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OPTIMIZATION OF A WATER TABLE TO STUDY AERODYNAMIC PHENOMENA

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OPTIMIZATION OF A WATER TABLE TO STUDY AERODYNAMIC PHENOMENA

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This project is the result of collaboration of Universidad Pública de Navarra (Pamplona, Spain) and Erasmushogeschool Brussel (Brussels, Belgium) in the ERASMUS program, and it allows the student above to finish the Degree of Industrial Technical Engineering (Mechanics).

Promoters: **dr. Mark Runacres (EHB Belgium)**
dr. ing. Tim De Troyer (EHB Belgium)
dr. Pablo Sanchis (UPNA Spain)

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ABSTRACT

The goal of this thesis is to optimize the water table to visualize shock waves and vortices in the water flow.

We can divide this goal in two. The first goal of this thesis is the adaptation of the water table of Erasmushogeschool Brussel in order to have a laminar flow (and also to control the speed of the flow) to create the phenomena, when a solid body is placed on the table, of boundary layer, vortices, and shock waves. The second goal is to visualize these phenomena in the best possible way.

The first step was to do a theoretical study of the phenomena that we wanted to create in our table and the laminar flow. So in this thesis are explained the phenomena of boundary layer, shock waves and vortices; also a study of what a laminar flow is was made.

After having obtained this theoretical background, seven experiments were made in order to get the first goal of this thesis; we had to define a design for the water table which reached the first goal of the thesis. After each experiment we got some conclusions that helped us to choose the next experiment to do and the best way to improve the water table. The experiments were made with one and with both pumps working. After the two first experiments a lot of leaks appeared in the table and they were fixed by putting silicon to solve the problem. The problem was solved rapidly.

We tried to eliminate the turbulences in the second deposit to get a smooth and laminar flow on the table (and to control the speed of the flow); we did six experiments to get this. As it is seen in this thesis we found problems like the lack of space in the second deposit, bad election of the materials, bad placement of the elements… We did also one experiment to make the flow more laminar after the entrance of the table.

After all this experiments the decision taken was that the best way to improve our table was to place permanently a plastic sheet and a grille in the second deposit. A sloping plate could be also placed or not; this is because not big differences are found with it installed in the table. With both pumps working we can vary the speed of the flow and the shock waves are seen in a good way. With one pump working an extra element is installed; a wood sheet with tracks to guide the water is placed on the table and the result is the best. The disadvantage is that we cannot vary the speed of the flow. This design has been installed in the table with good results; the flow is laminar and the shock waves are visualized (they can be visualized in a better way as it is explained below).

After having chosen the best design for our table, we studied two possible alternative designs for the water table. The first one consists in the installation of an

upper plate on the test area for a better control of the speed of the flow. The second one is a completely new water table design where the entrance to the test area is adjustable and it controls the speed of the flow.

The shock waves could be visualized in a better way and the boundary layer is not viewable. Four methods of visualization are studied in the final part of this thesis in order to get the second goal. These are Dye injection, air or hydrogen bubbles injection, aliminium particles (to see the boundary layer) and solid particles. The last one was experimented on our table by spreading rice grains on it.

This thesis can be used as a guide for who works in the future on this table, so he can choose the best system of visualization according to his needs and budget; it is also important to write some alternative water tables for the future needs, as it has been done.

As we have mentioned before, the design chosen after the experiments has been installed in the table; the wood sheet with the tracks can be removed when we work with both pumps switched on.

INDEX

Chapter 1.

INTRODUCTION

1.1 GENERAL INTRODUCTION

The purpose of this project is to work on the water table previously built by students of the Erasmushogeschool Brussel and to improve it in order to have a correct visualization of the effects that a solid object originates in a fluid flow.

Description:

Adaptation of the water table of Erasmushogeschool Brussel to simulate subsonic and supersonic fluid flows, straight and oblique shocks, special phenomena in the air intake of supersonic aircraft (choking), separation of the boundary layer, and re-entry of space capsules in the atmosphere.

Another application of the water table is visualizing the vortices that are created by a blunt body in a fluid flow. These vortices are now not visible due to the turbulence created by the pumps. The water table should be adapted to account for this problem.

This subject is based on the analogy between the Mach number in the flow of air, and the thickness of the water flowing over a horizontal plate (the so-called hydraulic jump). This thesis combines the theoretical study of aerodynamic and hydrodynamic effects with the practical application.

Goal:

The goal of this thesis is to optimize the water table to visualize shock waves and vortices in the water flow.

1.2 DESCRIPTION OF THE THESIS

Chapter 1. INTRODUCTION

The matter of this thesis is presented, explaining the purpose and goal of it; a brief description of what is wanted to be experimented on the table is given.

In *Description of the thesis* an explanation of how each chapter is written and what is written in it is given.

Chapter 2. DESCRIPTION OF THE WATER TABLE

Firstly, a general description is given, naming the important elements of the water table. The experiments that are made in this table are focused on controlling mainly the speed of the flow and the laminar flow; these purposes are explained here too.

Chapter 3. FUNDAMENTALS

The most important fundamentals for a good comprehension of this thesis are explained.

Chapter 4. EXPERIMENTS

Seven experiments are made in order to get the purposes of this thesis and each experiment is explained. Firstly why and how the experiment is made and secondly, the results are analyzed and a brief conclusion is given.

In *Conclusions* a final solution for our table is presented, according to what has been observed in the experiments.

Chapter 5. ALTERNATIVE DESIGNS

In this chapter an alternative design of a water table with an upper table installed is showed and explained. The explanation is very detailed because it is thought to be a good design that could be built in the future.

The other design would be another possible solution; but this is not so deeply explained because a completely new table should be built, and the result is not necessarily better than in the previous design.

Chapter 6. VISUALIZATION METHODS

Four visualization methods are presented and explained in this part of the thesis. The fourth one has been tried in our table and the results are explained.

In the *Conclusions*, some advices are given in order to choose the best method for our table. Any of them would work well in the water table; the election would depend on the needs for the future and the money that would be spent on this method of visualization.

Chapter 7. CONCLUSIONS AND RECOMENDATIONS

Some conclusions are also written in Chapter 4 and 6 and in the abstract of this thesis. The designs and solutions are not re-explained but there is a summary of what has been finally done in our table and how a future user should work, guided by this thesis.

Chapter 8. BIBLIOGRAPHY

Web pages, links and books used for the writing of this thesis.

Chapter 2.

DESCRIPTION OF THE WATER TABLE

2.1 GENERAL DESCRIPTION

This table has been pre-designed and created with an educational intention. In our case the fluid is water that can simulate other kinds of interesting fluid flows such as an air flow.

1.- The water is initially stored in a tank **(First deposit, reservoir)** below the table.

2.- Two independent **pumps** fill a **second deposit** (one pump is enough to fill it) connected with the table by an opening **(entrance)**. This tank has also a **regulated opening (adjustable opening)** that can re-send part of the flow to the reservoir. This should make the speed of the flow controllable. This adjustable opening controls the height of the water in the second deposit before the entrance; if the water is at a high level the speed is high too.

3.- The **table (test area)** has an inclination of 0.62 degrees and this is the part where the experiments are going to be made. The **solid bodies (models)** are placed on the table and around them appear some visible (with the eye naked) phenomena as the shock waves; the boundary layer appears too, but it cannot be seen with the eye naked.

4.- Finally the water goes back to the reservoir, simply by the effect of gravity force (the reservoir is at a lower height), by a tube **(recirculation tube)** that connects the table with the tank.

** The water follows a closed cycle so it is not necessary to refill the tank.

The names of the important elements of the water table are in bold type and these elements are named during this entire thesis with these names; this is done to facilitate the future readers the comprehension of this thesis.

In the plan *Water table plan* all these elements are shown and named.

PLAN

WATER TABLE PLAN

2.2 PURPOSES OF THE PROJECT

For a correct visualization of the shock waves, vortices, and boundary layer (if it is possible to see it) the flow should be **laminar**; however, the flow is very turbulent mainly due to the powerful pumps.

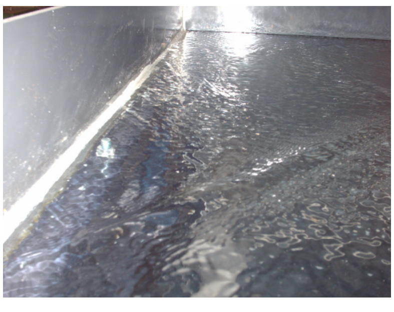
Another problem is the way of controlling the volume of flow in order to change the **speed of the flow**. The range of variation of the speed is not very wide; we could need a bigger range.

The visualization is something that also is wanted to be improved; but it is not a problem itself created by anything, it is just an improvement that would be very interesting for the docent purposes of this table.

