surface of the water in the channel and determines the time the plate exits the water. The residence time can be evaluated and compared with the residence time in the GDT.

b) A gravity current (GC)

The following images (figure 5) show the different steps of the evolution of the gravity current in the water channel for experiment 10. Experiment 10 is the reference for the following analysis. The dark color represents the blue salt solution of density $\rho = 1066 \text{ kg/m}^3$ and the clear color represents the water of density $\rho = 1000 \text{ kg/m}^3$. The first image (5a) shows the experimental setup at the beginning of the experiment. Then when the plate is pulled up, as shown in the image (5b) a mixing zone appears. The turbulence induced by the plate can be also observed. In the image (5c) the gravity current propagates along the bottom of the water channel and vortices due to Kelvin-Helmholtz instabilities (Simpson 1982) appear on the top of the gravity current. In the last image (5d) the gravity current has reached the end wall, and the stratification of the two mixtures can be observed.

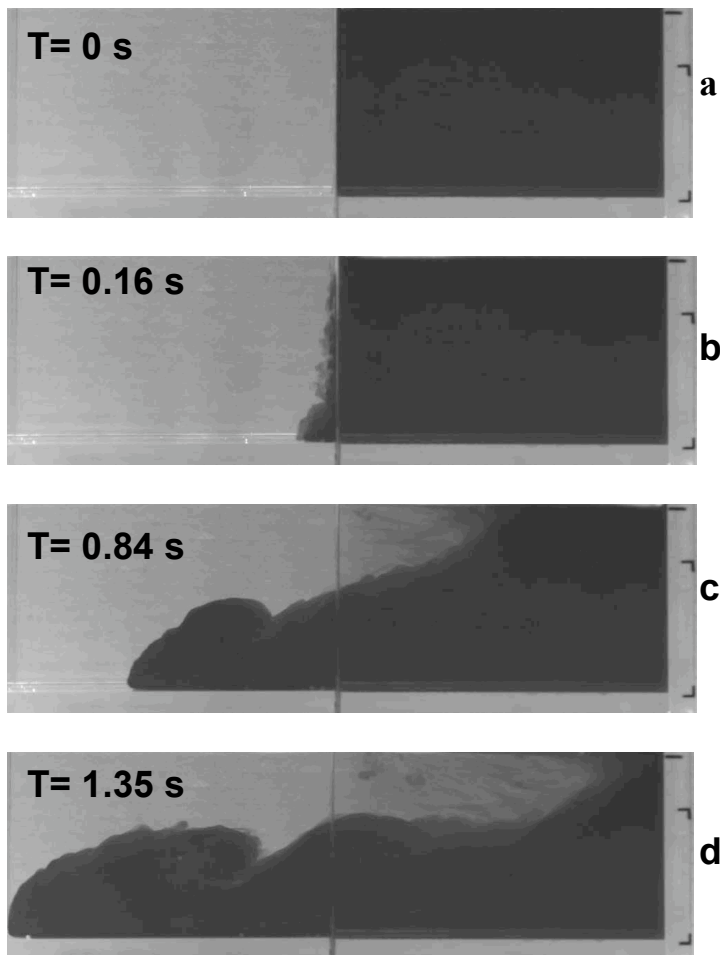


Figure 5: At the beginning of the experiment (a), the salt mixture with blue dye is on the right side and the clear water is on the left side. The plate is pulled up and the mixing zone appears as well as the nose of the gravity current (b). Then the gravity current moves along the bottom and some vortices appear (c). Finally the nose of the gravity current has touched the wall of the water channel. The fluids are starting to blend (d).

Typically the development of the gravity current starts as soon as the plate is removed. The heavier fluid, blue salt water solution, advances along the water channel surface and forms the head of the GC, also called the nose. The height of the head increases rapidly until reaching approximately half of the height of the water channel in a small time (~10 ms). Keulegan (1958) described the head as an abrupt and elevated swelling. The front head is followed by a layer of saline water of smaller depth also called the depressed layer or the underflow which form the “body” of the GC. The upstream region of the GC is a region in which of turbulence and mixing between the two fluids occur. The lighter fluid, water, travels in the upper part of the water channel and in the opposite direction. When the head of the GC touches the end wall the two fluid system evolves until reaching an equilibrium state. At the end of the experiment there are two layers in the water channel, the blue salt solution is located at the bottom of the water channel while the water, slightly bluish, is located on the top.

3.2) Gravity currents (GC) profile and velocity

The profile of the GC is determined with the mathematical program Matlab which allows the processing of images by using edge detection and threshholding.

Figure 6 shows the edge contours taken from the dye visualization experiments. For clarity, the pictures are sampled every 10 frames. The edge detection consists of finding the most accurate profile of the GC based on the contrast between the blue salt solution and the clear water solution. The processing of the video gives the profile of the GC advancing in the water channel.

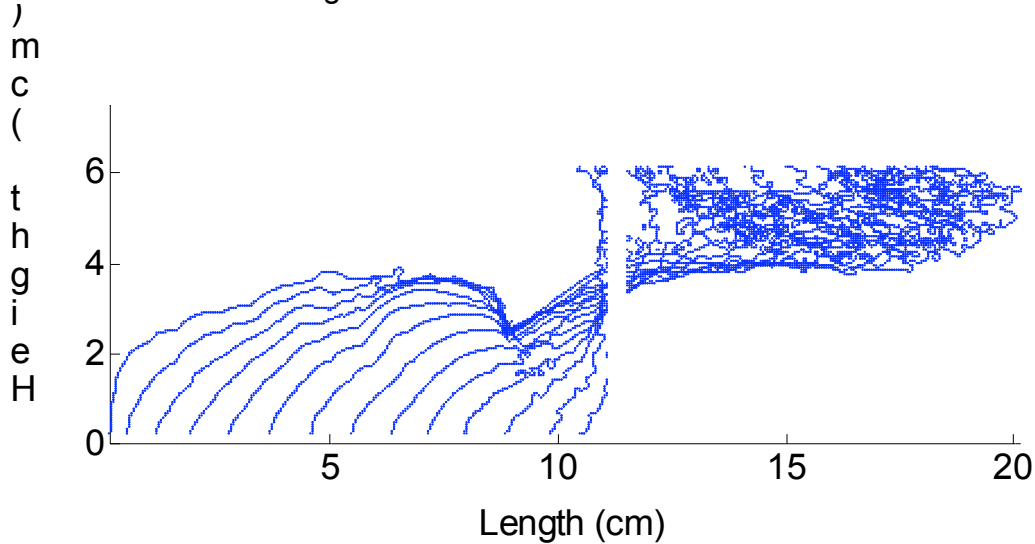


Figure 6: Gravity current profiles for exp10

With the profile, the velocity of the GC can be determined. Points at $y = 0.5$ cm are picked on each profile so Δx is obtained and Δt is known. The velocity of the GC is calculated by divided Δx by Δt :

$$v_{GC} = \frac{\Delta x}{\Delta t}$$

Figure 7 plots the time in second versus the distance in centimeter. The linear regression of this data gives the velocity of the GC.

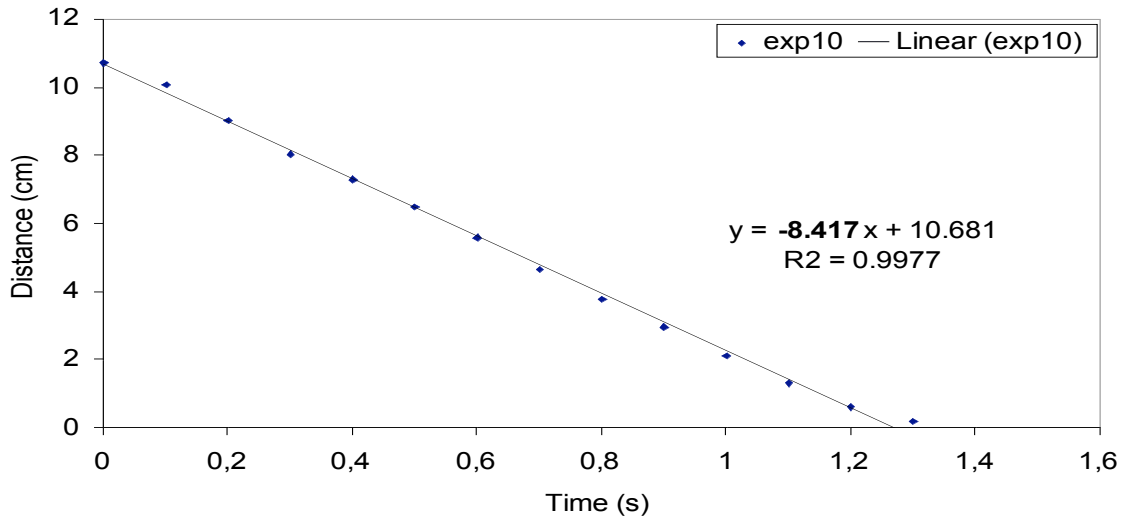


Figure 6: motion of the GC head in exp10

The average velocity of the GC in exp10 is 8.417 cm/s. The same computation is done for all the experiments with the same experimental setup that is to say with clear water in one side and blue salt water ($\rho = 1066 \text{ kg/m}^3$) in the other side of the water channel. The velocity of the GC ranges between 7.53 cm/s and 8.81 cm/s, and the average velocity is 8.08 cm/s. The uncertainty on the value of the velocity is about 1.2 cm/s. So the average velocity of the GC is **$8.08 \pm 1.2 \text{ cm/s}$** . The expected theoretical value of the GC velocity is 7.8 cm/s. The theoretical and the experimental value of the GC velocity are in good agreement. These figures confirm our observation that the gravity current travels along the water channel from the middle of the channel to the end wall with is about 13 cm in less than 2 s.

3.3) Boundary layer

The aim of the calculation of the boundary layer thickness is that gives information on the friction between the surface of the water channel and the fluid. The greater the forces of friction are, the more that they could affect the velocity of the GC. The goal of this analysis is to qualify the role the boundary layer plays in the GC experiment.

a) Definition

As an object moves through a fluid, or as a fluid passes an object, the molecules of the fluid near the object are disturbed and move around the object. Aerodynamic forces are generated between the fluid and the object and depend in a complex way on the viscosity of the fluid. As the fluid moves past the object, the molecules at the surface stick to the surface. The molecules just above the surface slow down as they collide with the molecules sticking to the surface.

These molecules in turn decelerate the flow just above them. The farther a molecule is from the surface, the less it feels the effects of the surface. This creates a thin layer of fluid near the surface in which the velocity increases from zero at the surface to the free stream value away from the surface. This thin layer is called the boundary layer because it occurs on the boundary of the fluid (see Prandtl 1953).

b) Estimation of the boundary layer thickness

The analysis done here is a simplified analysis considering only the flat bottom surface. Boundary layers may be either laminar or turbulent depending on the value of the Reynolds number. The Reynolds number Re in this case equals the velocity of the gravity current times the density ρ of the fluid (blue salt water) times a characteristic length scale x divided by the viscosity of the fluid μ :

$$Re = \frac{V_{GC} \rho x}{\mu}.$$

v_{GC} is the velocity of the GC ($v_{GC} = 8.417$ cm/s), ρ represents the density of the salt solution ($\rho = 1066$ kg/m³), x is the length of the water channel in cm, μ is the dynamic viscosity, and ν is the kinematic viscosity ($\nu = 0.1$ cm²/s).

The values of x are determined by picking different points on a GC profile. For instance, for the determination of the boundary layer, the profile of the GC on the 199th picture of exp 10 was chosen (see figure 8).

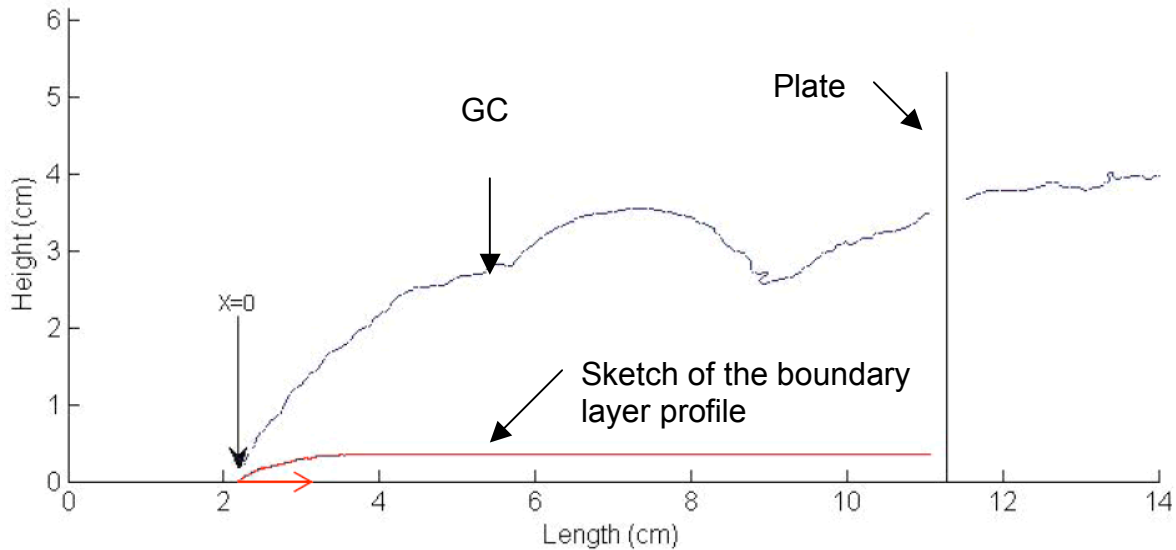


Figure 8: Determination of the values of x for the calculation of the Reynolds number

The Reynolds number found ranges from 0 to 602. For Reynolds number under 500000 the flow is laminar according to the book “Introduction to fluids mechanics” from R.W Fox and A.T Mc Donald. For lower Reynolds numbers, the boundary layer is laminar and the velocity near the surface changes uniformly as one move away from the wall.

The thickness of the boundary layer over a flat plate is defined as

$$\delta = \sqrt{\frac{\nu x}{v_{GC}}}$$

ν is the kinematic viscosity ($\nu = 0.1 \text{ cm}^2/\text{s}$), x is the length of the water channel in cm, and v_{GC} represents the velocity of the GC (8.417 cm/s).

With this formula the thickness of the boundary layer is known for each point x . Figure 9 shows the graph of the boundary layer thickness in cm versus the distance x in cm.

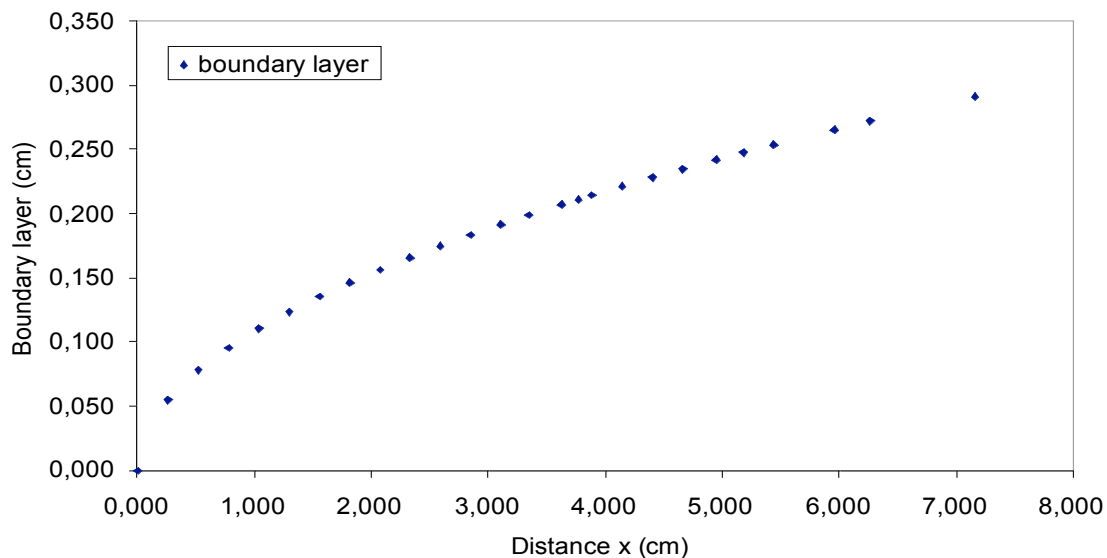


Figure 9: Evolution of the boundary layer behind the GC head

The boundary layer thickness is zero at the top of the nose of the GC and increases with the distance. At the center of the water channel (6cm), the thickness of the boundary layer is about 2.5 mm. The height of the water is 75 mm so the thickness of the boundary layer represents only 3% of the height of the water, in other words the effect of the boundary layer is small in comparison to the GC.

3.4) Experimental Validation: Effect of the wake and dye

Two major series of experiments were carried out. The first examines how the retracting of the plate affects the gravity current. The second examines the effects of the dye on the gravity current's shape and velocity. The first consists of putting clear water (W) on one side of the plate and blue water (BW) on the other side and the second major experiment consists of putting the dye in water (BW) and leaving the salt solution clear (SW).

In the first experiment, the purpose is to examine the effect of the density difference and turbulent wake of the plate on the shape of the GC. Figure 10 shows the reference (exp 10) on the right and the experiment with only water on each side on the left.