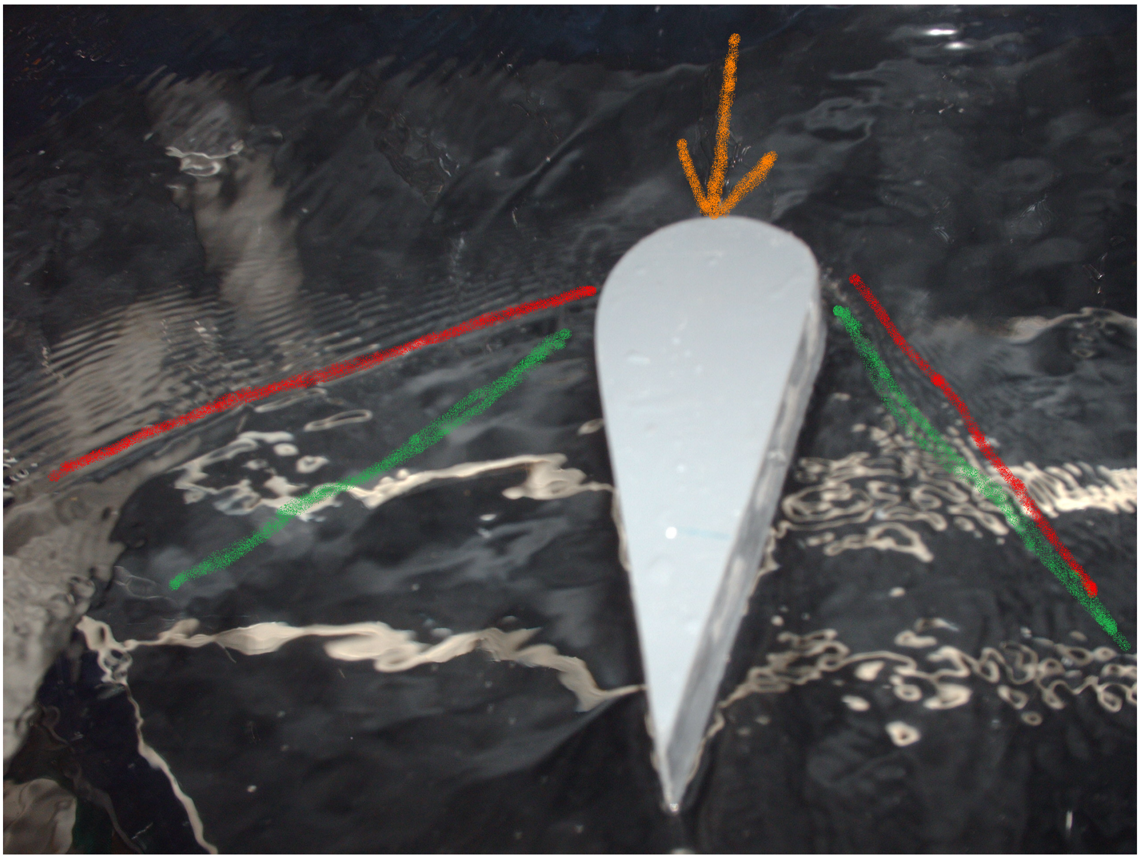
Laminar flow:

The purpose of this thesis is getting a laminar flow in the table in order to see the phenomena that a solid body causes in this flow. Actually, the flow that goes into the table is very turbulent and a lot of reflections are seen on the table (see Pic. 1). This turbulent flow is coming from the pumps and when it goes in the table by the entrance is still no laminar at all, so it goes down in a turbulent way.

The turbulences and reflections are visible and they continue down the table and we do not have any area of the table with a laminar flow.



Pic. 1 *Reflections against the walls.*



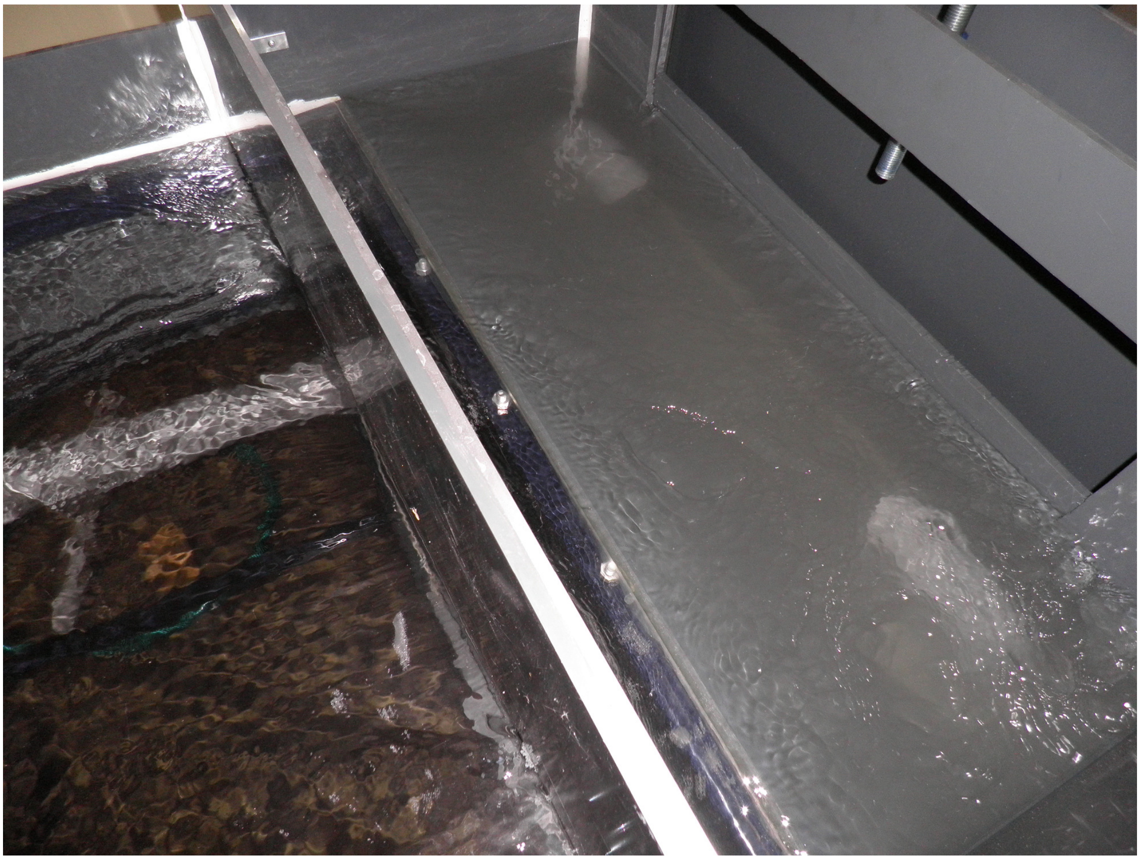
Pic. 2 *In this picture it can be seen that the vortices originated by the flow(direction indicated with the orange arrow) in a blunt body are not symmetrical (red lines). This body is placed in the direction of the flow. If the flow were laminar the shock waves originated would be more or less as they are indicated with the green lines (symmetrical).*

Speed of the flow:

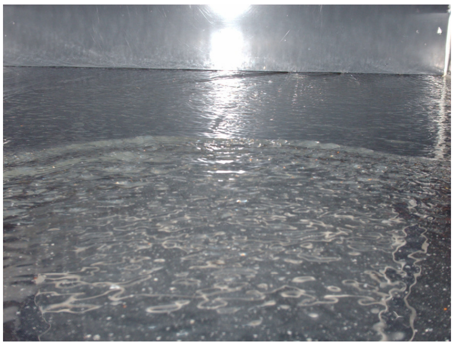
The volume of flow that is provided is constant and there is no way of regulating the pumps that are installed. The system to control the speed of the flow that was installed in the table consists in an **adjustable opening** just in front of the main opening (entrance) that takes the flow into the table. By this adjustable opening the volume of flow that it is not wanted to go to the table goes back to the first deposit (reservoir) and the rest goes in the table; in that way, the speed of the flow is controlled. If more volume is going in, the speed is higher. In other words, as the level of water before the entrance is higher, the speed of the flow is higher too.

It would be positive for our thesis to get a wider range of variation in the speed of the flow than the one that we actually have. We may not need it, but this is checked in the experiments *(Experiments)*.

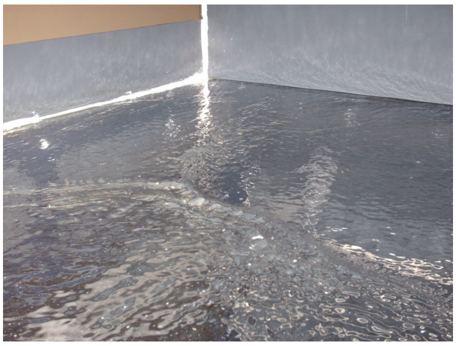
With both pumps working, the adjustable opening is able to change the height of the water in the second deposit before the water goes into the table by the 4 mm. entrance. Actually, when the both pumps are working the range of variation of the height before the entrance is not too wide; but this will be deeper studied in the chapter *"Experiments"* in the 4th experiment.



Pic. 3 *The turbulences can be seen on the left part of the picture.*



Pic. 4 *Turbulences.*



Pic. 5 *Hydraulic jump.*

Pic. 6 *The opening is completely opened and the volume of flow is still high and turbulent.*

When only one pump is working the volume of flow becomes quite small and the adjustable opening loses importance; this is because the volume of flow (provided by one pump) is so small that is not possible to send back to the first deposit some amount of flow. So in this case the volume of flow that goes in the table is not adjustable; it is permanently the volume of flow that comes out from one pump. The speed of the flow cannot be varied.

The adjustable opening is not hermetical and some volume of flow goes back to the first deposit by the sides of the adjustable opening even if it is not desired. This means that we cannot send all the volume of flow (if it is wanted) that comes from the pumps to the table, because some amount of it is always going back to the first deposit (reservoir) by this opening.

Pic. 7 *Some amount of flow goes back by the gaps in the sides of the opening*

Chapter 3.

FUNDAMENTALS

***This project requires some extra background in some fundamentals that are going to be seen in the water table. This part of the thesis is focused in providing this extra knowledge for a better comprehension of the project and the aspects of fluid mechanics that can appear on it.

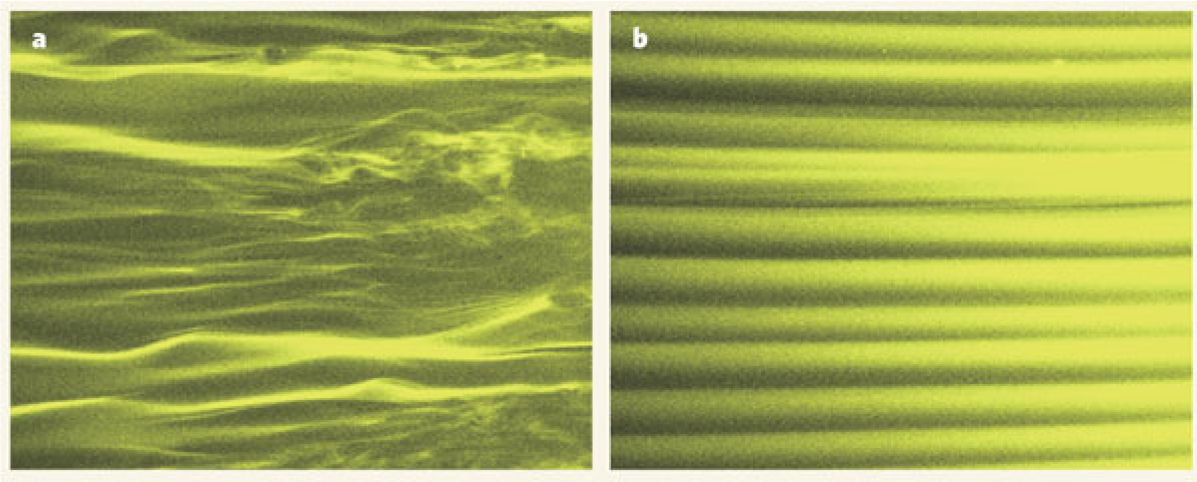
3.1 LAMINAR FLOW

*** This thesis is focused on getting a **laminar flow** on our table in order to see some phenomena that can appear in it when an object is placed. So it is essential to define what a laminar flow is and also to specify the particular case of a laminar flow on a horizontal surface (our table is almost horizontal).

Laminar flow, sometimes known as streamline flow, occurs when a fluid flows in parallel layers, with no disruption between the layers. In fluid dynamics, laminar flow is a flow regime characterized by high momentum diffusion and low momentum convection. It is the opposite of turbulent flow. In nonscientific terms laminar flow is "smooth," while turbulent flow is "rough." **[1]**

The chief criterion for laminar flow is a relatively small value for the Reynolds number, $Re = \rho VL/\mu$, where ρ is fluid density, *V* is flow velocity, *L* is body size, and μ is fluid viscosity. In the case of flow through a straight pipe with a circular cross-section, Reynolds numbers of less than 2300 are generally considered to be of a laminar type, however the Reynolds number upon which laminar flows become turbulent is dependent upon the flow geometry. When the Reynolds number is much less than 1, Creeping motion or Stokes flow occurs. This is an extreme case of laminar flow where viscous (friction) effects are much greater than inertial forces. [1] [2]

But we are interested particularly in the case of laminar flow above a horizontal surface. Laminar flow over a horizontal surface may be thought of as consisting of thin layers all parallel to each other. The fluid in contact with the horizontal surface is stationary, but all the other layers slide over each other. One thing that is very interesting for our project is that it is common only where the flow channel is relatively small, the fluid is moving slowly, and its viscosity is relatively high. [3]



“a” it is an example where the flow on a horizontal surface is turbulent, however in the picture “b” the different layers are appreciated being an example of laminar flow.[12]

<u>3.2 BOUNDARY LAYER</u>

***This table was built with the purpose of having a correct visualization of the effects that an object originates in a laminar fluid flow. Every time that we place an object in a laminar flow the **boundary layer** appears, a very small region of the flow around the solid.

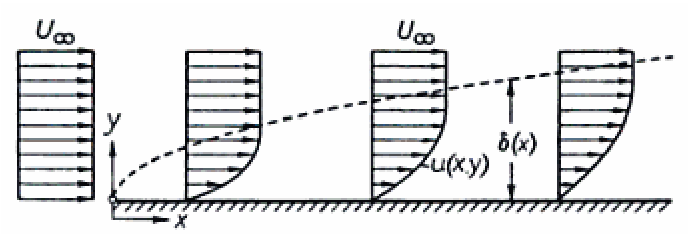
In physics and fluid mechanics, a **boundary layer** is that layer of fluid in the immediate vicinity of a bounding surface. [4]

To define the boundary layer in another way; we can start pointing out that the concept of the boundary layer implies that flows at high Reynolds numbers can be divided up into two unequally large regions. In the bulk of the flow region, the viscosity can be neglected, and the flow corresponds to the inviscid limiting solution. This is called the inviscid outer flow. The second region is the very thin boundary layer at the wall where the viscosity must be taken into account. **[10]**

So another good definition can be; the boundary layer is that portion of a fluid flow, near a solid surface, where shear stresses are significant and the inviscid-flow assumption may not be used. All solid surfaces interact with a viscous fluid flow because of the no-slip condition, a physical requirement that the fluid and solid have equal velocities at their interface. Thus a fluid flow is retarded by a fixed solid surface, and a finite, slow-moving boundary layer is formed. [5]

How big is the thickness of the boundary layer around a solid? The thickness of the velocity boundary layer is normally defined as the distance from the solid body at which the flow velocity is 99% of the freestream velocity, that is, the velocity that is calculated at the surface of the body in an inviscid flow solution. The thickness of the boundary layer δ, however, it must be made absolutely clear that it has been artificially introduced. **[4] [10]**

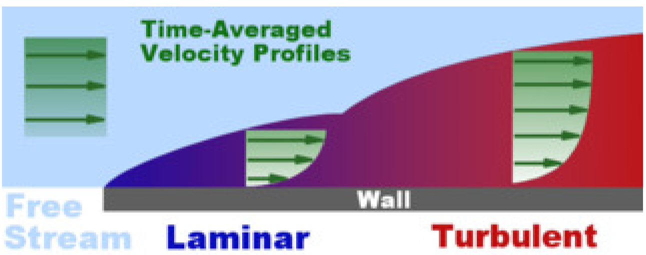
For example in the case of the thickness of a boundary layer on a flat plate $\delta(x)$ at zero incidence:



Boundary layer on a flat plate δ(x) at zero incidence [13]

Within the boundary layer the two flow forms (laminar and turbulent) can both occur, that is, the flow can be laminar or turbulent. One then speaks of laminar boundary-layer flows or laminar boundary layers for short, and equivalently of turbulent boundary layers.

If we take again the example of a plate at zero incidence in reality the boundary layer does not always remain laminar. After a certain distance $x = x_{crit}$ (from the leading edge of the plate), the boundary layer becomes turbulent. The boundary layer on a plate is laminar close to the leading edge and becomes turbulent further downstream, whereby the position of the transition point x_{crit} can be determined by the critical Reynolds number. Although the transition from laminar to turbulent is a region of finite length, a transition point is used for simplicity and it is frequently assumed that the transition is sudden. Re_{crit} is strongly dependent on how free from perturbation the other flow is. In strongly perturbed flow . $Re_{crit} = 3 * 10^5$ is typical, whereas for particularly smooth flow values of $Re_{crit} = 3 * 10^6$ have been reached. **The transition from laminar to turbulent flow forms is most noticeable by a great increase in the boundary-layer thickness δ(x) and in the wall shear stress.** [10]

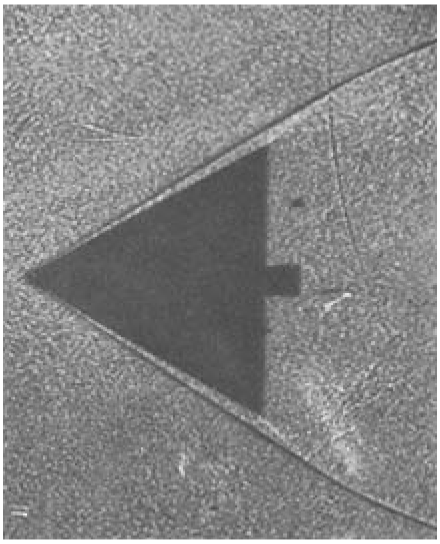


The transition point can be observed in this example, where the boundary-layer thickness increases noticeably. [14]

3.3 SHOCK WAVE

***When we place a solid object on our table, it disturbs the flow creating a change visible to the human eye. This change in the flow has a different size and shape depending on the speed of the flow and the shape of the solid body that we place on the table; this phenomenon is named **shock wave**.

A shock wave is a type of propagating disturbance and, like an ordinary wave, it carries energy and can propagate through a medium (in our thesis a liquid fluid is interesting). In other words it is an area or sheet of discontinuity (i.e., of abrupt changes in conditions) through which the fluid undergoes a finite decrease in velocity accompanied by a marked increase in pressure, density, temperature and entropy. The energy of a shock wave dissipates relatively quickly with distance. [6] [7]



Shock wave caused by a triangular body [15]

There are a lot of types of shock waves like the moving shock, detonation wave… But not all of them are on our table, so we are going to explain the one that is in our table; the **detached shock** and below the particular case of an **oblique shock wave**.

Detached shock:

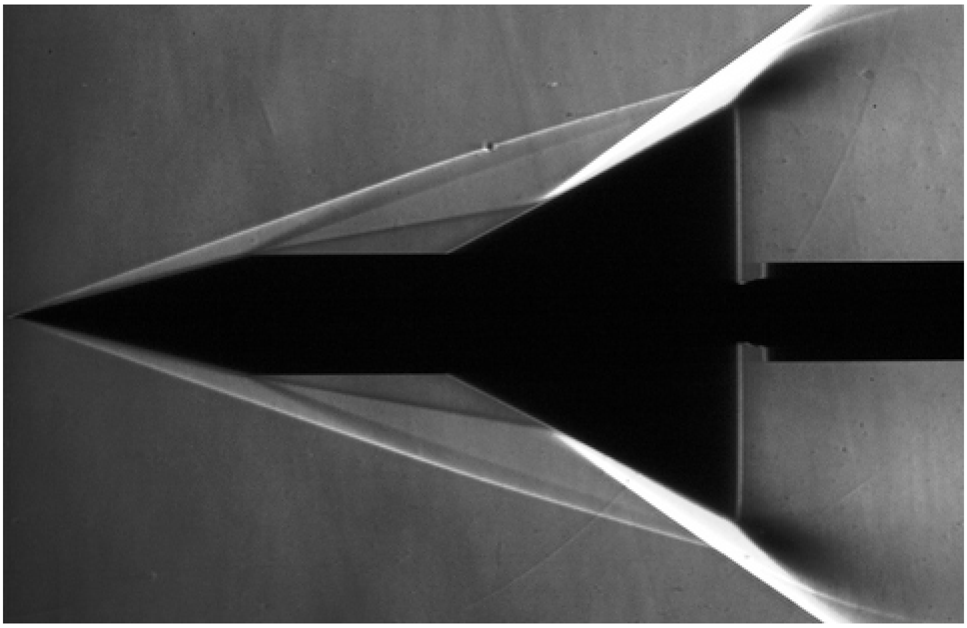
These shocks are curved, and form a small distance in front of the body. Directly in front of the body, they stand at 90 degrees to the oncoming flow, and then curve around the body. Detached shocks allow the same type of analytic calculations as for the attached shock, for the flow near the shock. They are a topic of continuing interest, because the rules governing the shock's distance ahead of the blunt body are complicated, and are a function of the body's shape.