Exp10: W /BSW in water channel

Exp27: W/BW in water channel

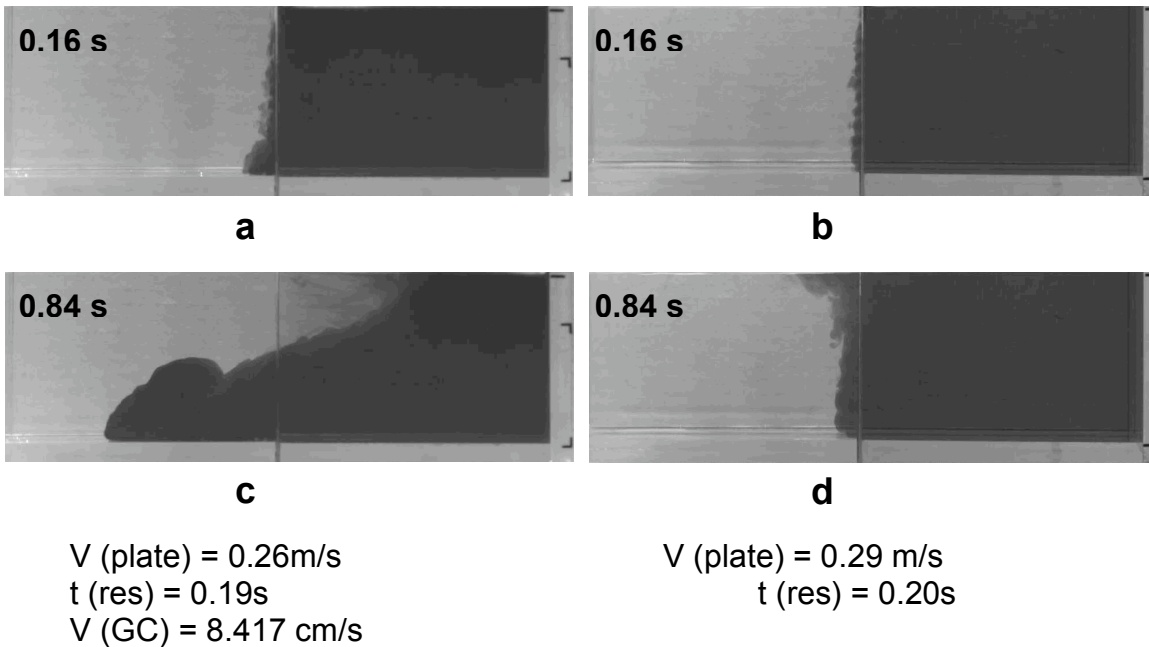


Figure 10: Picture of exp10 and exp 27 for $t=0.16 \text{ s}$ and $t= 0.84 \text{ s}$. The first image (a) shows the reference experiment (exp10) at 0.16 s when the plate is just out of the water and the GC begins to move. In experiment exp27 (b), on one side there is water (W) and on the other side there is blue water (BW) (20 ml of dye are added for 1L of water). This picture shows the experiment when the plate is just out of the water at 0.16 s. Picture (c) is the reference experiment at 0.84 s when the gravity current is halfway to the wall. The nose of the GC travels along the flat surface at an average velocity of 8.417 cm/s. Finally image (d) represents exp 27 at 0.84 s. we can notice that no GC is formed and that the dye slowly diffuses in the clear water.

A mixing zone, also referred to as a turbulent wake is observed. The plate affects the shape of the gravity current only in the first ten millisecond of the experiment. At $t=0.16$ s, both experiment 10 and 27 exhibit similar types of turbulence. But as the nose of the GC starts to move in the water channel, the turbulence or wake zone plays a secondary role. This comparison also shows that the dye does not produce a GC, in other words that the gravity current is only generated by the difference of density between the clear water and the salt water solution. In a magnification of the same experiment (see figure 11) the turbulence due to the retracting off the plate is well visualized.

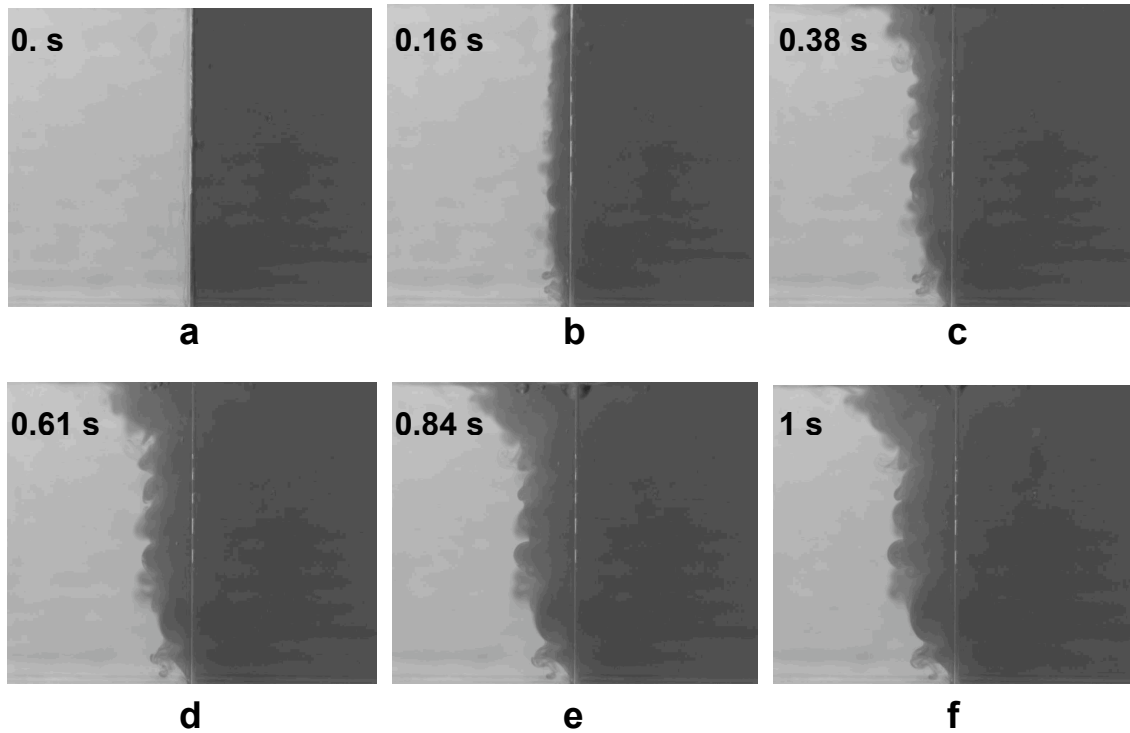


Figure 11: Magnification of exp27 at different time. At the beginning of the experience (a) at $t=0$ s the plate is in the slit. As soon as the plate is out off the water; turbulence is visible and looks like rolls (b). Then the diffusion of the dye into the clear water occurs but turbulence due to the plate are still visible (c, d, e and f).

This magnification shows the diffusion of the dye and can be used to estimate the effect of the diffusion of the dye on the GC. The diffusion velocity is experimentally determined in figure 12.

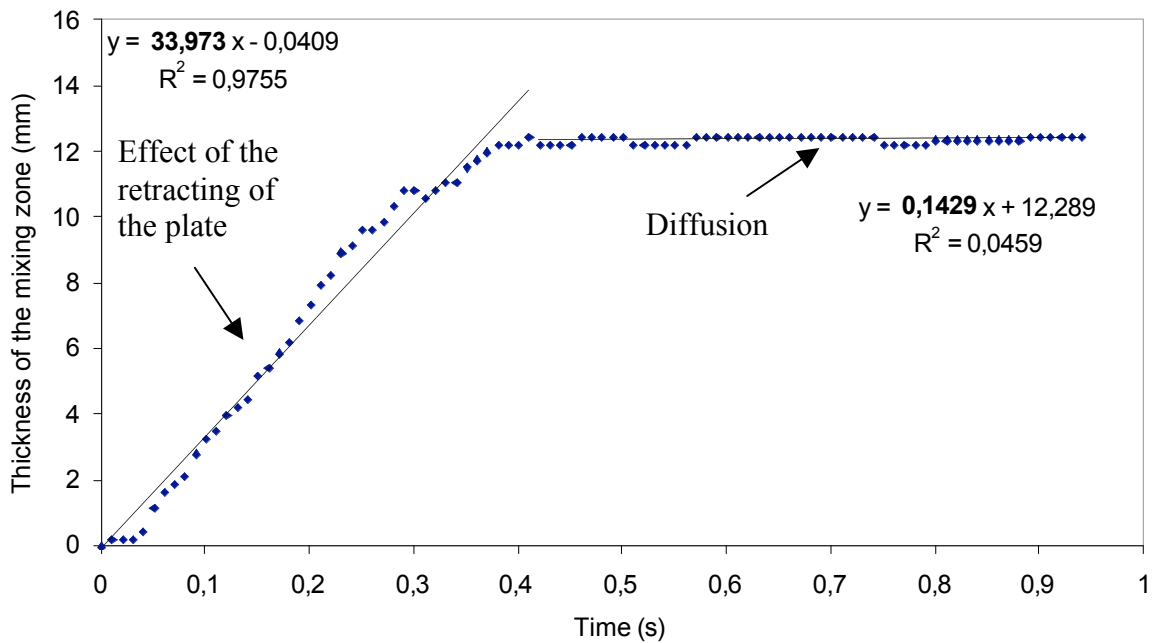
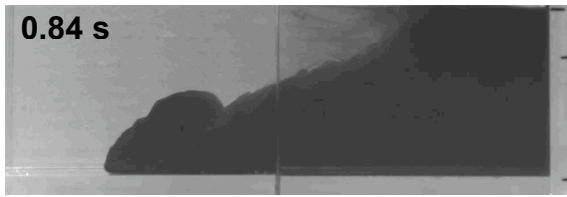


Figure 12: Motion of the mixing front (mm) as a function of time (s). In this experiment there is no density difference.

This graph highlights two different phenomena. The first part of the graph from $t=0$ s to $t=0.4$ s corresponds to the retracting of the plate and the wake effect that results. The mixing front advances in the channel of 1.2 cm in a short time. In other words the retracting of the plate thrust the blue water in the clear water in a short time. This demonstrates that the plate has a non negligible effect on the formation of the GC just after the retracting. The other part of the graph corresponds to the velocity of the mixing front. The velocity of the mixing front represents the diffusion of the dye in the water. This velocity is approximately 0.15 mm/s. We can so admit that for the time scale of these experiments that the diffusion is negligible. The velocity of the GC being equals to 80.8 mm/s, the velocity of the mixing front represent only 0.19 % of the GC velocity. We can conclude that the dye has a negligible effect on the velocity of the GC.

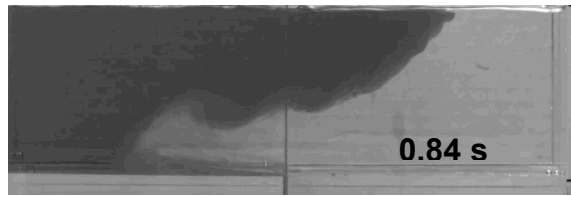
The following experiments (figure 13) show the reference (exp10) and the configuration blue water (BW) in one side and clear salt water (SW) in the other side of the water channel in experiment 33.

Exp10: W /BSW in water channel 2



V (plate) = 0.26 m/s
 t (res) = 0.19 s
 V (GC) = 8.417 cm/s

Exp33: BW/SW in water channel 2



V (plate) = 0.28 m/s
 t (res) = 0.20 s
 V (GC) = 9.1945 cm/s

Figure 13: GC picture at $t = 0.84$ s in normal condition, exp10, and when the dye is reversed, exp33.

The two GC seems to be the same. In fact the velocity of the plate, the time difference, and the velocity of the GC are similar but when the two pictures are overlayed other differences appears (figure 14). The red color corresponds at the GC in experiment 10 and the black color represents the blue water in experiment 33.

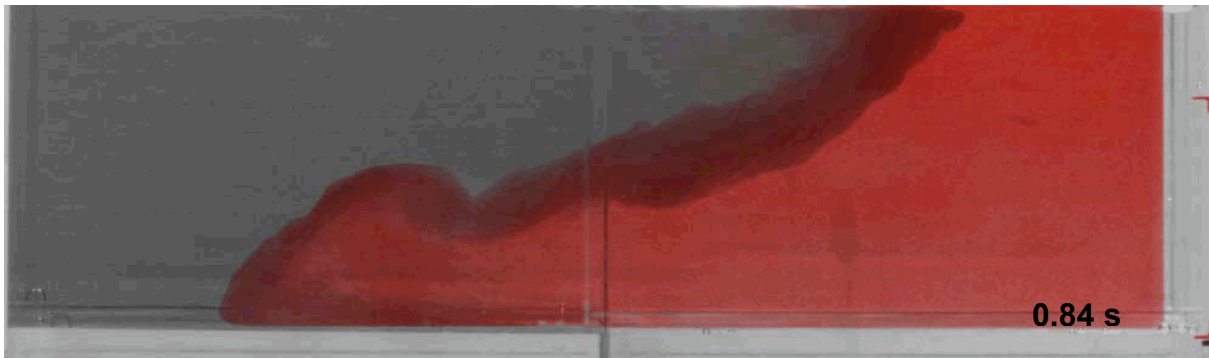


Figure 14: Overlay of experiment 10 and 33 at $t=0.84$ s

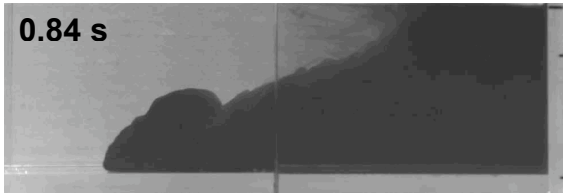
The first observation is that the shapes of the GC nose are very similar in the two cases. However, the major difference observed on this overlay is situated on the top of the GC also called the roll-up region. This is a region where a lot of mixing occurs. Because of the dye, the vortices generated by the water could not be visualized but here this mixing zone appears clearly. During the motion of the salt water head in the fresh water, the water flow moves in the opposite direction causing an eddy formation, generates waves at the interface between the two flows and a mixing takes place. In this zone, the velocity of the GC could not be determined since a lot of complex hydrodynamics phenomena occur.

3.5) Characterization of the gravity current

a) Addition of a top on the water channel

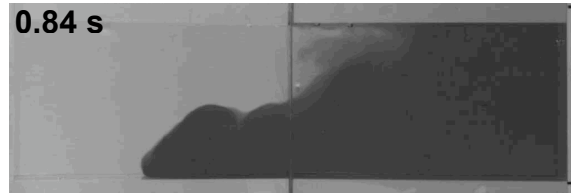
A top was added on the water channel to avoid the free surface. Experiments were carried out with the standard conditions of exp10. Figure 15 is picture of the GC with (exp42) and without (exp10) a top.

Exp10: W/BSW in water channel



V (plate) = 0.26 m/s
 t (res) = 0.19 s
 V (GC) = 8.417 cm/s

Exp42: W/BSW in water channel – top



V (plate) = 0.25 m/s
 t (res) = 0.19 s
 V (GC) = 8.477 cm/s

Figure 15: Picture of experiment 10 and 42 at $t=0.84$ s. Exp 10 is the reference at $t=0.84$ s, the gravity current is moving in the water channel along the surface. Exp 42 is the same experiment that is to say same mixture on each side of the water channel and at the same time but with a top. In this picture the GC is also moving along the channel but with a slower velocity.

All the parameters such as the velocity of the plate, of the GC and the residence time are similar. With the top, the GC appears less high and the nose of the GC is smaller. Also the rolls which are formed normally on the top of the GC are less marked. The addition of the top doesn't change the principle parameters of the GC but changes the shape slightly.

b) Variation of the density of the salt solution

In the following experiment, the density of the salt water solution was changed. Figure 16 shows exp42, the experiment in the normal condition with the top and exp49, in which the blue salt solution has a density of 1033 kg/m^3 .

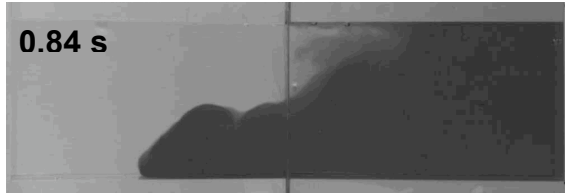
This experiment demonstrates that the velocity of the Gravity current is strongly dependent on the density of the salt solution. In fact, the speed of the GC at the same time is a lot slower in exp49 than in exp42. The GC is 26% slower in exp49. And also the shape is different the little vortices which usually appear in the top of the GC are almost non-existent in exp 49. If we assume that the velocity of the GC is

approximately equals to $\sqrt{\frac{\Delta\rho}{\rho}}$, the theoretical difference between the velocities with

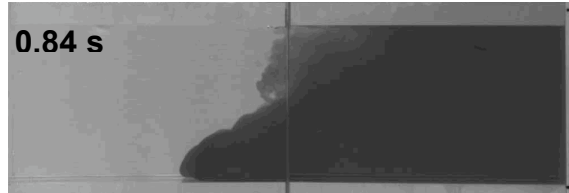
difference density is about 30%. Moreover the theoretical ($v_{GC}=5.5$ cm/s) and the experimental ($v_{GC}=6.3 \pm 1.2$ cm/s) value of the GC velocity are in good agreement.