Additionally, the shock standoff distance varies drastically with the temperature for a non-ideal gas, causing large differences in the heat transfer to the thermal protection system of the vehicle. See the extended discussion on this topic at Atmospheric reentry. These follow the "strong-shock" solutions of the analytic equations, meaning that for some oblique shocks very close to the deflection angle limit, the downstream Mach number is subsonic. Such a shock occurs when the maximum deflection angle is exceeded. A detached shock is commonly seen on blunt bodies, but may also be seen on sharp bodies at low Mach numbers.

Examples: Space return vehicles (Apollo, Space shuttle), bullets, the boundary (Bow shock) of a magnetosphere. The name "bow shock" comes from the example of a bow wave, the detached shock formed at the bow (front) of a ship or boat moving through water, whose slow surface wave speed is easily exceeded.

Oblique shock wave:

An **oblique shock** wave, unlike a normal shock, is inclined with respect to the incident upstream flow direction. It will occur when a supersonic flow encounters a corner that effectively turns the flow into itself and compresses. The upstream streamlines are uniformly deflected after the shock wave. The most common way to produce an oblique shock wave is to place a wedge into supersonic, compressible flow. Similar to a normal shock wave, the oblique shock wave consists of a very thin region across which nearly discontinuous changes in the thermodynamic properties of a gas occur. While the upstream and downstream flow directions are unchanged across a normal shock, they are different for flow across an oblique shock wave. [6]



Example of an oblique shock wave [16]

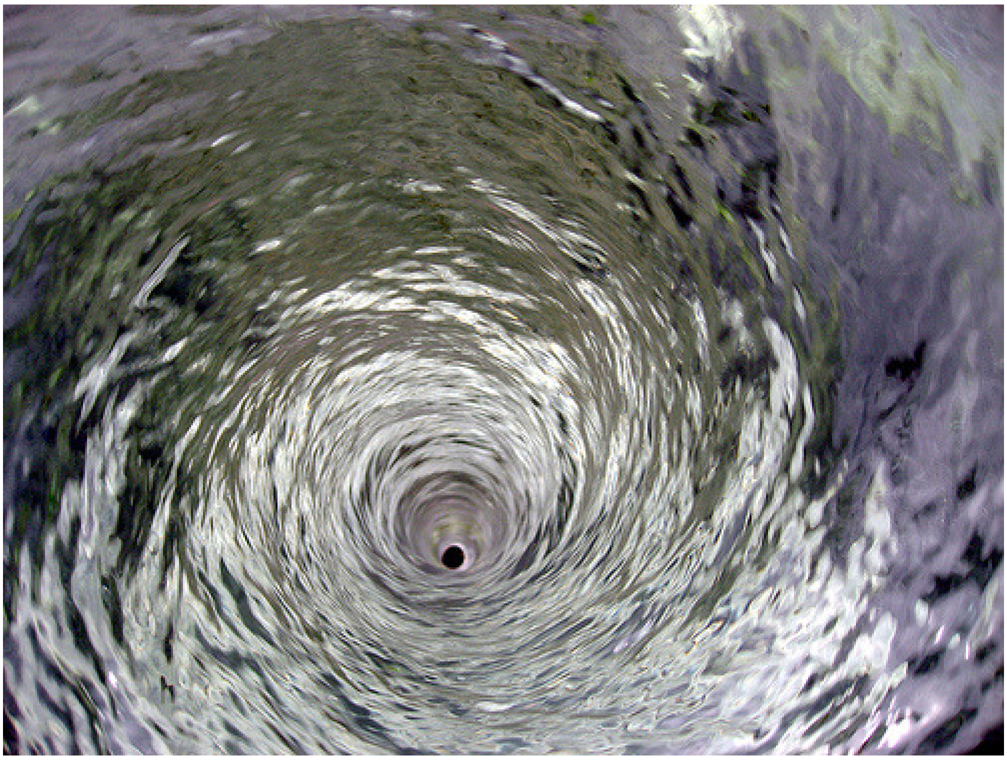
The **normal shock waves** do not often occur and they are very difficult to find in the nature and also in our table.

3.4 VORTEX

***Despite the phenomenon that normally is going to be seen in our table when we place a solid body is a shock wave, the **vortices** could also appear on our table, depending on the shape of the solid body that we place on it.

A **vortex** (*plural:* vortices) is a spinning, often turbulent, flow of fluid. Any spiral motion with closed streamlines is vortex flow. The motion of the fluid swirling rapidly around a center is called a vortex. The speed and rate of rotation of the fluid in a free vortex are greatest at the center, and decrease progressively with distance from the center, whereas the speed of a forced (rotational) vortex is zero at the center and increases proportional to the distance from the center. Both types of vortices exhibit a pressure minimum at the center, though the pressure minimum in a free vortex is much lower.

A vortex can be any circular or rotary flow. Perhaps unexpectedly, not all vortices possess *vorticity*. Vorticity is a mathematical concept used in fluid dynamics. It can be related to the amount of "circulation" or "rotation" in a fluid. In fluid dynamics, vorticity is the circulation per unit area at a point in the flow field. It is a vector quantity, whose direction is (roughly speaking) along the axis of the swirl. The vorticity of a free vortex is zero everywhere except at the center, whereas the vorticity of a forced vortex is non-zero. Vorticity is an approximately conserved quantity, meaning that it is not readily created or destroyed in a flow. Therefore, flows that start with minimal vorticity, such as water in a basin, create vortices with minimal vorticity, such as the characteristic swirling and approximately free vortex structure when it drains. By contrast, fluids that initially have vorticity, such as water in a rotating bowl, form vortices with vorticity, exhibited by the much less pronounced low pressure region at the center of this flow. Also in fluid dynamics, the movement of a fluid can be said to be *vortical* if the fluid moves around in a circle, or in a helix, or if it tends to spin around some axis. [8]



Vortex in a water flow. [17]

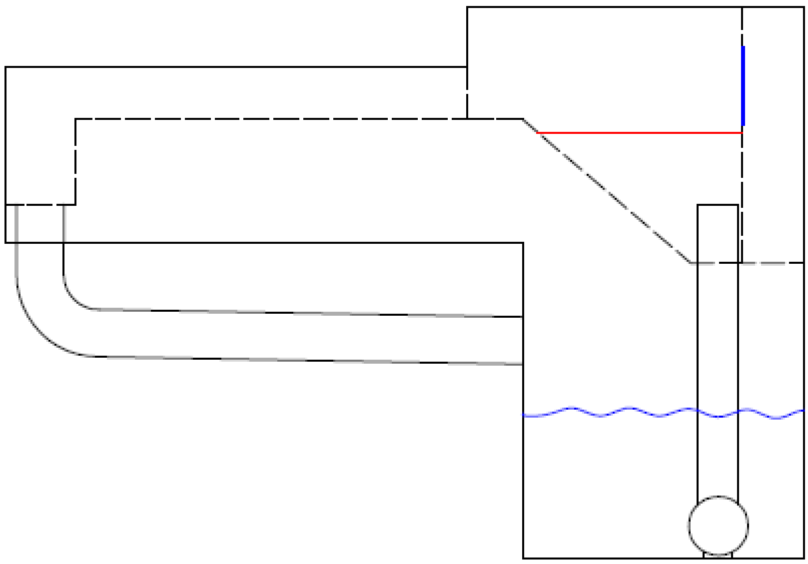
But as we said at the beginning of the explanation, in our table we are going to study mainly the shock waves and if it is possible the boundary layer. The vortices will be harder to see.

Chapter 4.

EXPERIMENTS

4.1 INSTALLATION OF A GRILLE IN THE SECOND DEPOSIT

The first experiment consists in the installation of a grille between the exit of the tubes and the entrance of the ramp. This is installed with the intention of decreasing the turbulences and stopping the shocks in the second deposit. The grille is installed horizontally because the water from the pumps comes out horizontally too but, rapidly, some reflections and turbulences start to move in the vertical direction. **It is thought that this placement of the grille can eliminate these turbulences and leave space enough in the second deposit for more elements that can make the turbulences disappear.**

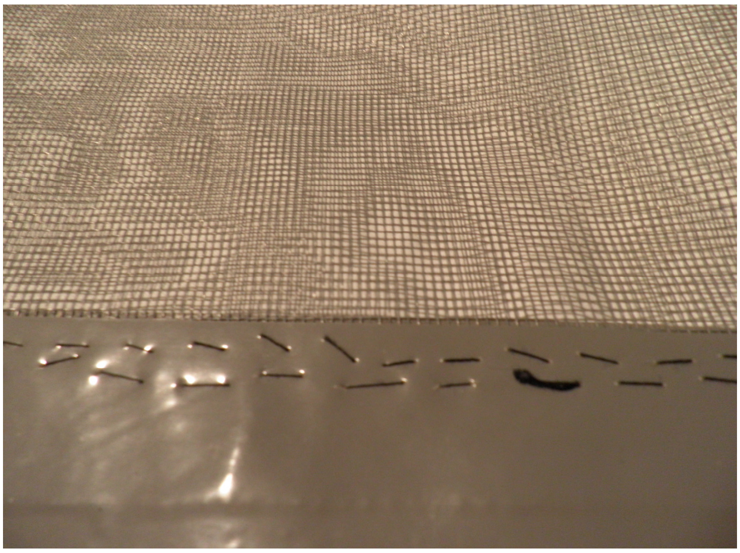


In this section the red line indicates where the grille is going to be installed

The decision taken is to use the plastic grille for the first experiment. It is the most economic and the installation is quite easy. To place the grille between the tubes and the ramp a water resistant adhesive tape is going to be used.

This was tried but the grill removed very easily from the adhesive tape with the pressure of the flow.

To solve this problem the grille has been sewed to the tape as you can see in the following picture.

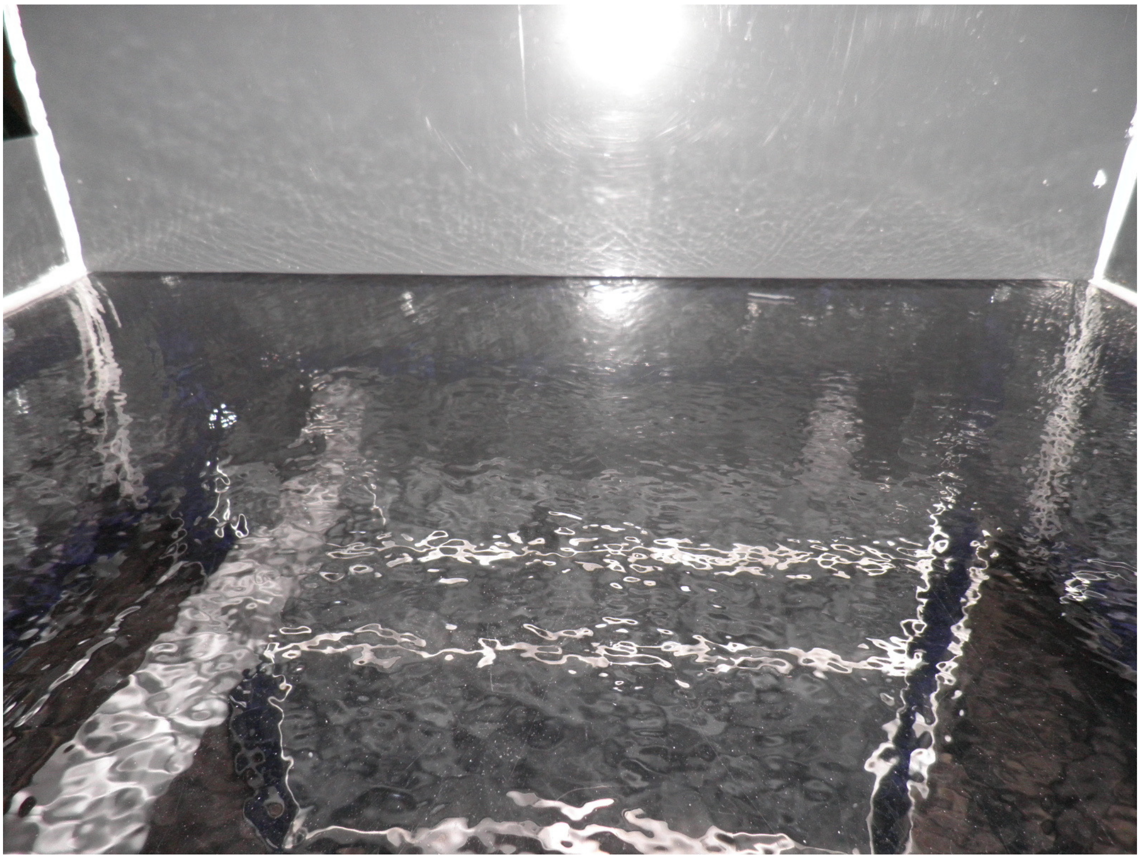


Pic. 8 *Grille sewed to the tape.*

Results:

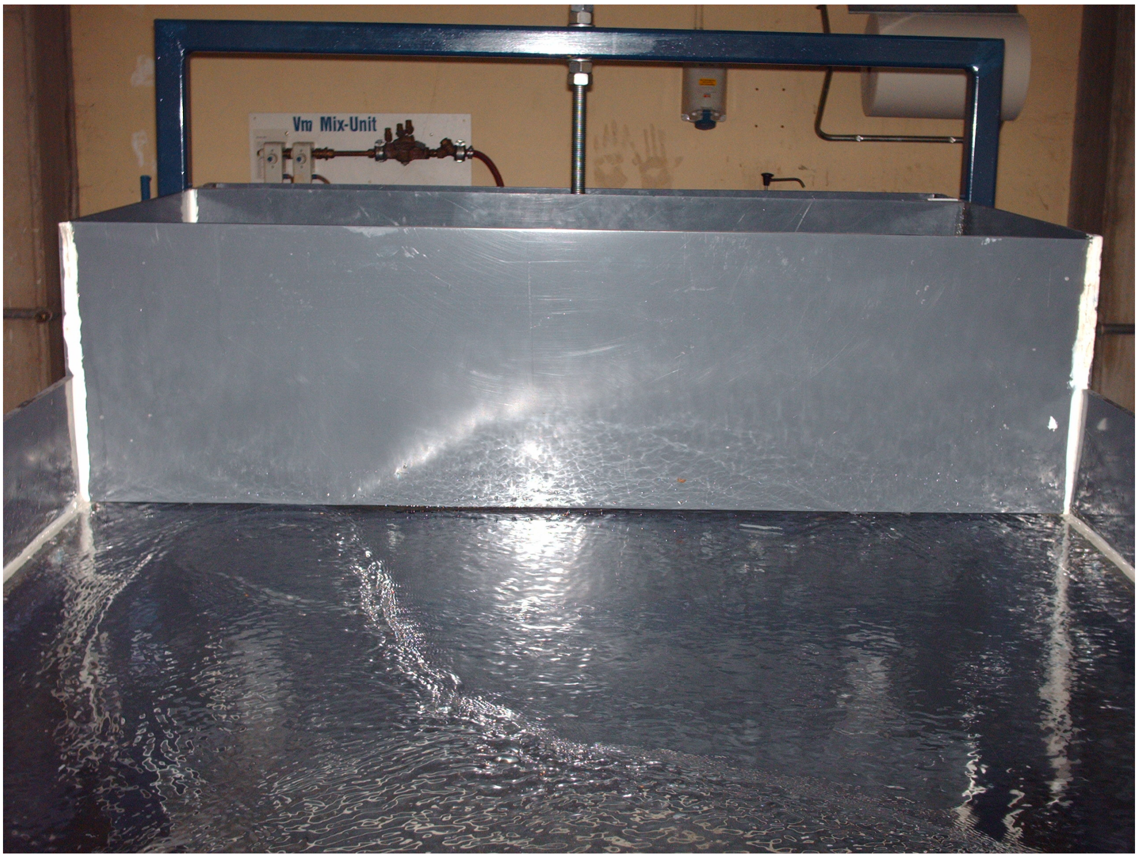
After installing the grille in the table we switch on one pump.

With one pump working the flow becomes more laminar and the shocks against the walls have decreased. The range of variation of the volume of flow that goes in the table is inexistent.

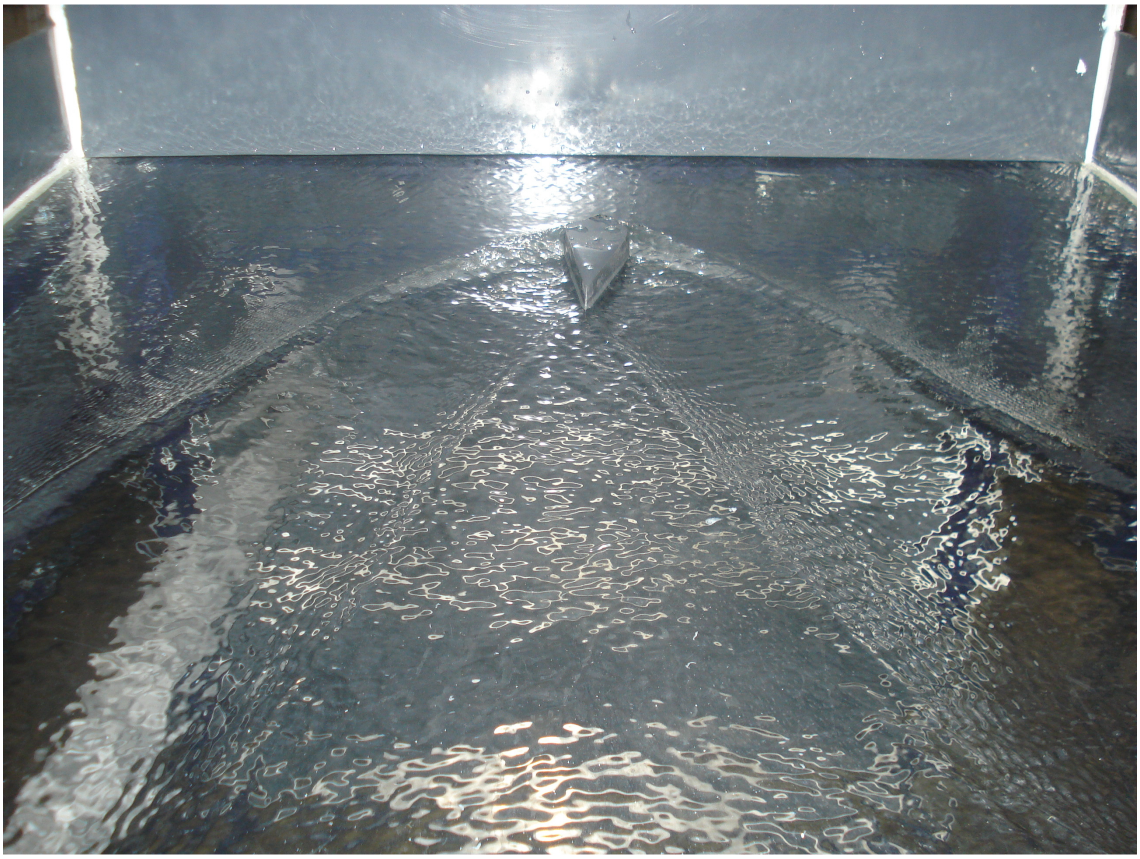


Pic. 9 *One pump working.*

The variation in the volume of flow is interesting for the table, so we do the experiment with both pumps working. When the two pumps are working together we still have the problem of excessive speed of the flow but it becomes more laminar and the shocks against the walls have decreased also in a noticeable way. The shock waves originated by the flow in a blunt body that is placed in the direction of the flow are now symmetrical, not as in the past.



Pic. 10 *Two pumps working: Turbulences without the grille installed.*



Pic. 11 *Two pumps working (with the grille installed): The turbulences have decreased and we can visualize shock waves in blunt bodies in a better way than before (it is not already a good result but it is better than without the grille).*

This experiment has shown us that the grille can be useful and that perhaps if we placed more grilles in the same place we would get a more laminar flow. The results are still not good but this experiment has shown us a way to continue our work.

To sum up with this grille we have found a possible solution to reduce the turbulences and to reach the goal of a laminar flow. But we still have an excessive speed of the flow with both pumps working and the result can be improved.