Exp42 : W/BSW - $\rho = 1066$ kg/m³

Exp 49: W/BSW - $\rho = 1033$ kg/m³



V (plate) = 0.25 m/s
 t (res) = 0.19 s
 V (GC) = 8.477 cm/s



V (plate) = 0.3 m/s
 t (res) = 0.16 s
 V (GC) = 6.256 cm/s

Figure 16: Variation of the density exp 42: $\rho = 1066$ kg/m³ and exp49: $\rho = 1033$ kg/m³

c) Velocity of the GC determine by PIV

In order to understand the movement of the GC when it advance along the surface in the water channel, a PIV experiment was done. The results are shown in figure 17 (for more detail see PIV picture in appendix). The red colour corresponds to a magnitude of 250 mm/s and over, the yellow colour correspond to a magnitude between 200 and 250 mm/s, the green colour correspond to a magnitude between 100 and 200 mm/s, and the blue colour correspond to a magnitude between 50 and 100 mm/s.

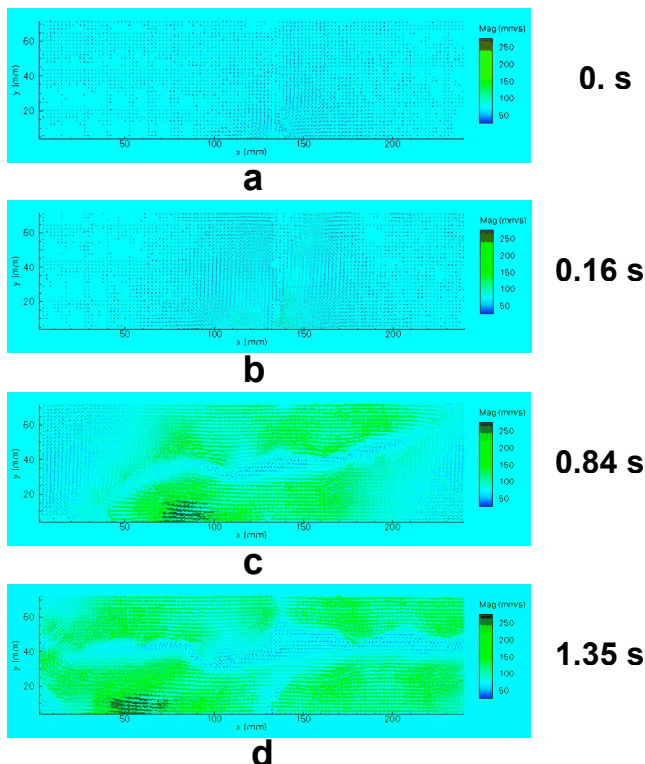


Figure 17: PIV results

(a) shows the water channel when the plate is down in the slit. In next image (b) the plate is just out of the water and the fluid start to move. When the GC is half way from the wall (c) different colours appear. The colours show the difference of speed of the flow. Red represents the highest speed. The GC approaches to the end wall in the last image (d).

The highest speeds are located in the region of the nose of the GC and the “body” of the GC is moving with approximately the same speed. A localised high flow velocity (250 mm/s) appears in the head of the GC but the bulk flow is about 100 mm/s. This value is similar to the value of the GC velocity found with the dye visualization experiments. The time that the head of the GC takes to reach the end wall is approximately (2 s) the same as the time in the dye experiments. The nose or the head of the GC is a special region in which there is a lot of variation of speed. This particular shape and variation of velocity of the head, according to Prandtl, are presumably due to the fact that the liquid in the middle of the section of the channel moves forward with velocities greater than the velocity of the front itself. Fluid elements reaching the front are deflected upwards and during this motion, mixing with fresh water takes place. Then, it appears that the mixing liquid is sucked back into the head. Nevertheless, the velocity of the “body” of the GC in the PIV experiments is similar at the velocity found in the dye visualization experiments; this velocity ranges from 50 to 100 mm/s.

3.6) Comparison with the GDT experiment

Similar tests done in the water channel experiments were done in the GDT. In those experiments instead of using liquids, gases were used so water corresponded to nitrogen and the salt solution to an equimolar mixture of acetone and helium. Acetone is used because of the ability to fluoresce when a sheet of the Excimer (308 nm) laser passes through it.

a) Velocity of the GDT plate.

To make sure that the two experiments, the GDT and the water channel are comparable, we should make sure that the residence times are similar. The same operating mode as for the water channel is implemented (see section 3.1a). The graph (Figure 18) shows the four sliding plate velocity measurements carried out with the GDT. The four experiments are repeatable and have the same residence time which is 0.18 s.

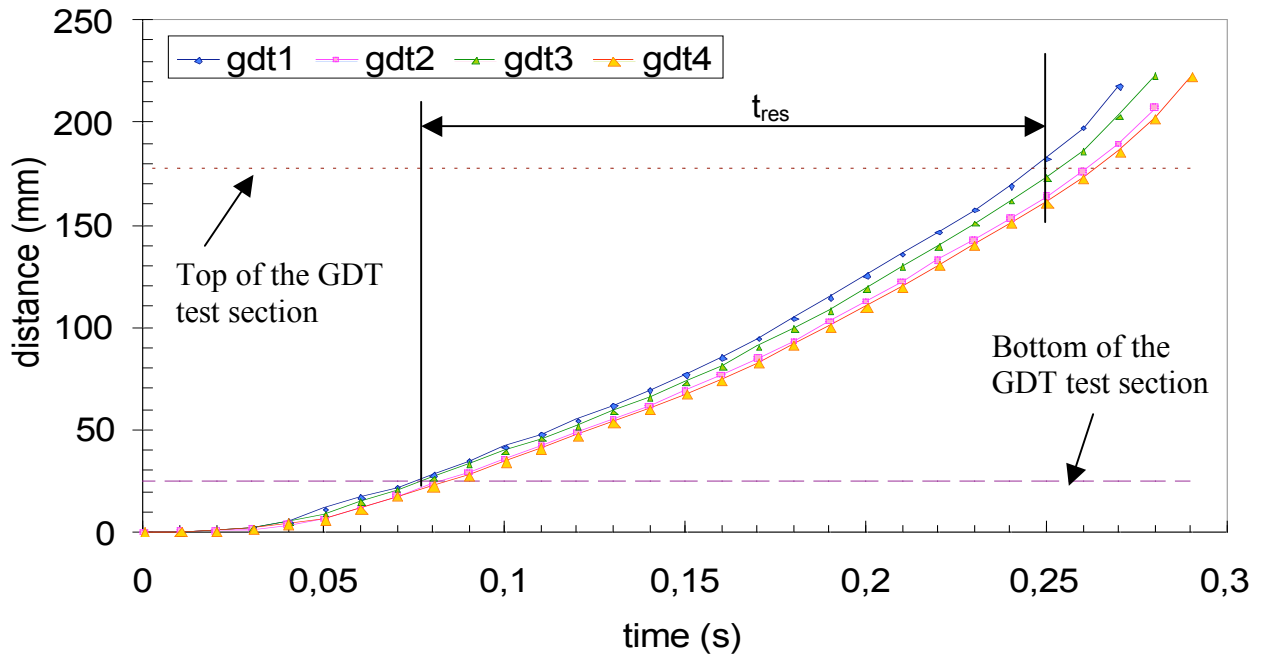


Figure 18: Travel distance (mm) of the GDT plate as a function of time (s)

The residence time in the water channel experiment ranges from 0.11 to 0.25 s and the average time residence is 0.184 s. We see that the two experiments are comparable.

b) Gravity currents in the test section

In the following experiment (figure 19) the GDT is filled with an Acetone/helium mixture and nitrogen is introduced in the test section. When the plate of the GDT is retracted by a falling mass, the Acetone/helium mixture enters into the test section and the gravity current induced is visualized with a planar laser induced fluorescence setup.

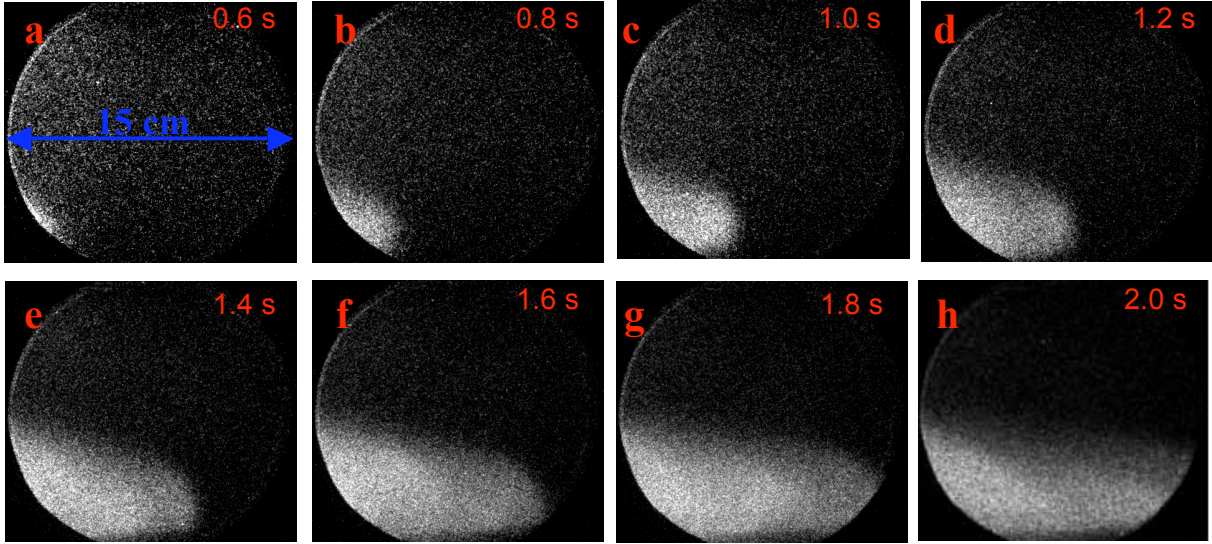


Figure 19: Gravity current in the GDT. The plate is retracted and the gravity current starts to move in the test section (a) the white colour represents the acetone/helium mixture and the dark colour is nitrogen. In the four next images (b, c, d and e) the nose of the gravity current is growing and moving along the surface of the test section. In image (f) the entire nose of the GC is visible in the window. In the two last images (g and h) the GC body is advancing into the test section. There are no rolls.

The nose of the GC in the water channel and the GDT are similar; they both take half the height of the channel. But there are some differences, the Kelvin-Helmholtz instabilities are not resolved in the top of the GC in the GDT. The velocity of the GC has been measured and equals to 95.7 ± 12 mm/s. We know that the velocity of the GDT (V_{GDT}) and the velocity of the water channel (v_{WC}) are related by the following equation:

$$V_{GDT} = V_{WC} \sqrt{2}$$

$$\text{So } V_{GDT} = 95.7 \pm 12 \Rightarrow V_{WC} = \frac{V_{GDT}}{\sqrt{2}} = 67.7 \pm 8 \text{ mm/s}$$

The value found experimentally in the water channel is 80.8 ± 12 mm/s so the experimental uncertainty is about 16% of the nominal value. The difference is on the order of uncertainties of each measurement. This difference can be explained by the fact that the equation used assumes that the constant C, in the definition of the velocity (section 1), is the same for both the liquid mixture and the gas mixture. However, we know that the constant depends on the nature of the fluid. For instance Keulegan found experimentally a constant $C=1.05$ while Benjamin found theoretically $C = \frac{1}{\sqrt{2}}$.

Given this uncertainty, there is a reasonable agreement between the velocity of the GC for both experiments GDT and water channel.

4) Conclusion

The purpose of this project was to study how a gravity current generated by fluids developed over time in a water channel. This leads to an understanding of the mixing zone occurring at the interface between the test section and the tube section in the GDT. The gravity current was generated by two fluids of differing densities placed on each side of a water channel and separated by a plate.

The gravity current is formed as soon as the plate is removed. The fluids of higher density, the blue salt water solution, flow beneath the fluid of lower density, water, forming the head of the gravity current. The analysis experiment is stopped when the head reaches the end wall of the water channel. The most important part is the head of the GC, also called the nose. It has been observed that the head of the GC has a particular shape and a variation of velocity due to the motion of the fluid in the water channel. The head generates a mixing zone on the upstream region of the GC; this region is associated with turbulence and vorticity.

The experiments carried out enabled us to characterise the GC and to determine an average velocity of the GC which is $8.08 \pm 1, 2$ cm/s. It has been demonstrated that the boundary layer and the diffusion of the dye have small effects on the velocity of the GC. In addition, the retracting of the plate affects the GC only in the first 0.4 s of the experiment and generates a wake. The velocity of the GC is intimately connected to the density of the salt solution. It has been observed that both the shape and the velocity change with the density. When the density is lowered both the height of the head and the velocity of the GC are lowered too. However, the addition of the top appears to have a negligible effect on the GC, but could probably have an effect on the water flow.

Finally a comparison between the GDT experiment and the water channel experiments has demonstrated that the velocities of the GC in the GDT and in the water channel are similar. In other words we can assume that the motion and the mixing zone at the interface between the two fluids in both experiments are similar.

5) References

John E SIMPSON, 1982. *Gravity currents in the laboratory, atmosphere and ocean*. Annual Review of Fluid Mechanics, **14**:313-334.

T.B. BENJAMIN, 1968. *Gravity currents and related phenomena*. Journal of Fluid Mechanics, **31**:209-248.

John E SIMPSON, 1987. *Gravity currents: in the environment and the laboratory*. John Wiley & sons, Inc., New York.

F.PINTGEN and J.E.SHEPHERD, 2003. *Mixing and combustion in rich fireballs*. Technical report FM2003-004, GALCIT. Explosion Dynamics Laboratory Report to Sandia National Laboratory.

Daniel H.LIEBERMAN and J.E. SHEPHERD, 2005. *Shock wave induced Mixing Reaction*. Abstract for 20th ICDERS.

G. H. KEULEGAN; 1957. *An experimental study of the motion of saline water from locks into fresh water channels*. US Natl. Bur. Stand., Rep. 5168

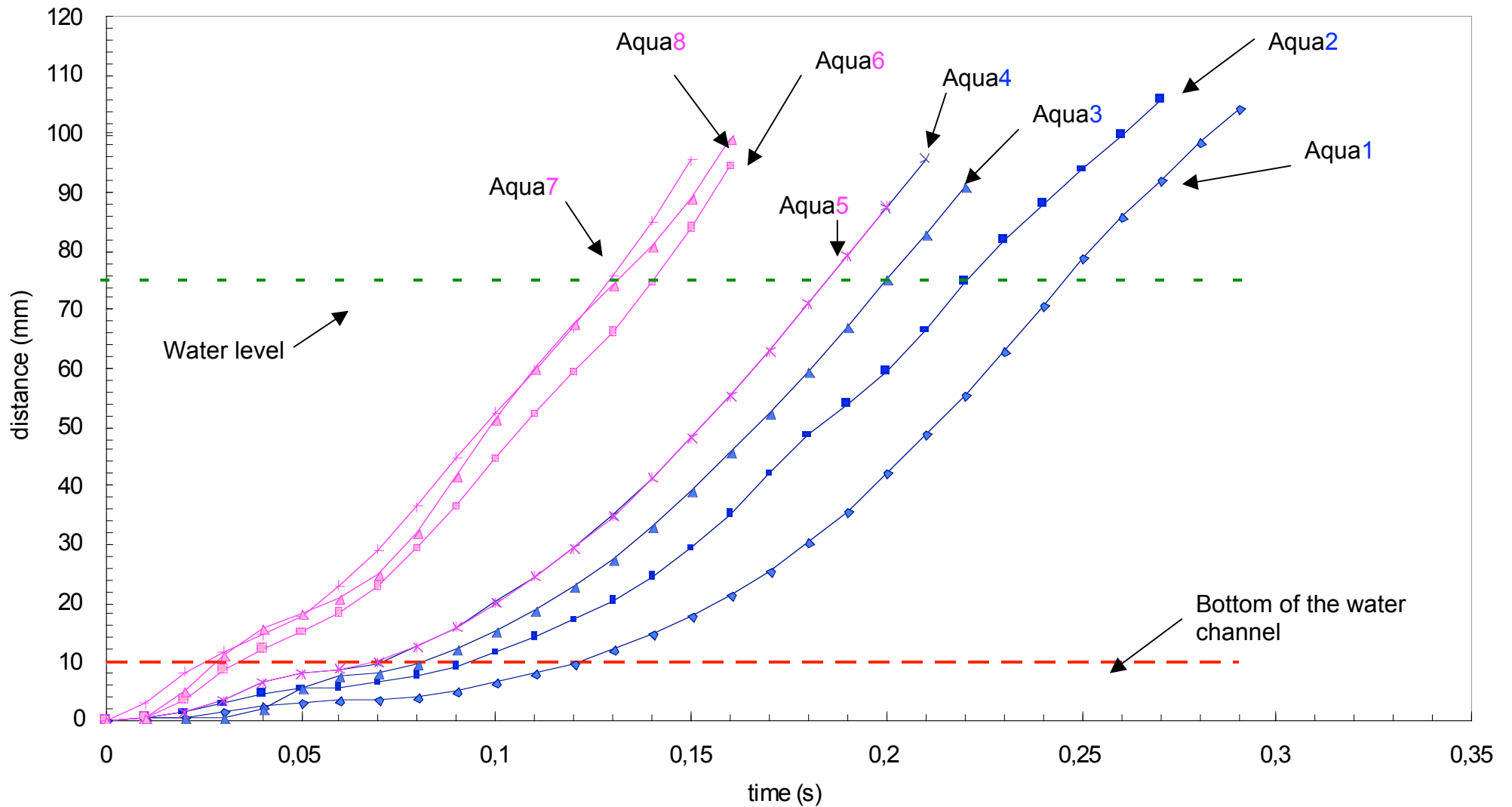
G.H. KEULEGAN, 1958. *The motion of saline front in still water*. US Natl. Bur. Stand., Rep. 5831

L. PRANDTL, 1953. *Essentials of fluids mechanics*. Hafner Pub. Co., New York.

R.W. FOX and A.T. Mc DONALD, 1998. *Introduction to fluids mechanics*. John Wiley & sons, Inc., New York. 5th edition.