4.2 STARTING WITH A STILL MASS OF WATER

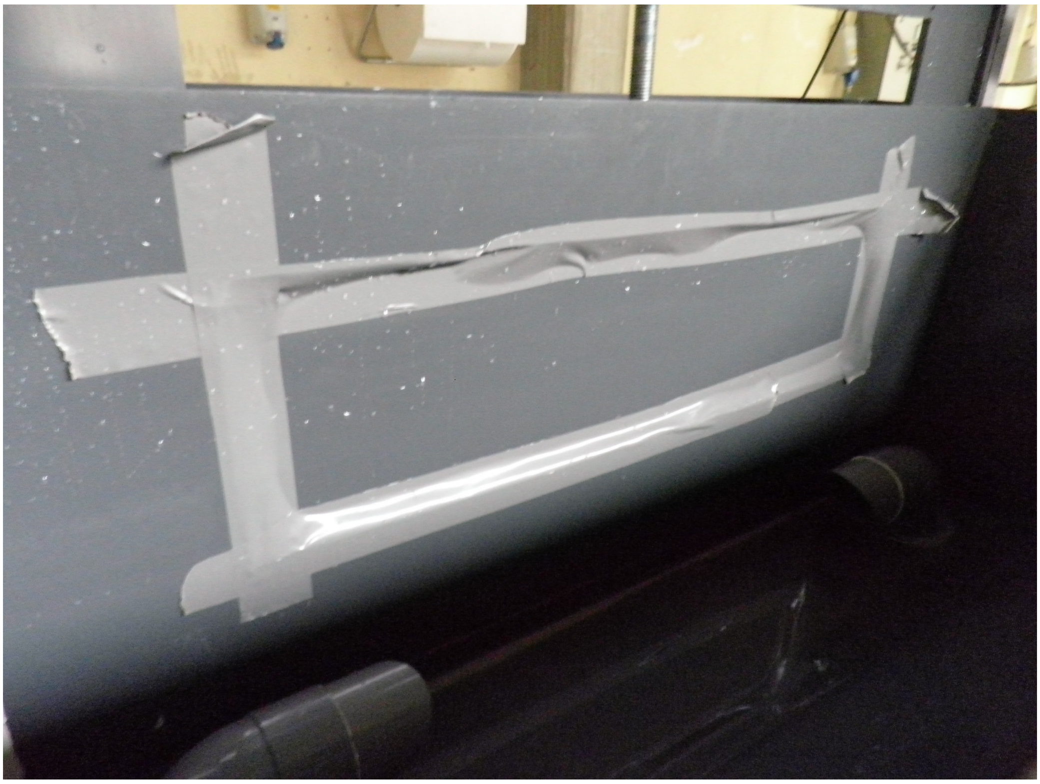
It is not known if we can get a laminar flow and eliminate the turbulences before the water comes into the table but, first of all, we have to check if this is going to be useful; or in another way, if it is useful to try to get a calm mass of water before the entrance of the table. To check if we are working in the good way a experiment has been done; it is not useful as a final solution but it tells us what we need to know before the next experiments and it can show us a way to continue.

The experiment consists in filling the second deposit (where the water comes out from the pumps) and let the mass of water reach a still state. Then we let the water go into the table without the initial turbulences, because they have disappeared (the water stays some time in the second deposit in order to reach the calm state), and we observe the result.

We have got this by displacing a piece of plastic in the entrance of the table that can be removed quickly to open the way.

Pic. 12 *Entrance blocked.*

We also block the adjustable opening to regulate the speed of the flow using some adhesive tape.



Pic. 13 *Adjustable opening blocked.*

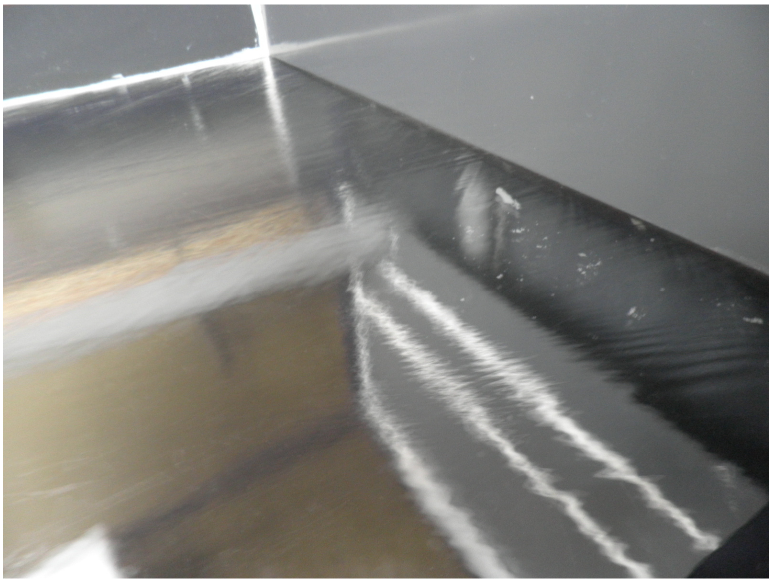
Finally, after filling the second deposit, we also block the tubes connected to the pumps that take the water from the first deposit to the second one. We do this because if not the water can come back by the same tubes to the reservoir. We block the tubes with a simple method, we use a pair of plastic gloves and they work very well.

Pic. 14 *Tubes blocked.*

Results:

After preparing the experiment we do it and the results are quite satisfactory. It is very clear that it is not a final solution as we said before. What we have checked is that mostly all the turbulences on the table are due to the pumps; because now, without the pumps working, the turbulences are not there and the flow is smooth.

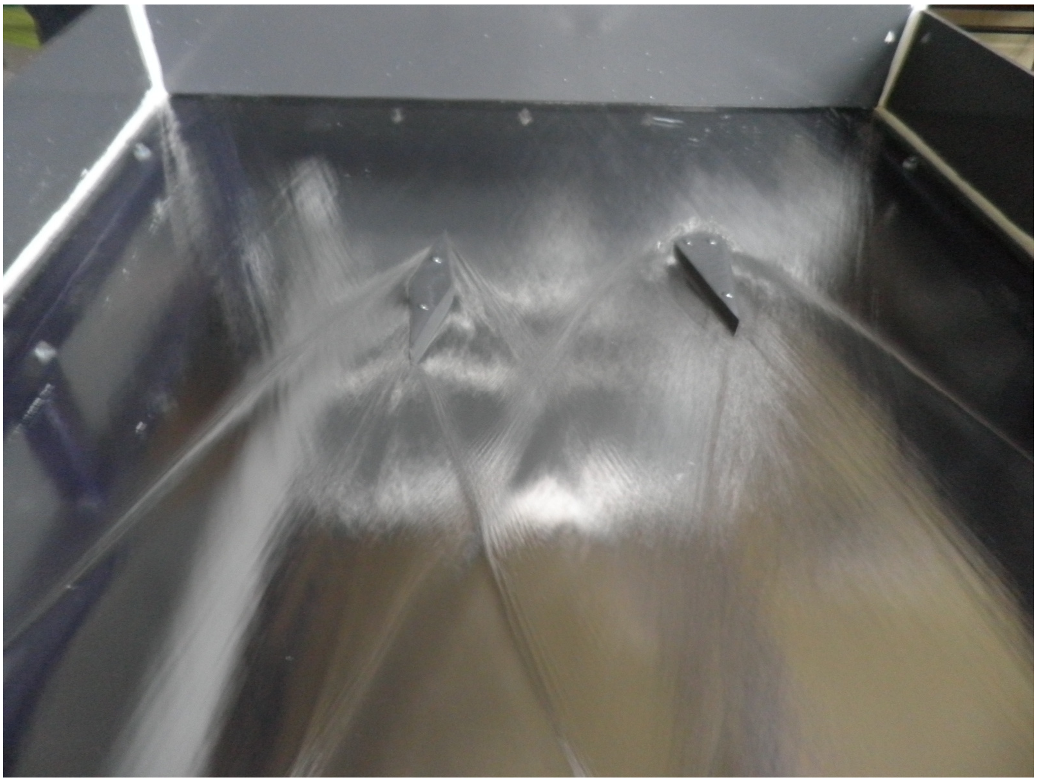
Pic. 15 *Turbulences with the pumps working.*



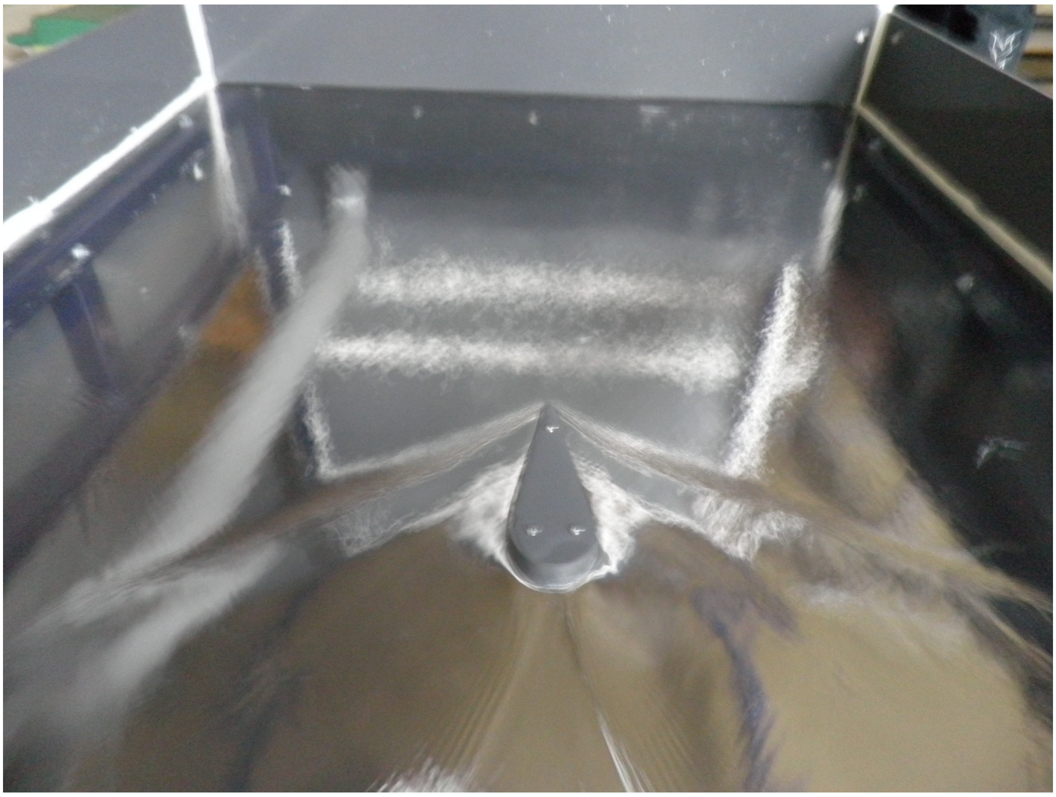
Pic. 16 *Turbulences mostly disappeared during the experiment.*

In this experiment normally the flow is too fast, because we reach a big high before the entrance at the beginning of the experiment. But when a small amount of water is left it works better, and it is very close to what we want to reach, a laminar flow.

The shock waves are also more symmetrical as it can be seen in these pictures.



Pic. 17 *Symmetrical shock waves 1*.



Pic. 18 *Symmetrical shock wave 2*.

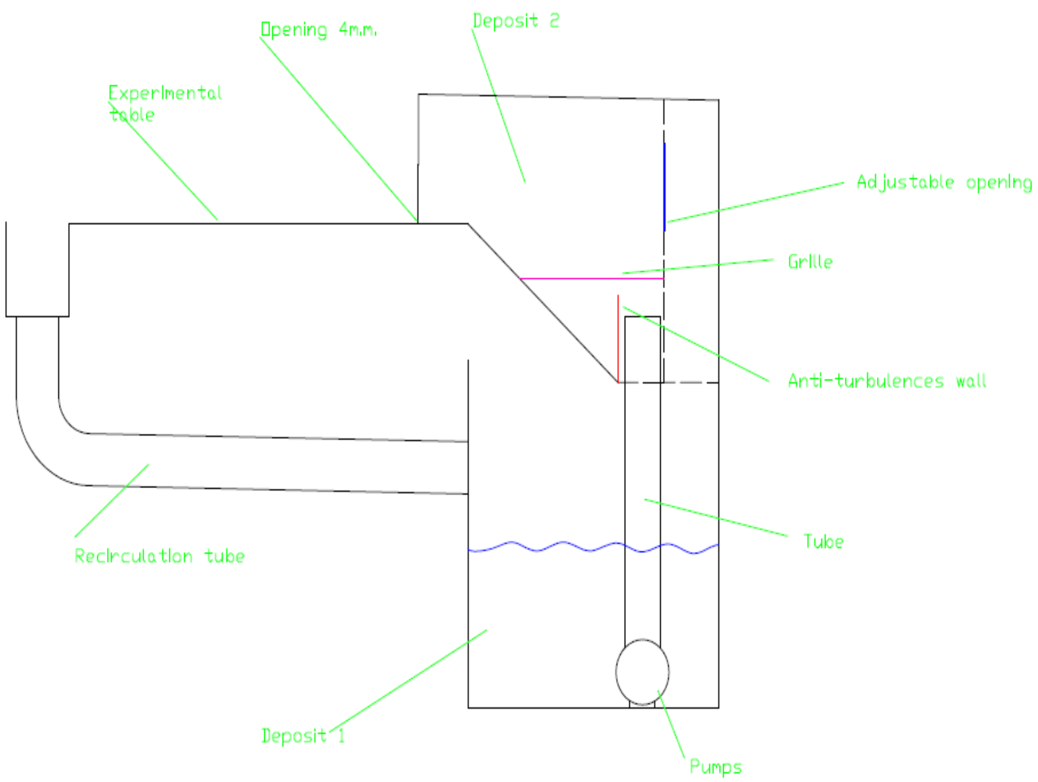
To sum up, the experiment shows us that if we eliminate the turbulences before the entrance the water table should work well. But a problem that we can find with this it is that we may not have too much space in the second deposit to make these turbulences disappear.

According to this experiment we can conclude, as we mentioned before, that mostly all the turbulences are created by the pumps.

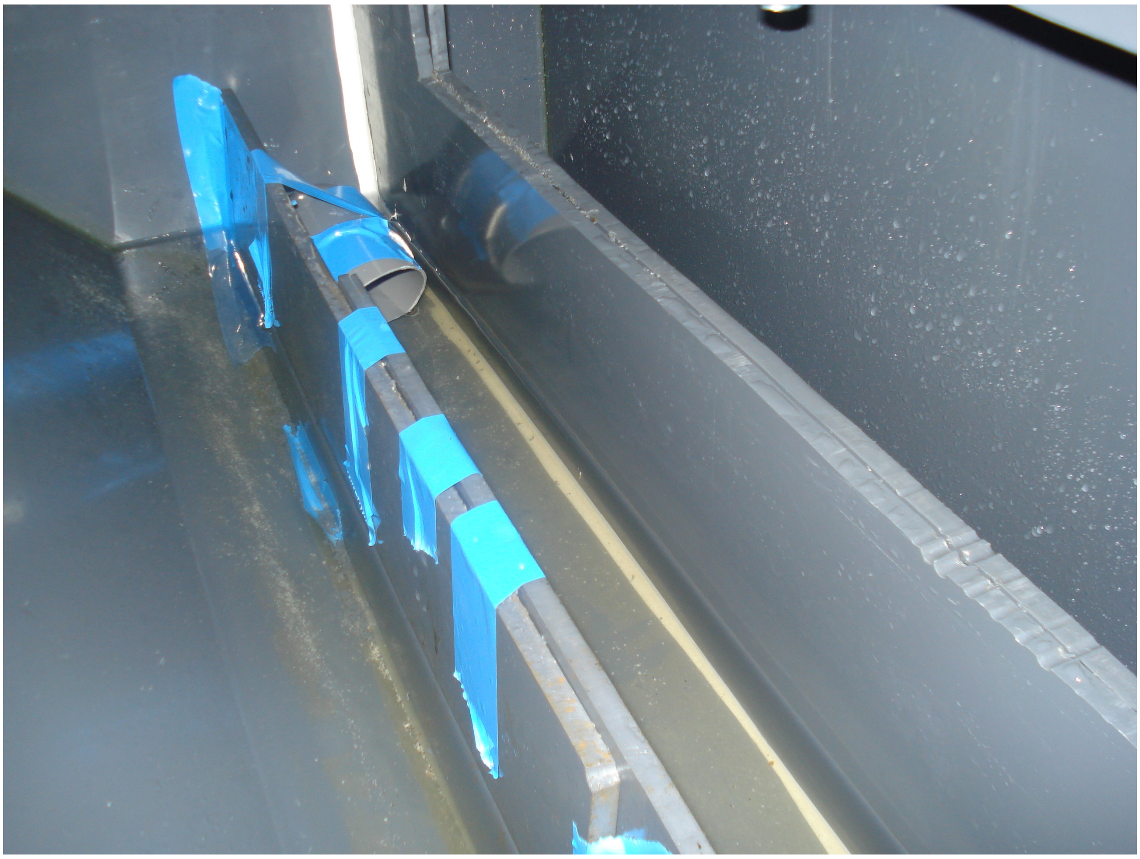
4.3 COMBINING A PLASTIC SHEET WITH A PLASTIC GRILLE IN THE SECOND DEPOSIT

The previous experiment has shown that we could focus in getting a no turbulent mass of water before the entrance. Our next experiment is about the possibility of getting this calm state in the second deposit. A doubt exists about if there is space enough between the pumps and the entrance that takes the water to the table to stop these turbulences. We try to check this with this experiment.

We do this experiment in two steps. We install a plastic sheet (red line) and after observing the results we add above it a grille (pink line), the same that was put in the first experiment.



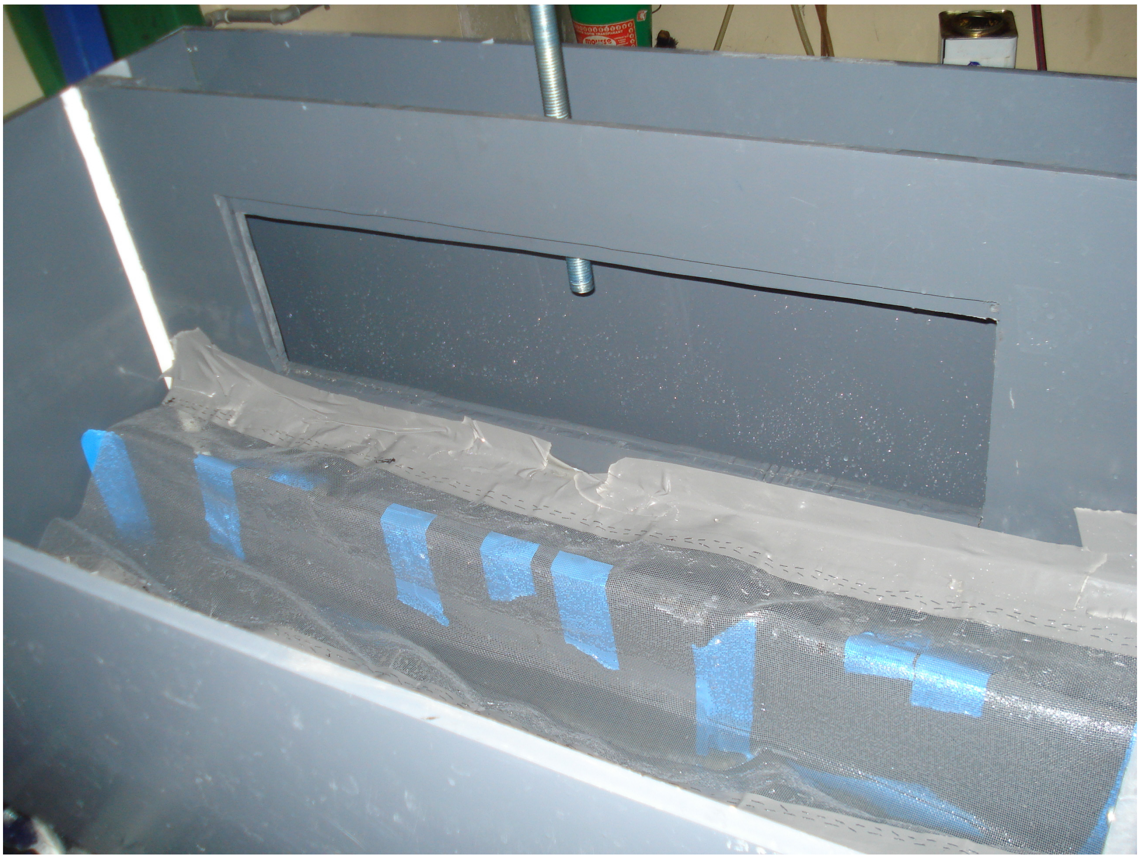
First we place a plastic sheet (100cm. x 20cm.) placed with adhesive tape next to the pumps, trying to reduce the initial turbulences. It is supposed to absorb some of them and let a calmer mass of water in the second deposit.