Appendix

Appendix 1: Velocity of the plate



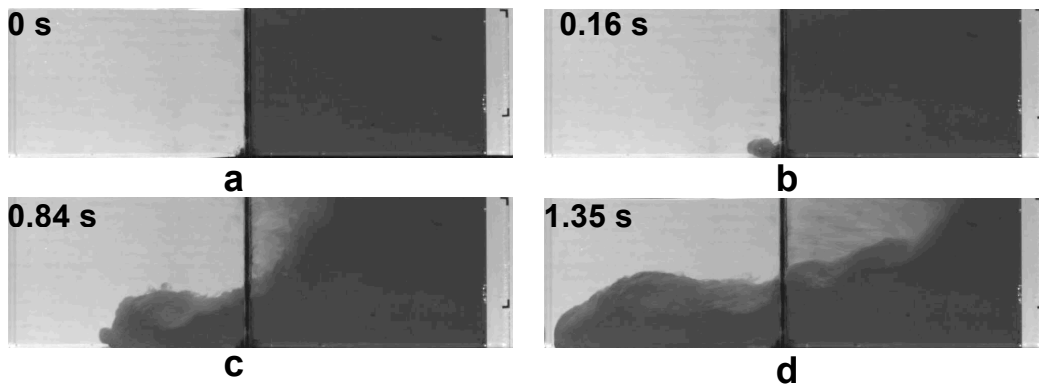
This graph shows the velocity of the plate for 8 experiments (aqua1 to aqua8). The blue curves were determined with a weight equals to 3.5 kg and the pink curves with a weight equals to 2.9 kg. The experiment carried out with a 3.5 kg weight give repeatable results.

Appendix 2: Image of the GC

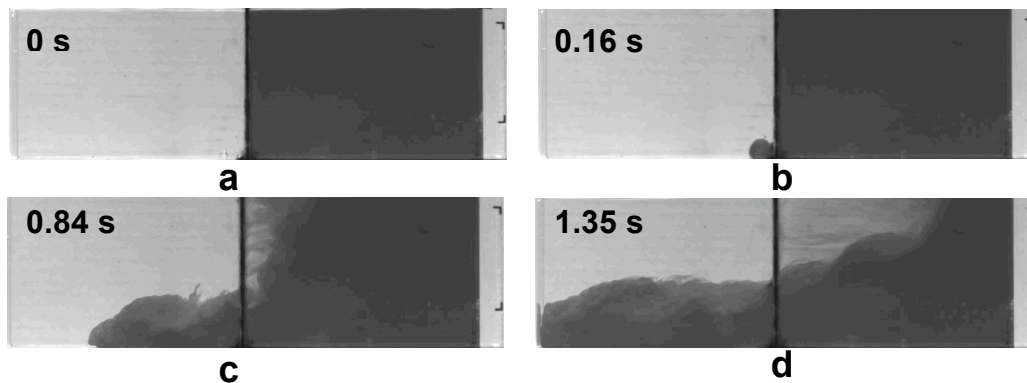
In the following experiments the first image (a) represents the water channel at $t=0$ s just before sliding the plate. The salt solution is on the right part and the water is on the other part. The next picture (b) shows the beginning of the GC at $t=0.16$ s. Then, at $t=0.84$ s, the GC is moving along the water channel (c). The final image at $t=1.35$ s, the GC is reaching the end wall. Experiments where there are water on both side of the water channel no GC is formed.

Experiments 2 to 4: Water / Blue salt water in the water channel N⁰ 1

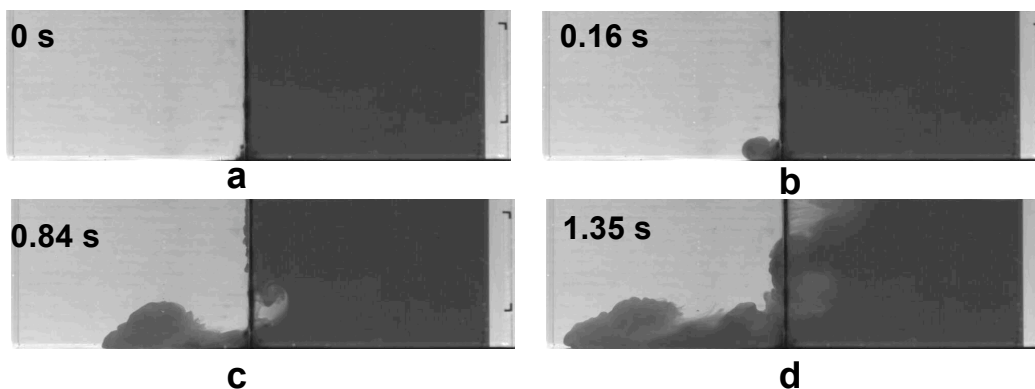
Exp2:



Exp3:

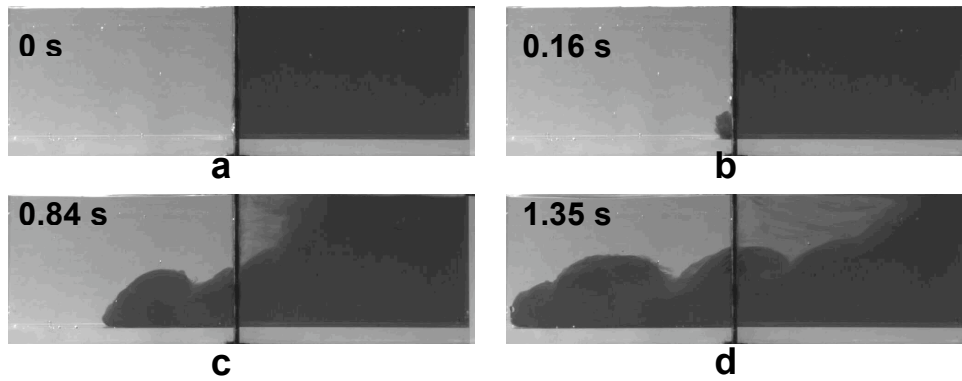


Exp4:

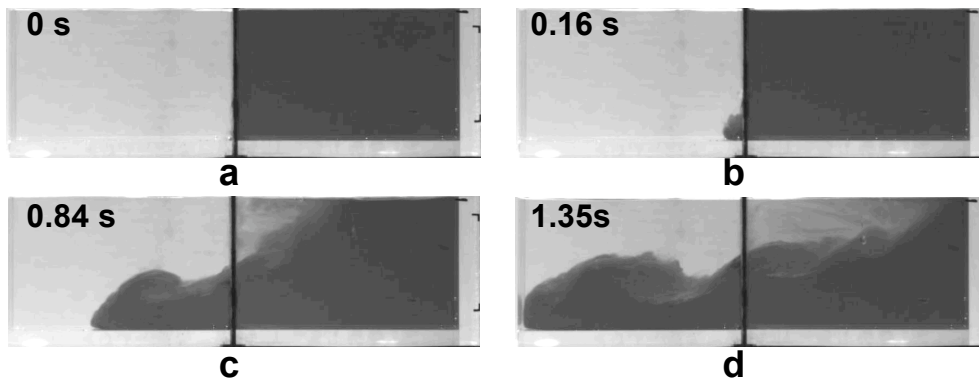


Experiments 5 and 6: Water/Blue salt water in the water channel N⁰ 1 with a bottom

Exp5:

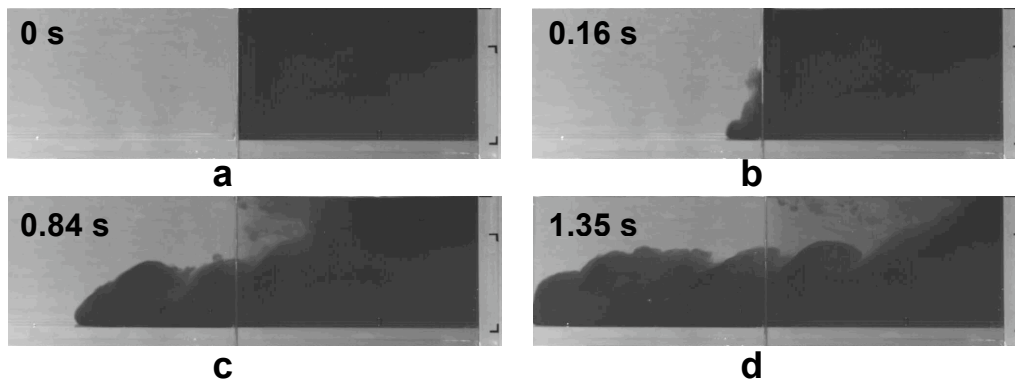


Exp6:

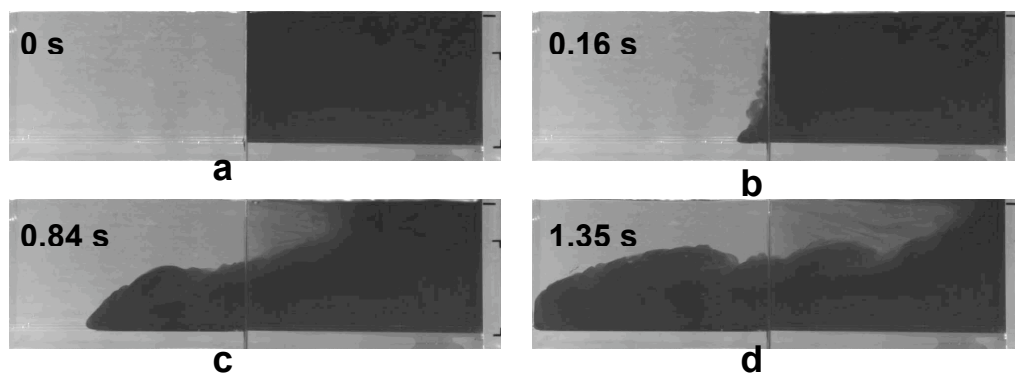


Experiments 7 to 17: Water/Blue salt water in the water channel N⁰ 2 with a bottom

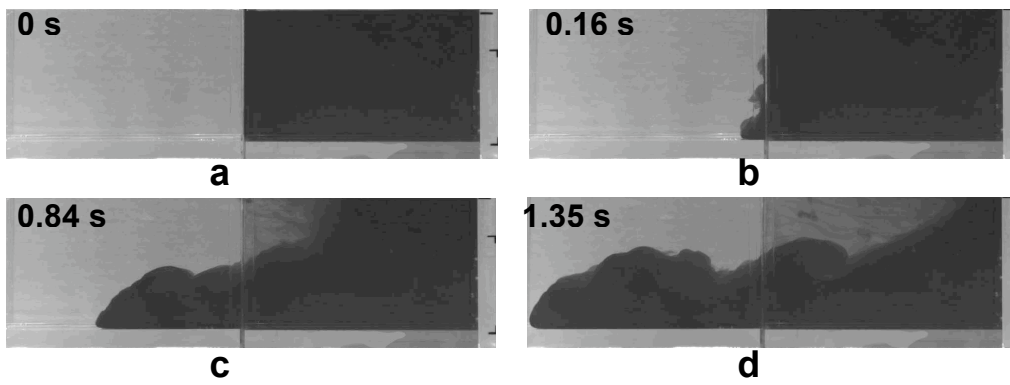
Exp7:



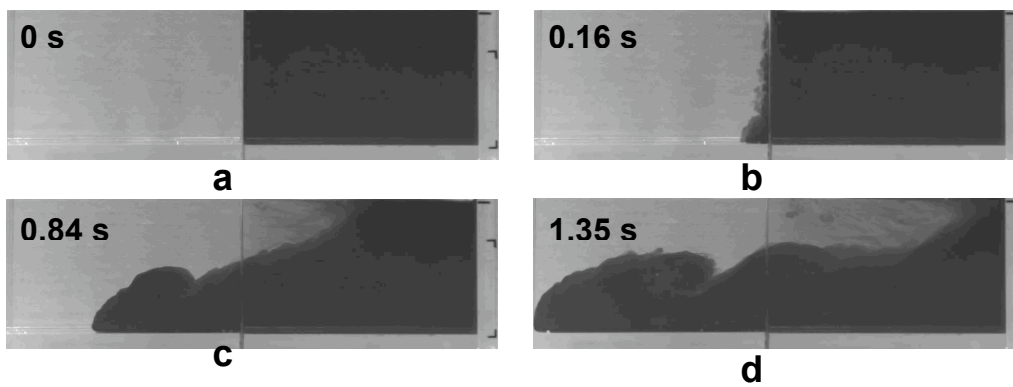
Exp8:



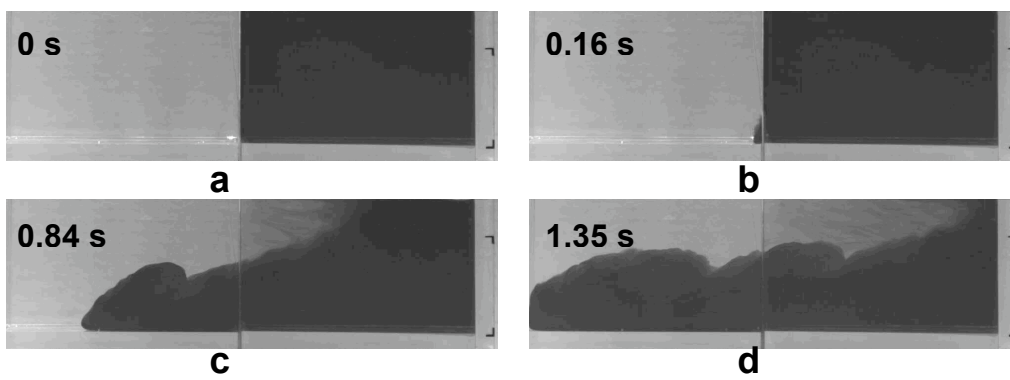
Exp9:



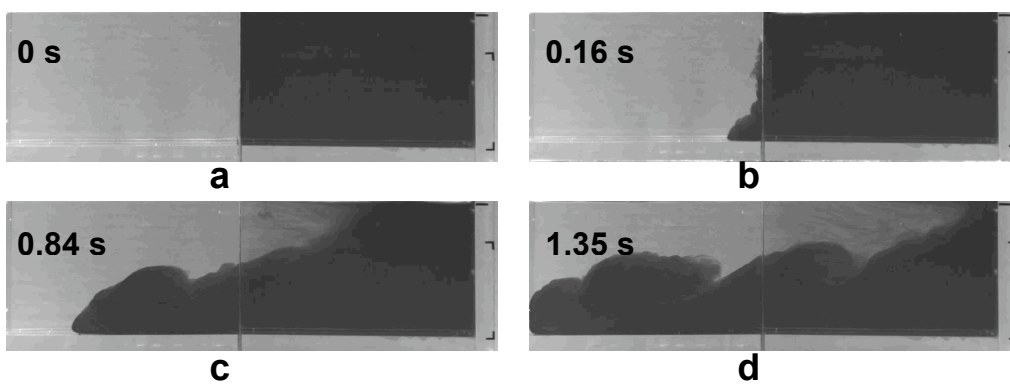
Exp10:



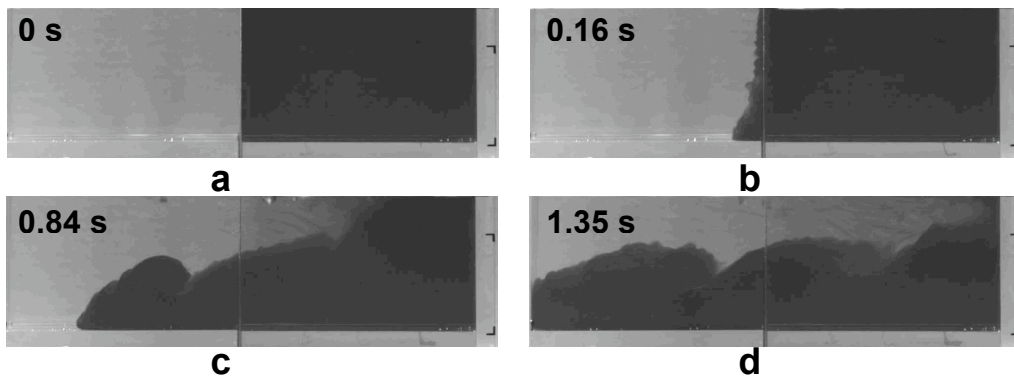
Exp11:



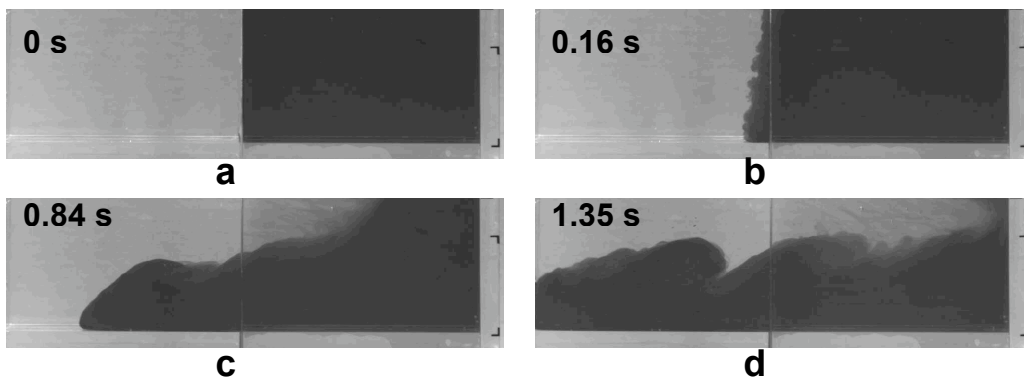
Exp12:



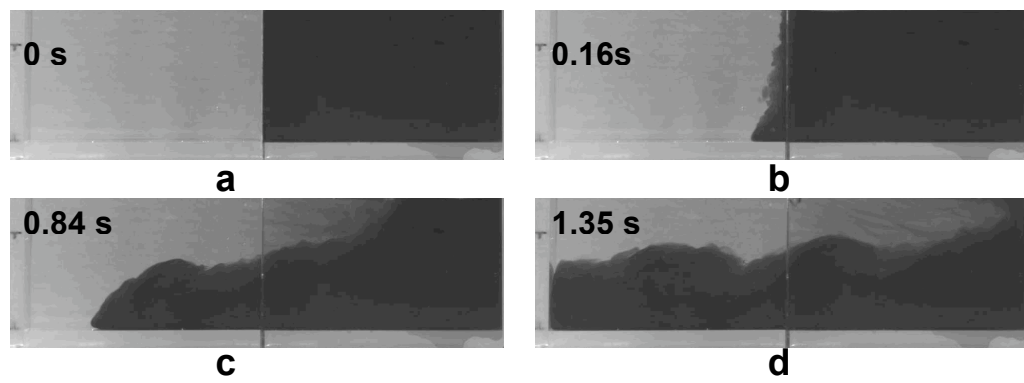
Exp13:



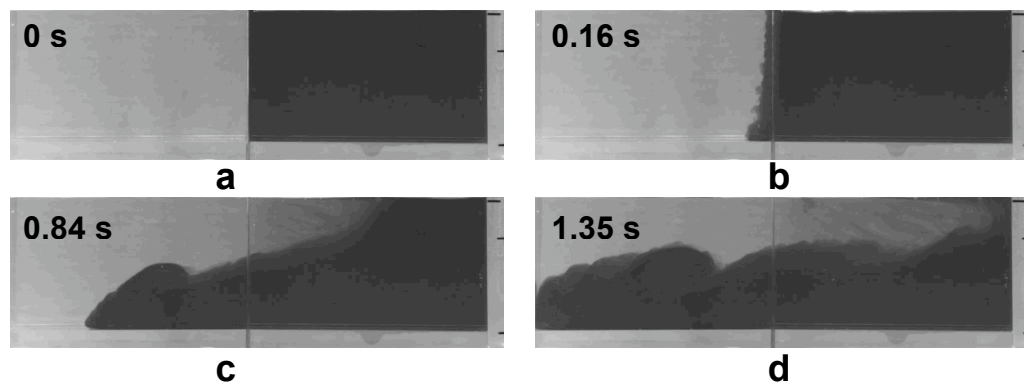
Exp14:



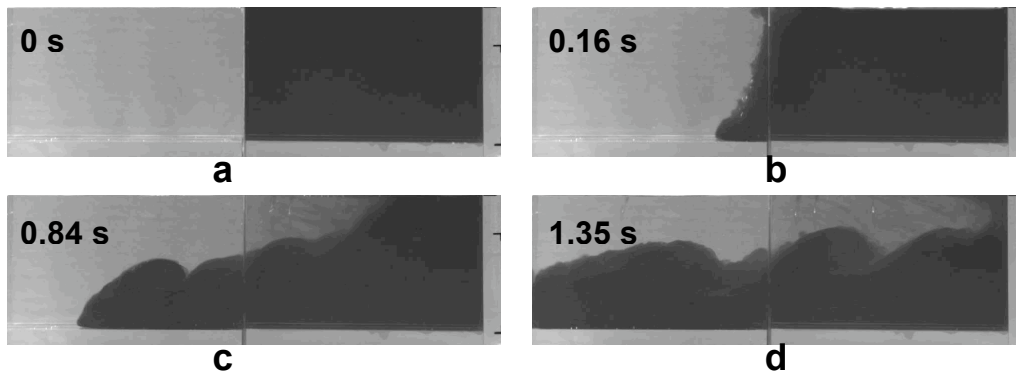
Exp15:



Exp16:

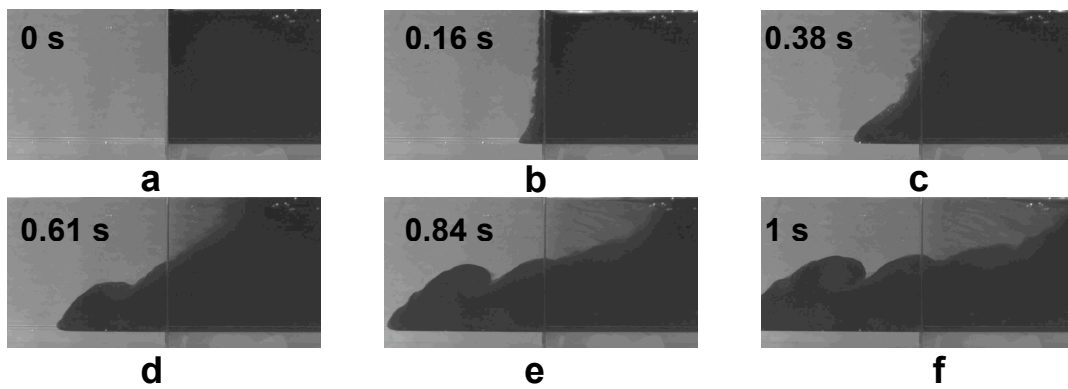


Exp17:

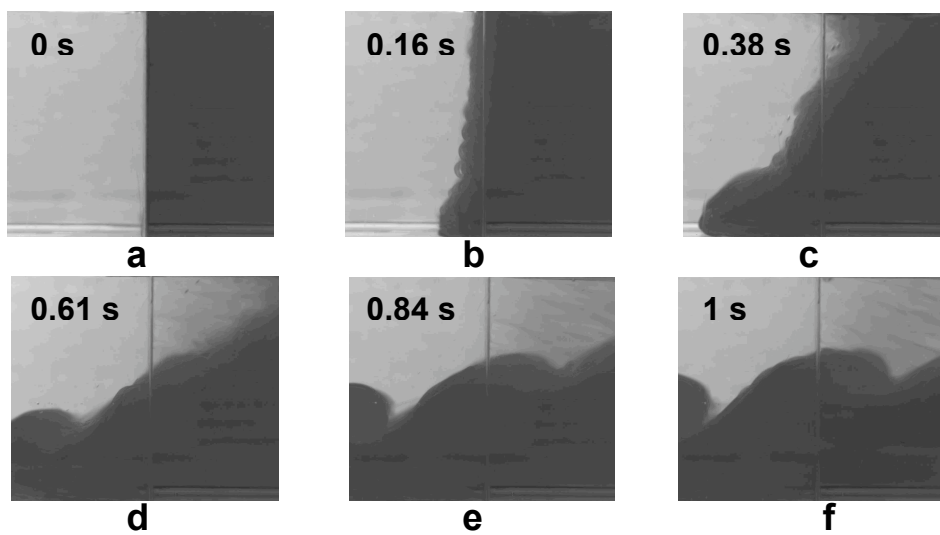


Experiments 18 to 23: Water/Blue salt water in the water channel N^o 2 with a bottom Zoom

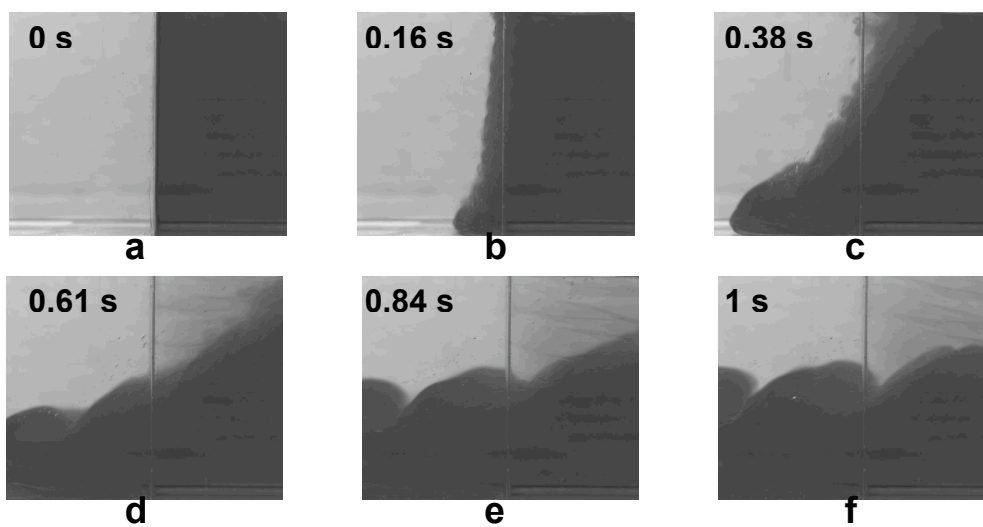
Exp18:



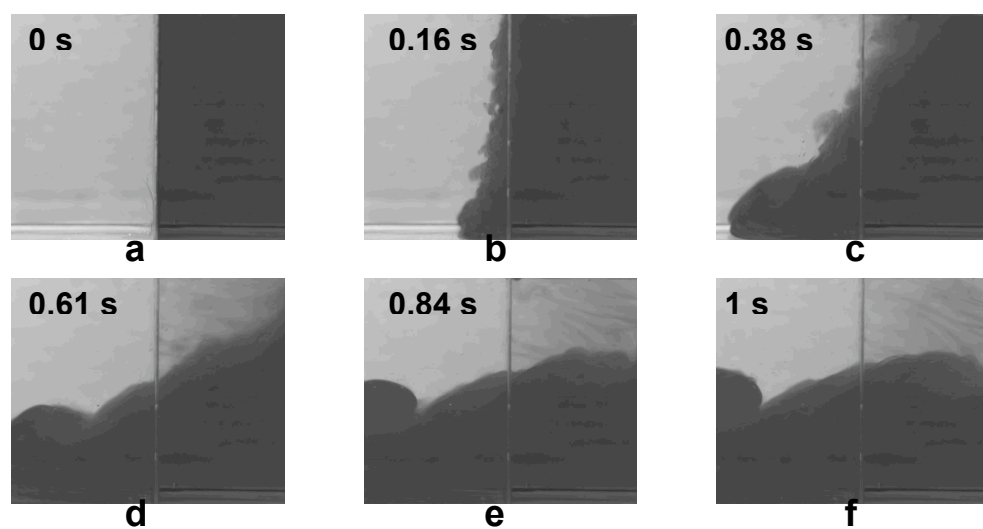
Exp19:



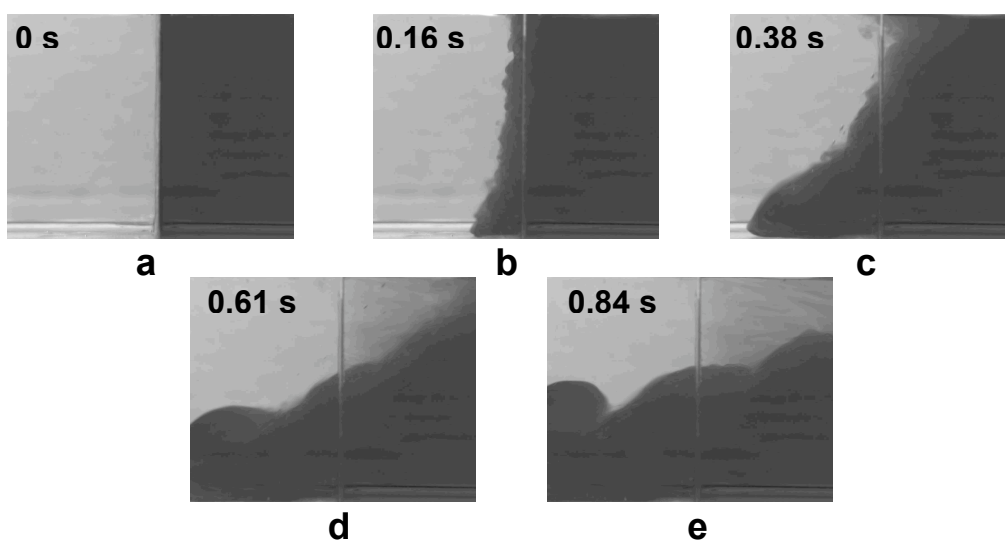
Exp20:



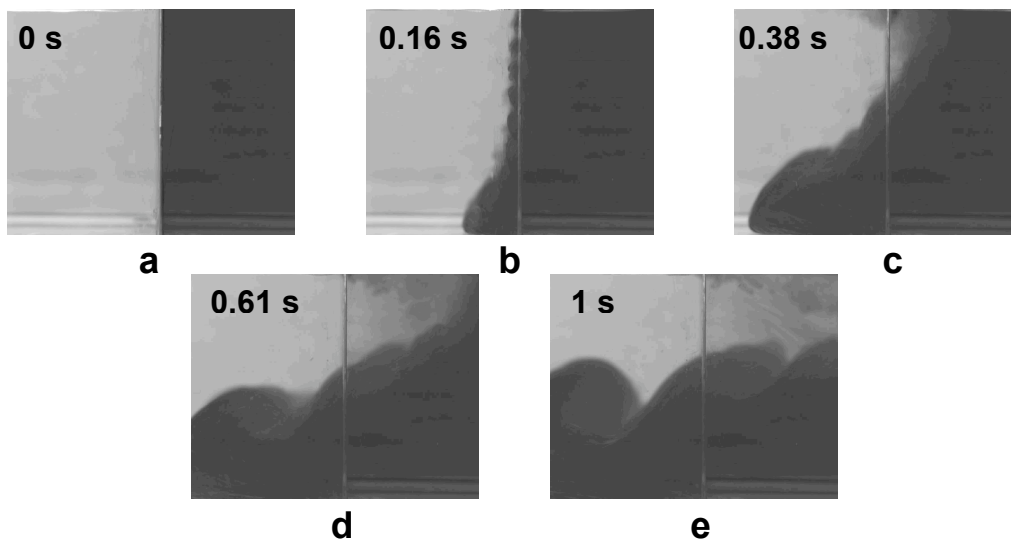
Exp21:



Exp22:

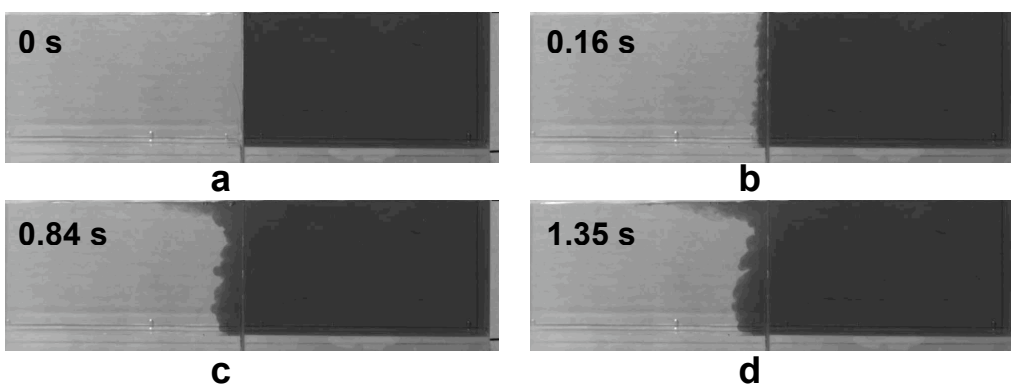


Exp23:

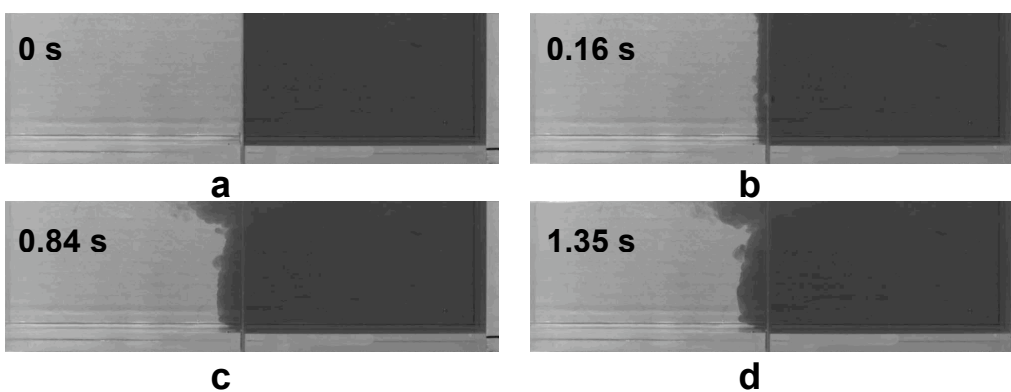


Experiments 24 to 28: Water/Blue water in the water channel N⁰ 2 with a bottom

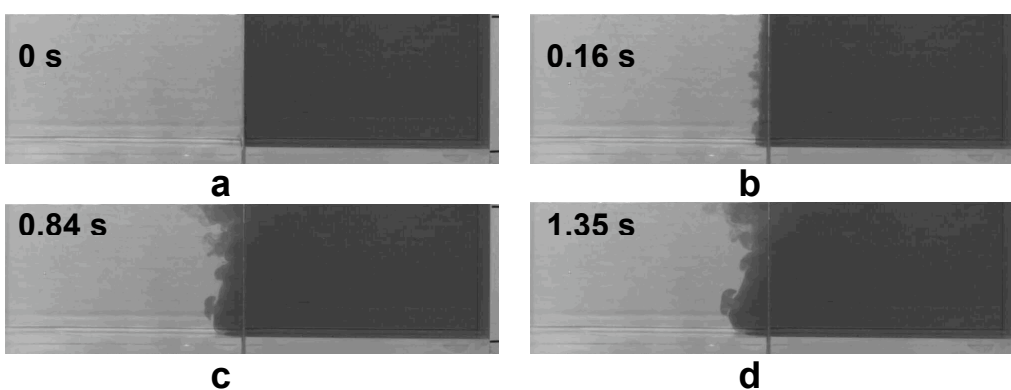
Exp24:



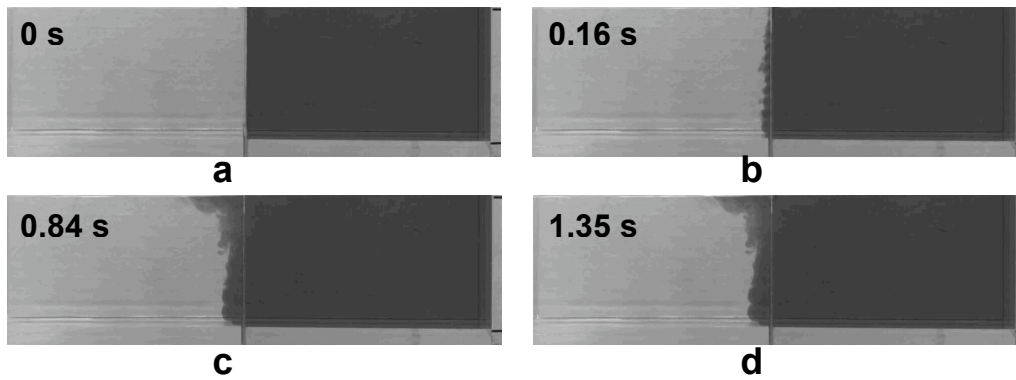
Exp25:



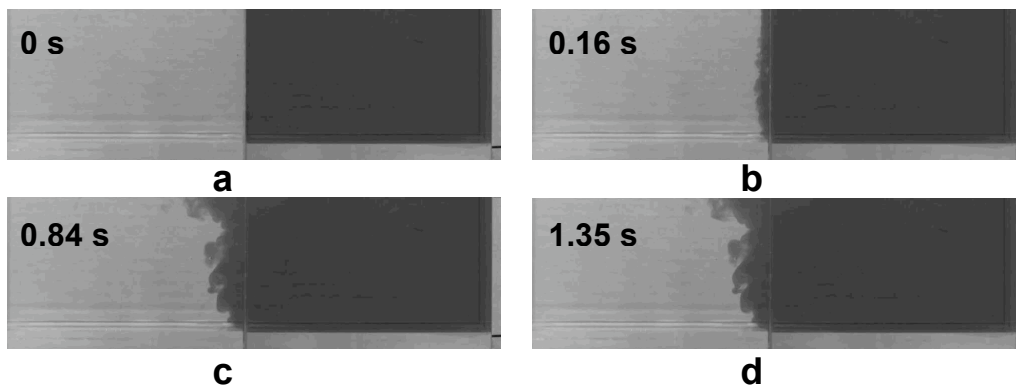
Exp26:



Exp27:

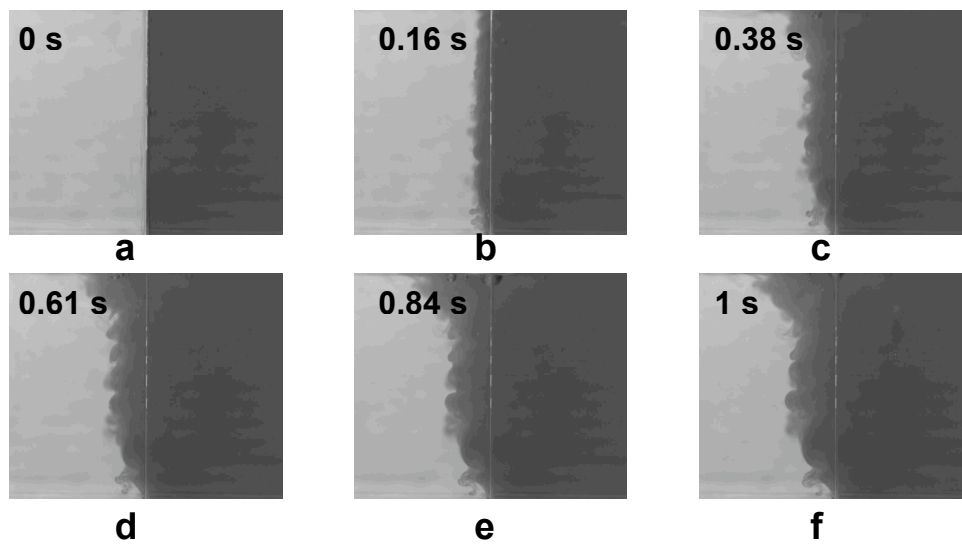


Exp28:

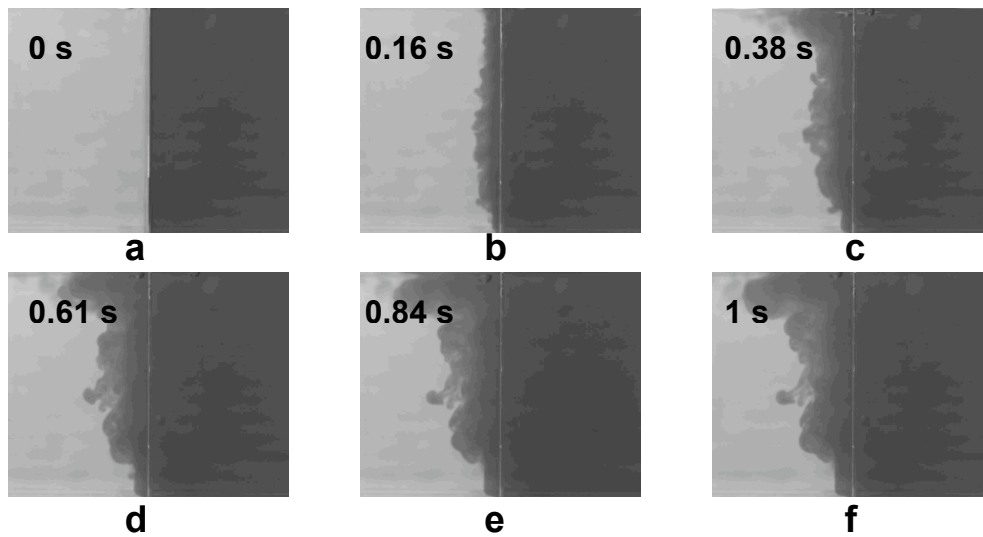


Experiments 29 to 30: Water/Blue water in the water channel N⁰ 2 with a bottom Zoom

Exp29:

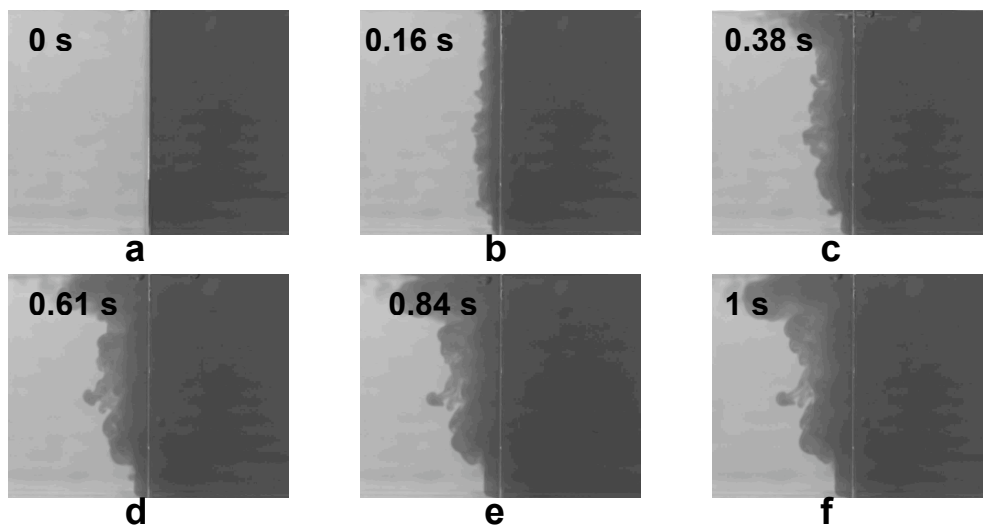


Exp30:

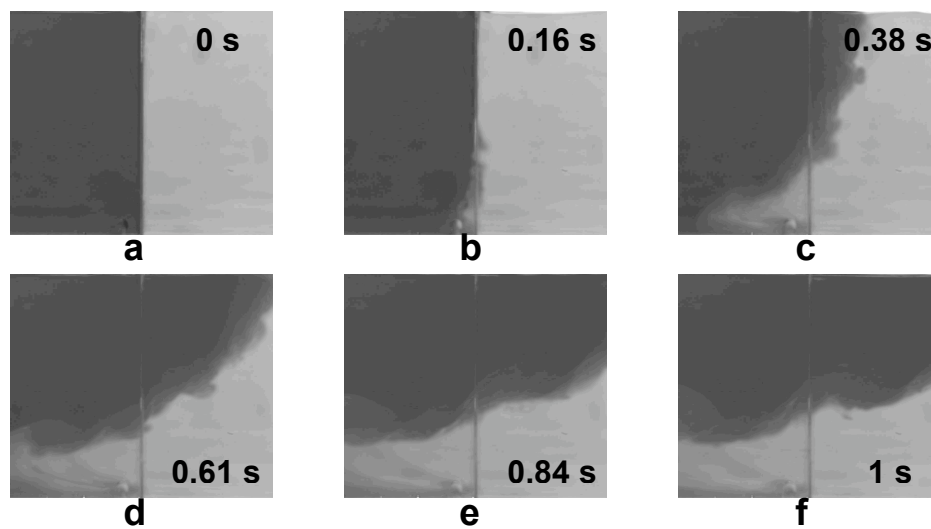


Experiments 31 to 32: Blue water/Salt water in the water channel N⁰ 2 with a bottom Zoom

Exp31:

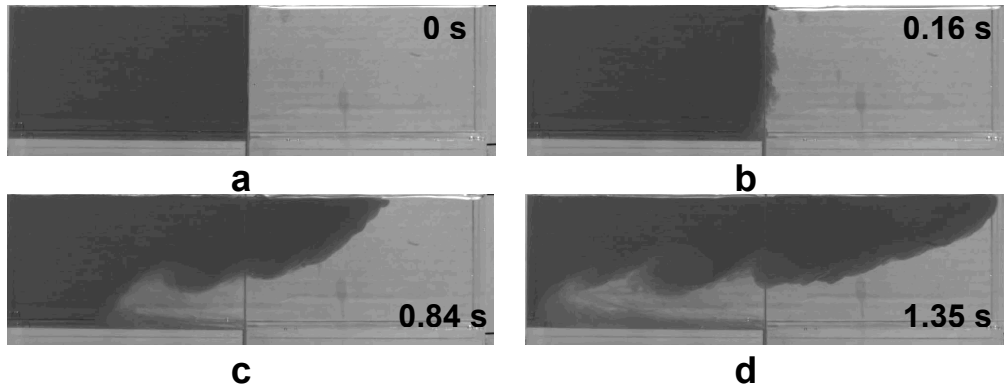


Exp32:

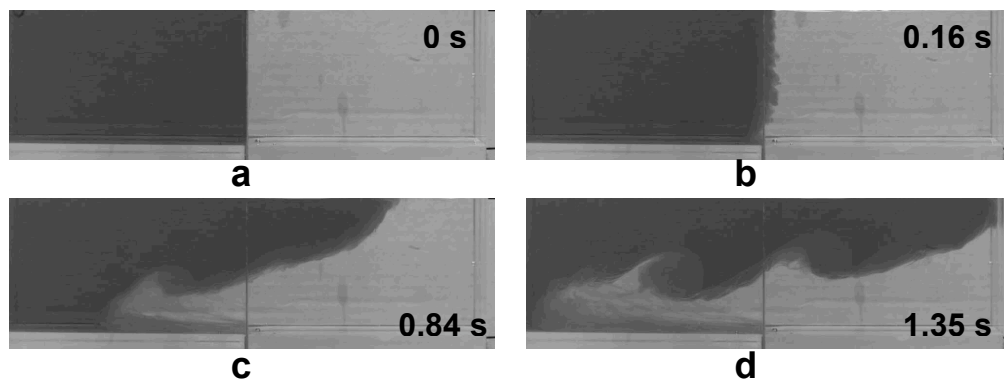


Experiments 33 to 35: Blue water/Salt water in the water channel N⁰ 2 with a bottom

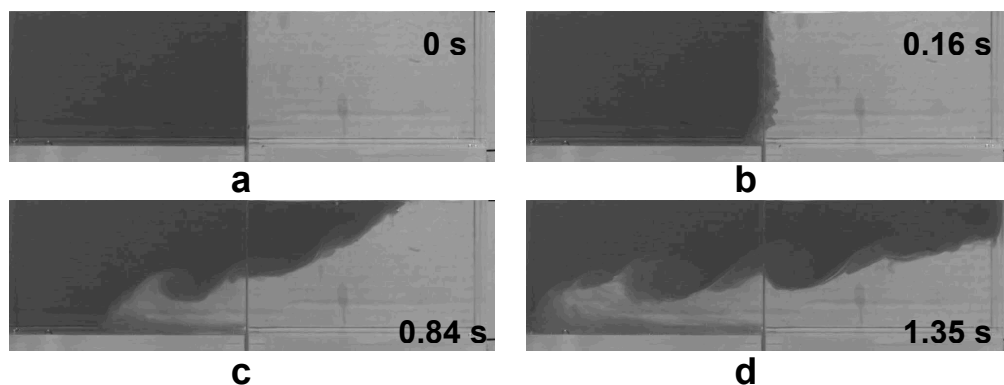
Exp33:



Exp34:



Exp35:

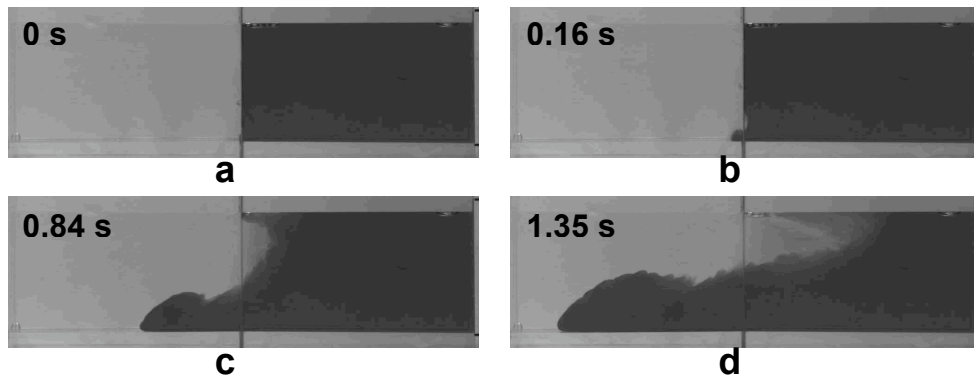


Experiments 36 to 43: Water/Blue salt water in the water channel N⁰ 2 with a bottom and a top

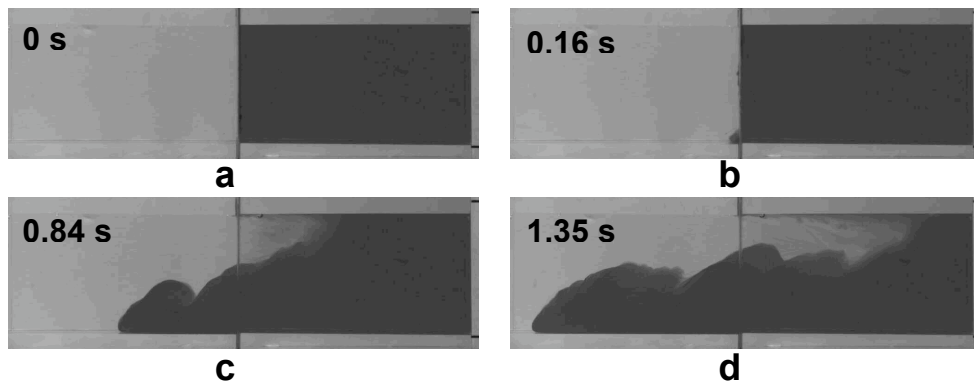
Exp36:

No pictures are available for this experiment because of a problem during the recording of the video with the Phantom camera.

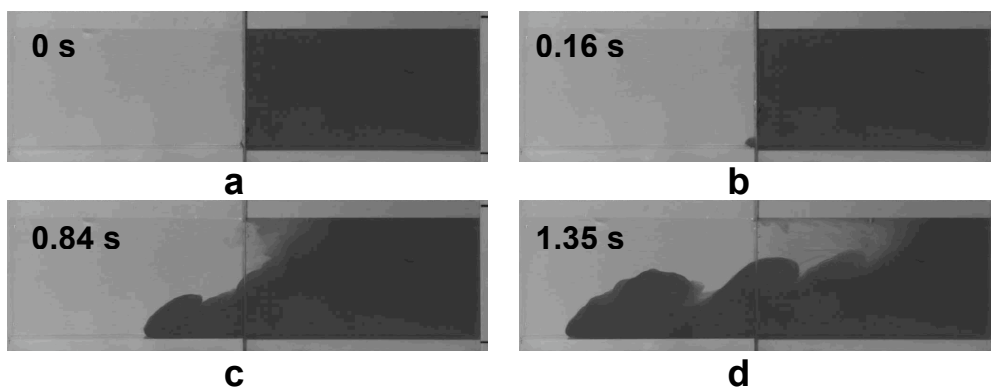
Exp37:



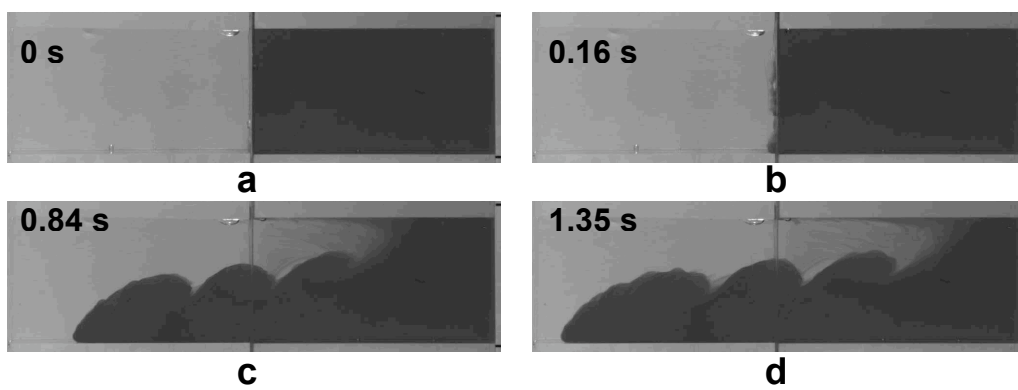
Exp38:



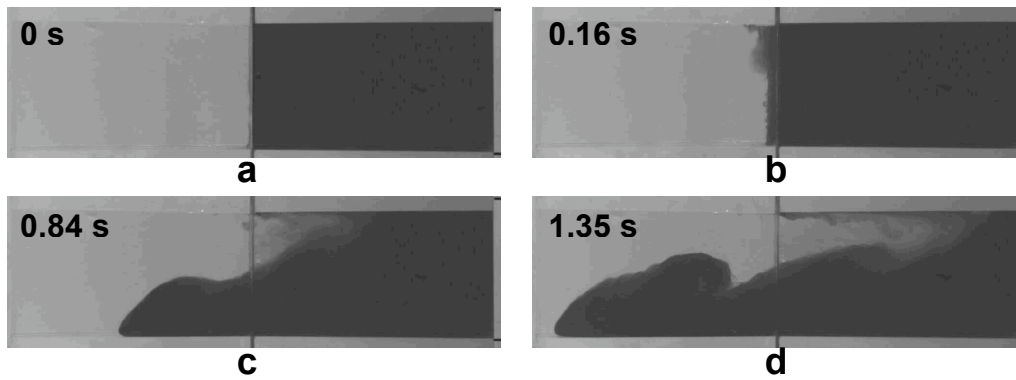
Exp39:



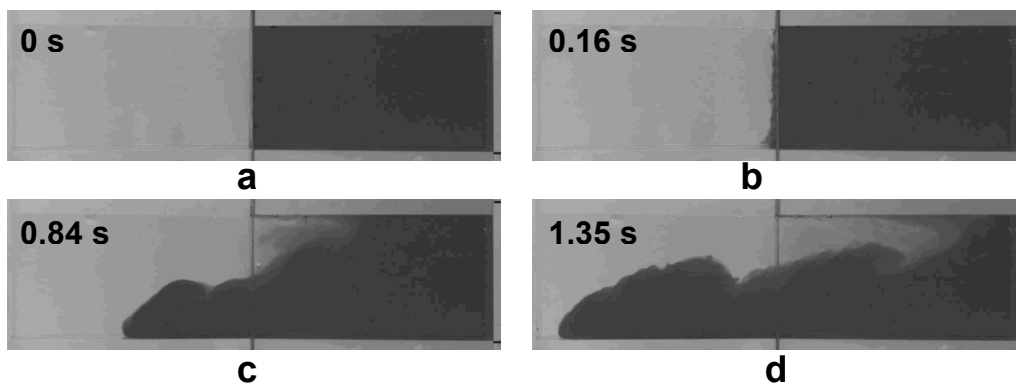
Exp40:



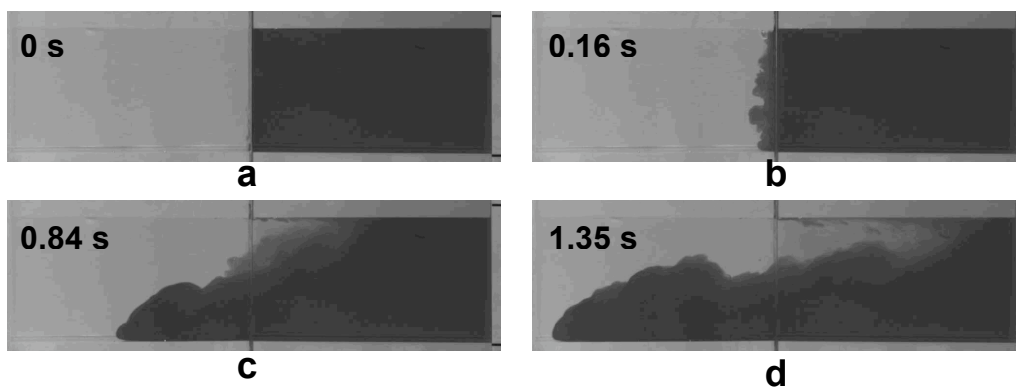
Exp41:



Exp42:

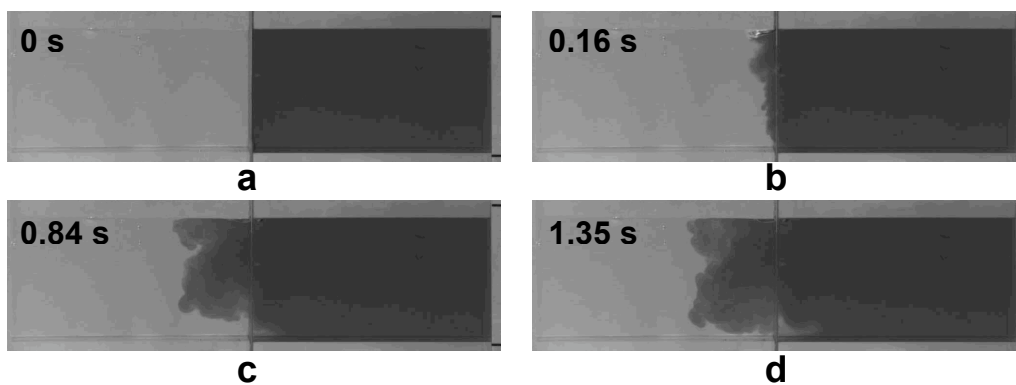


Exp43:

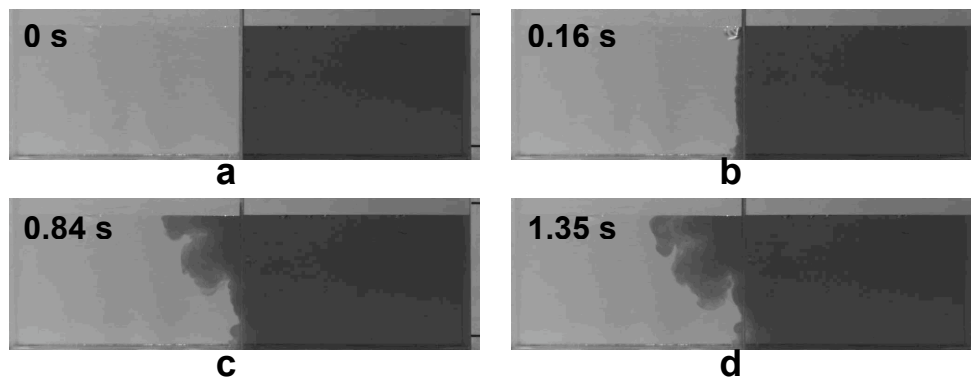


Experiments 44 to 46: Water/Blue water in the water channel N⁰ 2 with a bottom and a top

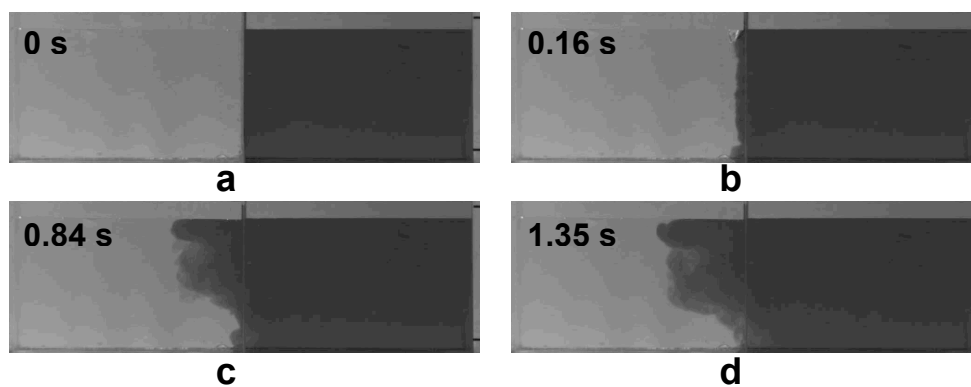
Exp44:



Exp45:

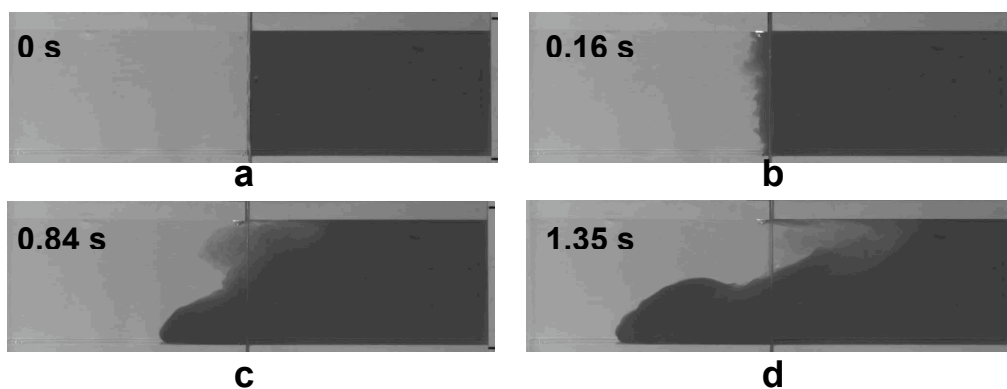


Exp46:

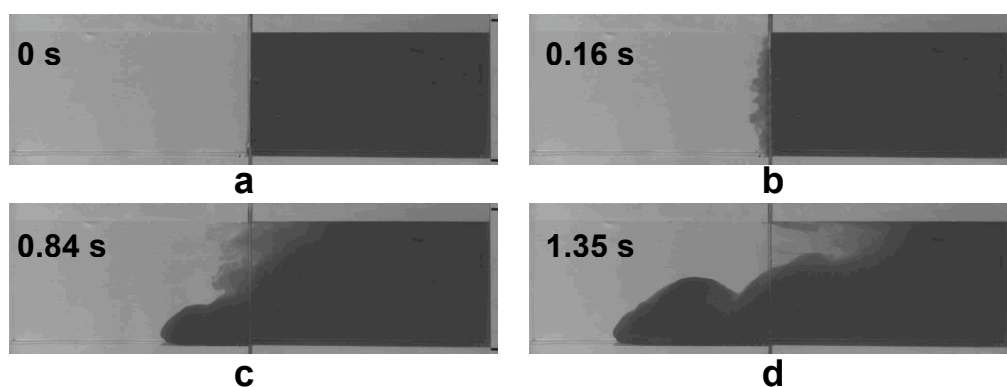


Experiments 47 to 49: Water/Blue salt water in the water channel N⁰ 2 with a bottom , a top and $\rho=1033 \text{ kg/m}^3$

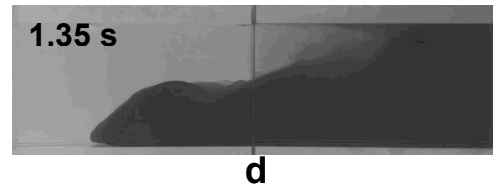
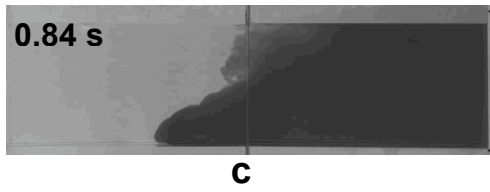
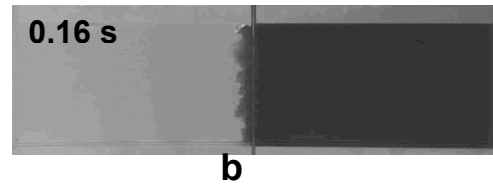
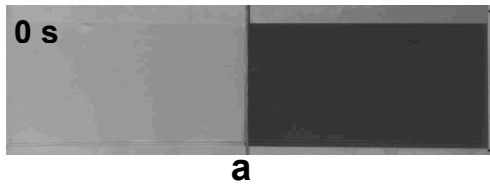
Exp47:



Exp48:



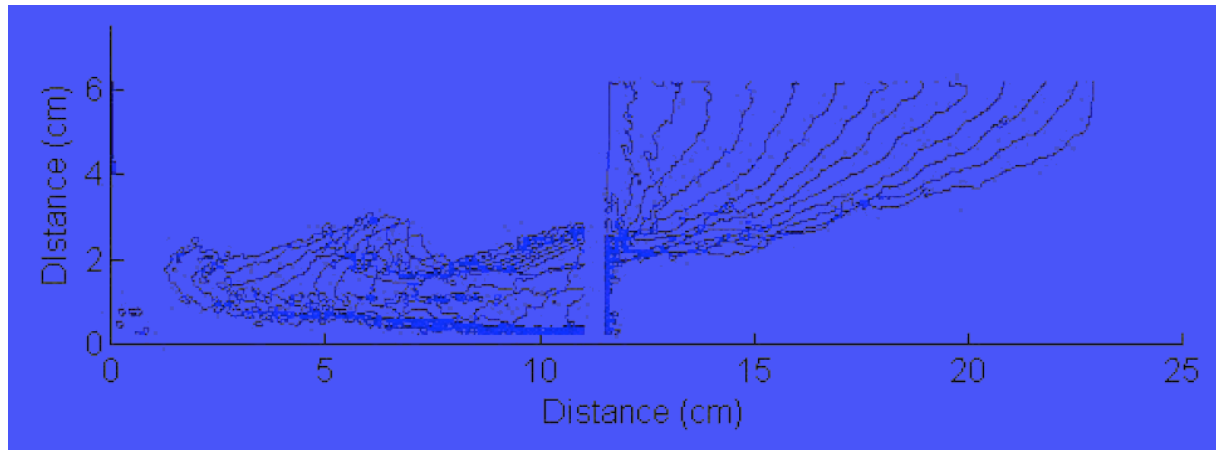
Exp49:



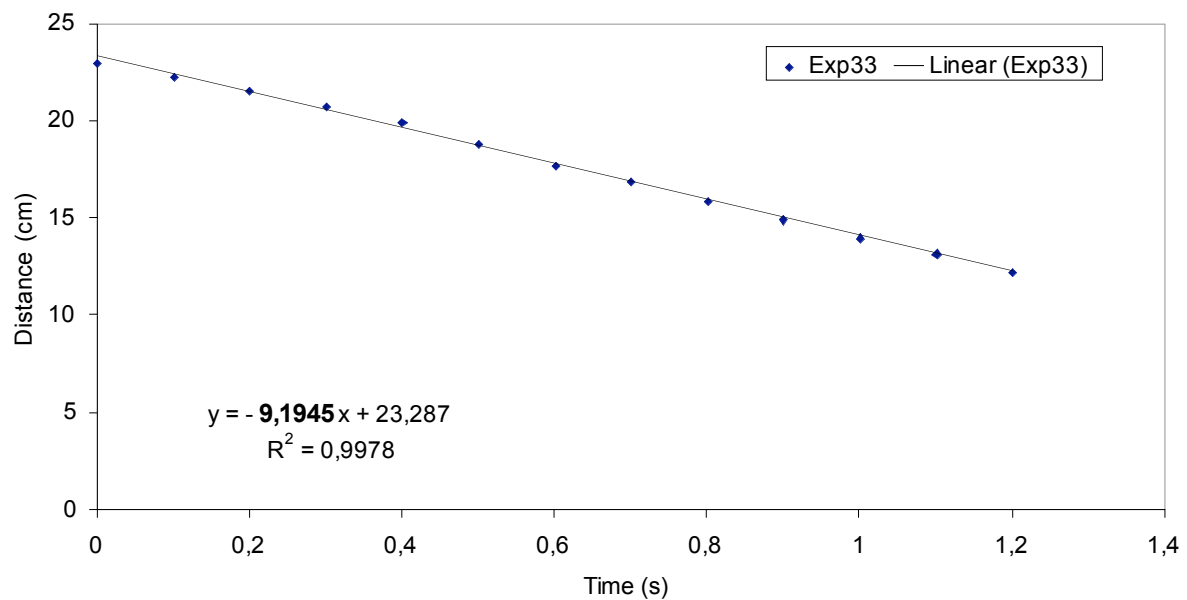
Appendix 3: Graphs of the velocity of the gravity current

a) Exp33

In this experiment, the salt solution is clear (at right) and the dye is the water (at left).



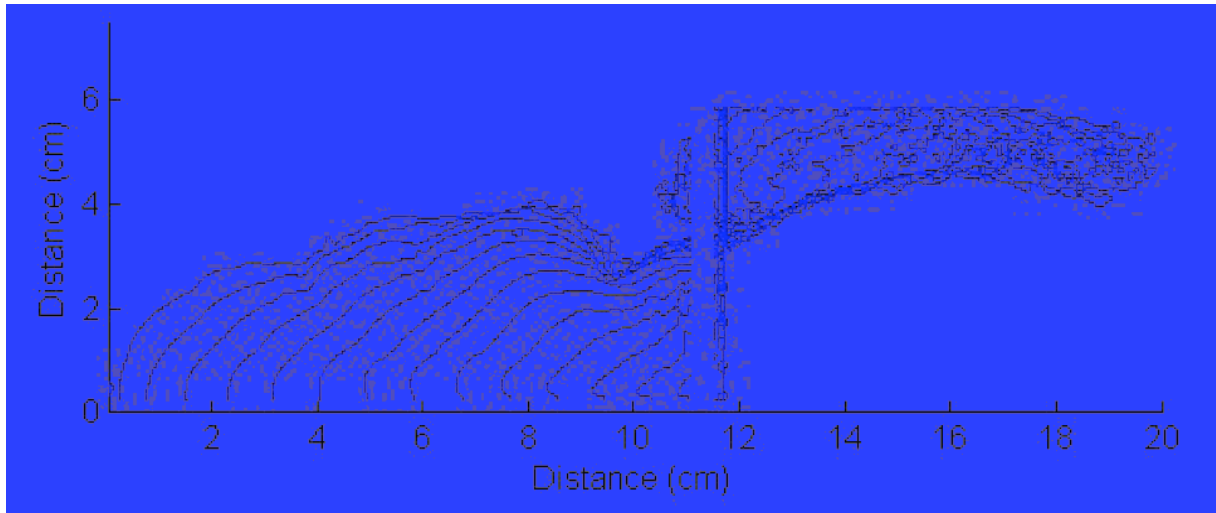
Gravity current profiles for exp33



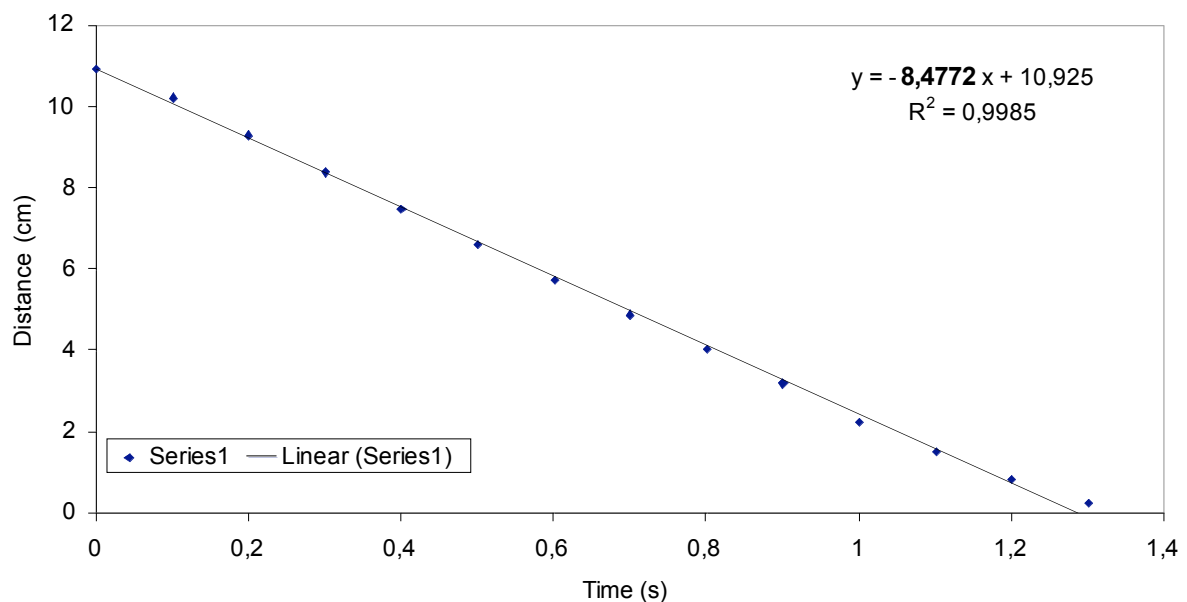
Motion of the GC head in exp33

b) Exp42

Exp42 shows the formation of the gravity current in the water channel with a top to avoid the free surface. On the right side there is the blue water solution and the clear water is on the left side



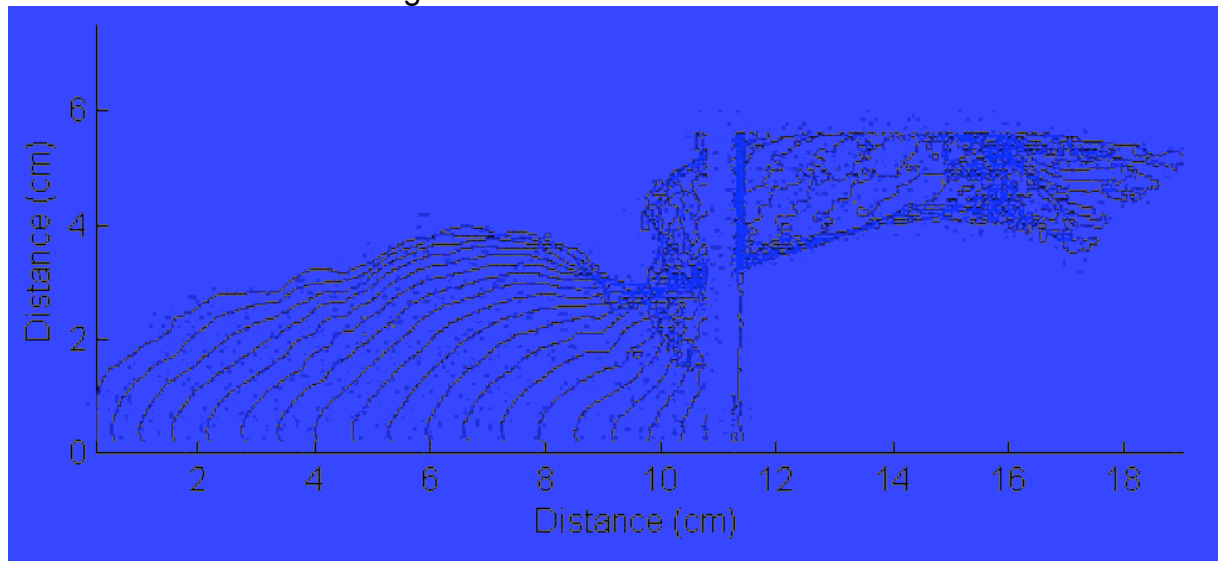
Gravity current profiles for exp42



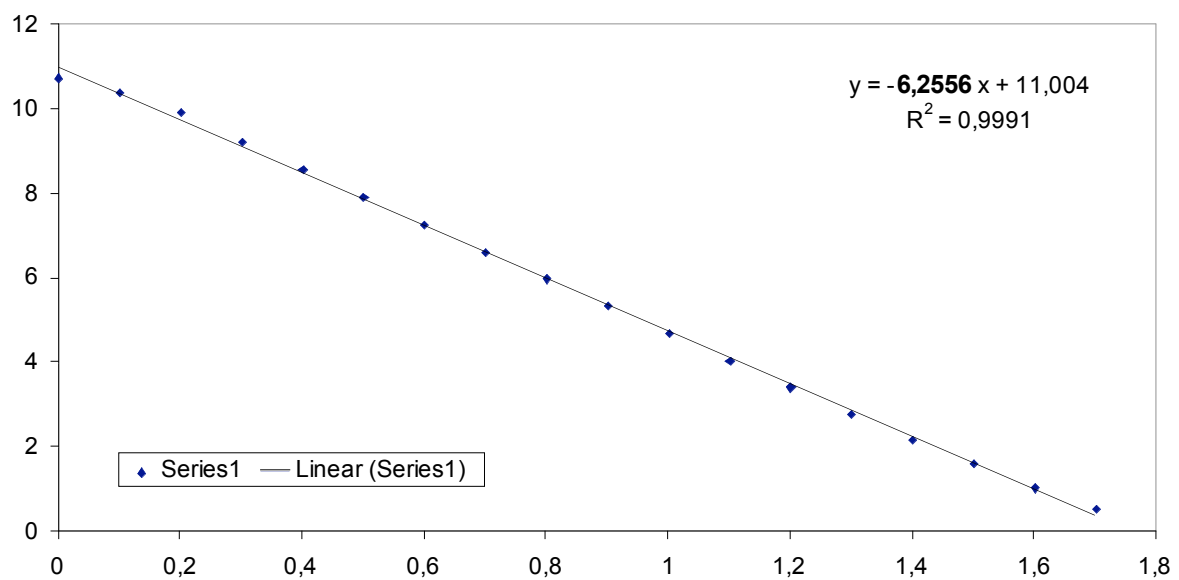
Motion of the GC head in exp42

c) Exp49

Exp49 shows the formation of a gravity current with a density of 1033 kg/m^3 . The blue salt solution is on the right side and the water on the left side.

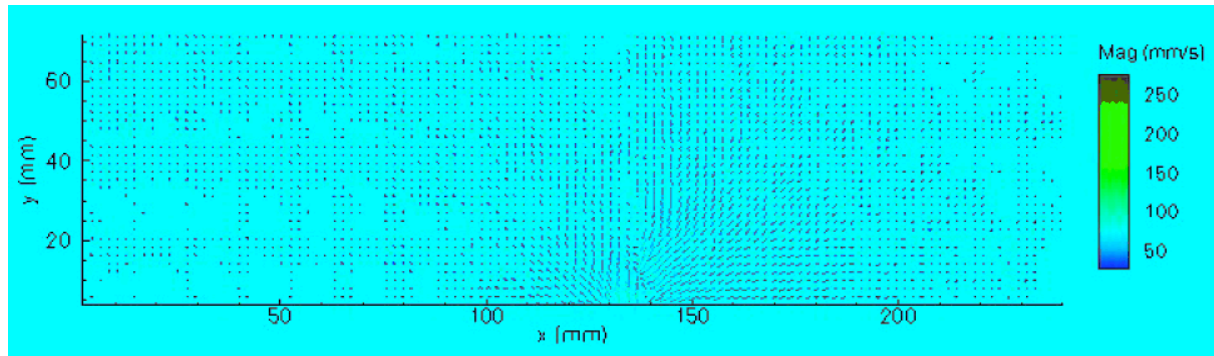


Gravity current profiles for exp49

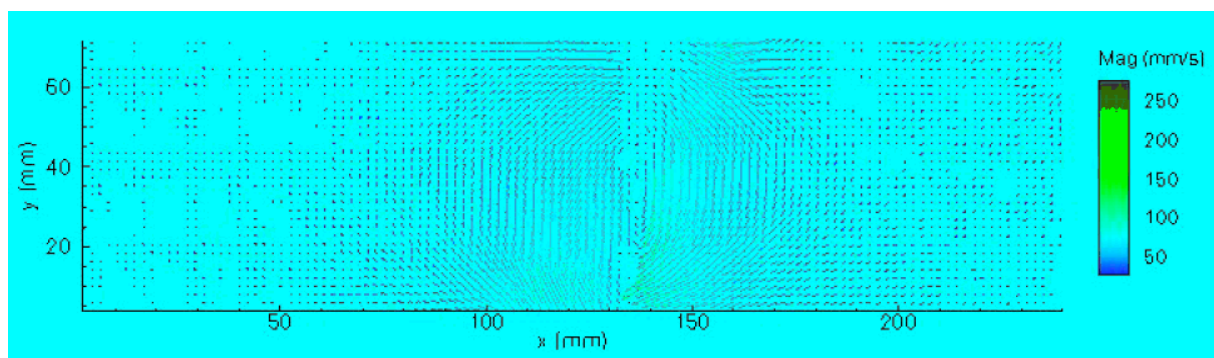


Motion of the GC head in exp49

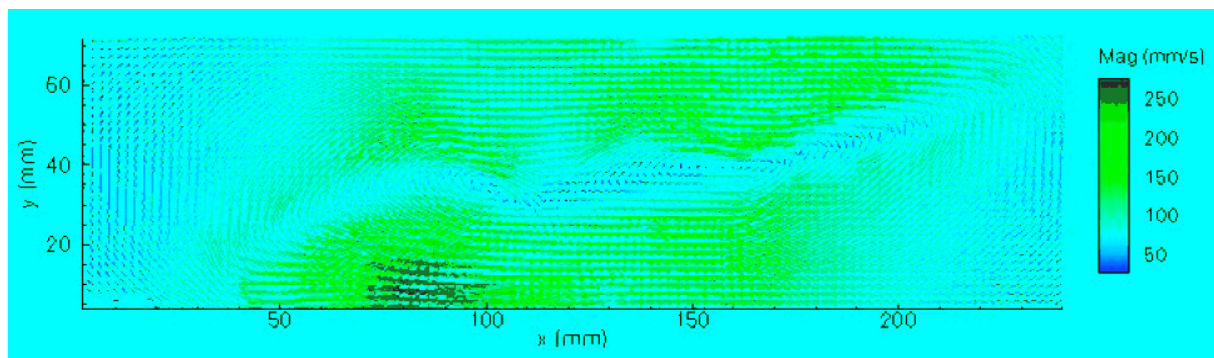
Appendix 4: PIV picture



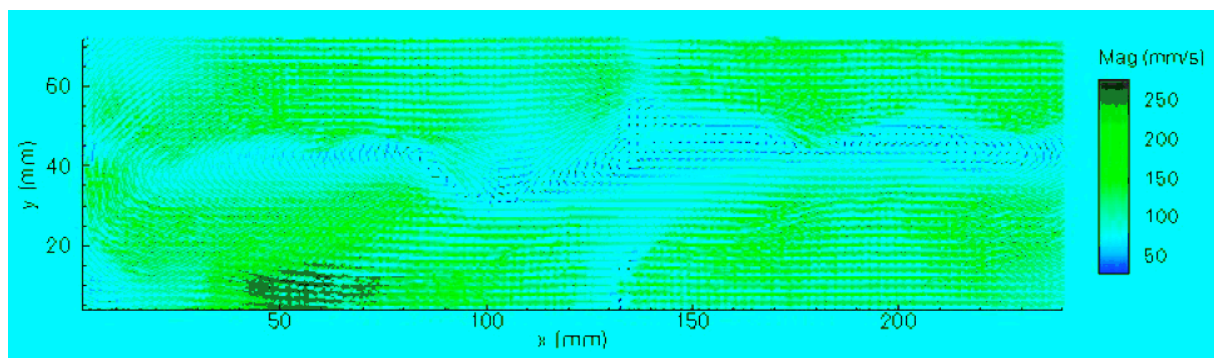
$T = 0$ s



$T = 0.16$ s



$T = 0.84$ s



$T = 1.35$ s