Pic. 19 *Plastic sheet in front of the pumps.*

After displacing the sheet the pumps are turned on and we observe the results.

Secondly we put the grille above the sheet covering an entire section of the second deposit. This grille is another way of reducing the turbulences; we are just trying to use the space that we have in the deposit.

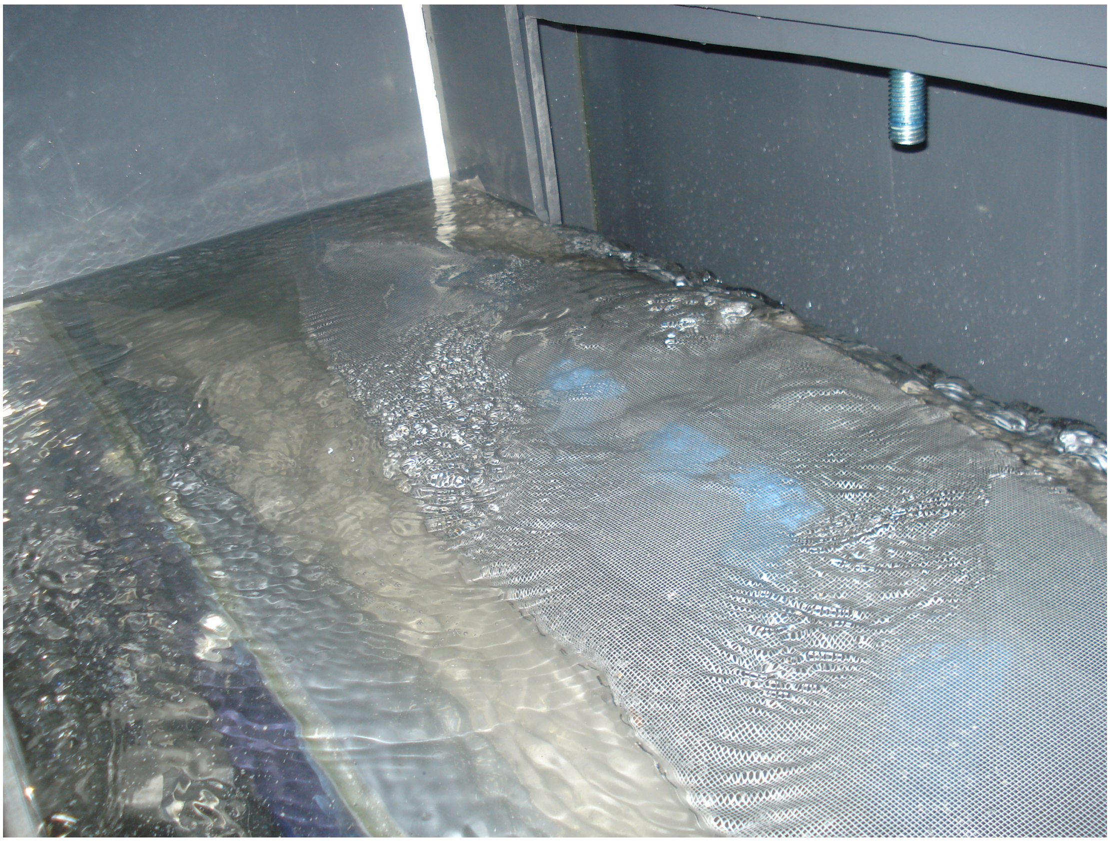


Pic. 20 *Grille covering the pumps.*

When everything is ready we turn on the pumps again and we observe the results.

Results:

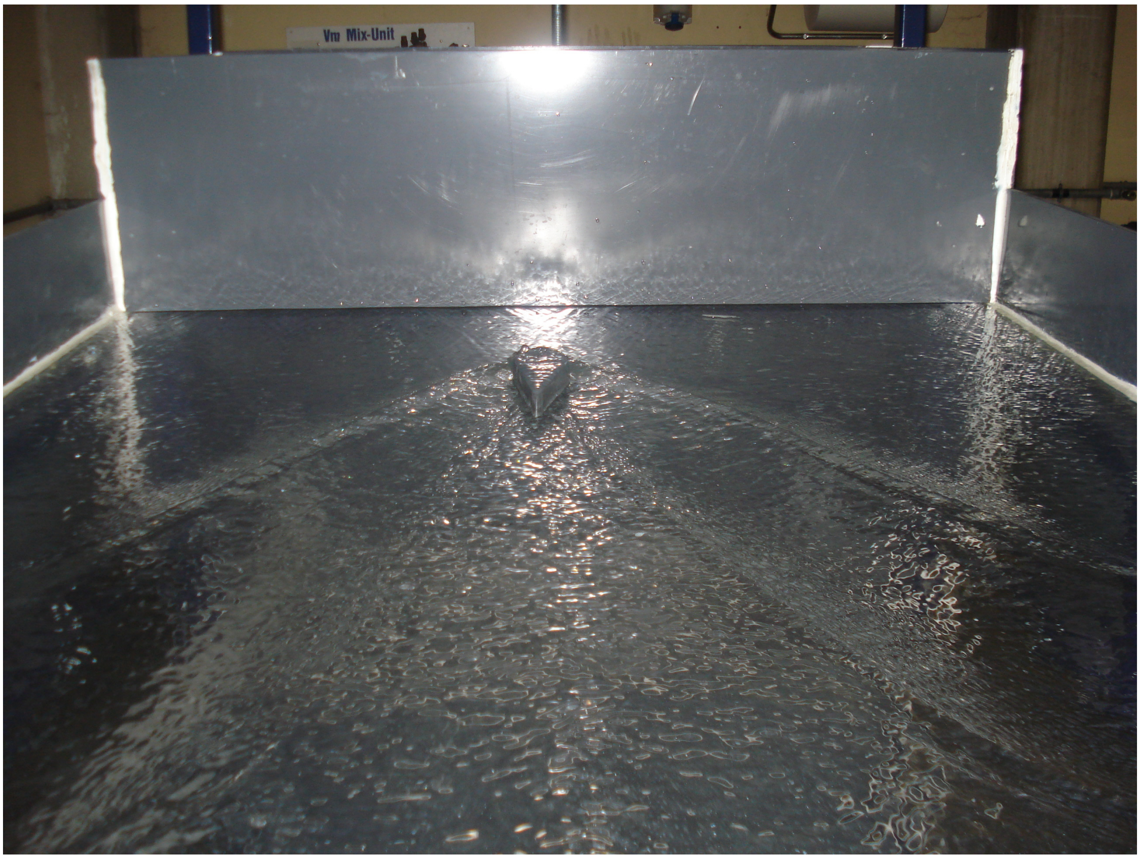
When the table is working with the sheet placed the effects of this one are very small. It reduces the turbulences and waves in a very small proportion and the space used for the sheet is quite big.



Pic. 21 *There are still a lot of turbulences in the second deposit.*

So the results with the plastic element are not satisfactory and it does not seem a good solution.

With the grille the situation improves in comparison with the first step of the test.



Pic. 22 *Both pumps working: The flow is not so turbulent and the result is quite good.*

The result is better than at the end of the **experiment 1**, when only the grille was installed. So it is proved that also the plastic sheet is helping in a small proportion to eliminate the turbulences and reflections in the second deposit.

With both elements installed we have used a lot of space in the second deposit (around 40%).

We have not made difference between one or both pumps working because in both cases we have a good result.

With **one pump working** the volume of flow is small and smooth; the shock waves are very clear. The volume of flow cannot vary as it has been mentioned before.

Pic. 23 One pump working: Clear image of a shock wave

With **both pumps working** the result is also good as it is seen in the Pic. 22; the flow is quite smooth and the shock waves are quite clear. The speed of the flow is controlled by the adjustable opening in a better way; this is because the water in the second deposit is calmer than before.

In conclusion, at the beginning of this experiment our purpose was to know if we could stop the waves and shocks before the entrance using the space that we have. As this experience has shown us, a smoother flow is got, but if we want to get a perfect result the lack of space in the second deposit can be a problem. Despite this, <u>the result is good and the shock waves are clear.</u>

Maybe we ought to look for another way to get a perfect laminar flow by not trying to eliminate all the turbulences before the entrance. By the moment we insist in this idea of eliminating them before because more possibilities can be checked.

4.4 CHECKING THE HEIGHT OF THE WATER IN THE SECOND DEPOSIT

More experiments, apart from the grille and the plastic sheet, are planned to do in the second deposit in order to get a still state of the water in it. We are planning to displace a plate that can create a kind of separate small deposit (third deposit) where the water could stay calm *(experiment 5)*. But this experiment is going to be done after checking what is explained in the paragraph below.

We are going to check how high the water can be in the second deposit in order to make the next experiment. We want the water to be high enough (in the third deposit) to eliminate the turbulences before the water goes in the test area. The height in the future third deposit would be the same that it is actually in the second deposit (see *Experiment 5*). If the turbulences are in the highest part of the mass of water they may disappear in the low part, where the entrance is.

We also check in this experiment if we can get a bigger range of variation of the speed of the flow. As it has been mentioned before *(Chapter 2, Description of the water table),* the speed of the flow is controlled by the adjustable opening, which varies the height of the water before the entrance. If the range of variation of the height before the entrance is big, the range of variation of the speed is big too.

First part:

To start making this test we close completely the adjustable opening so the height of the water before the entrance is going to be as high as possible.

Pic. 24 *At the right part of the picture it can be seen the opening completely closed and at the left part the height (60 mm.) of the mass of water.*

Results (first part):

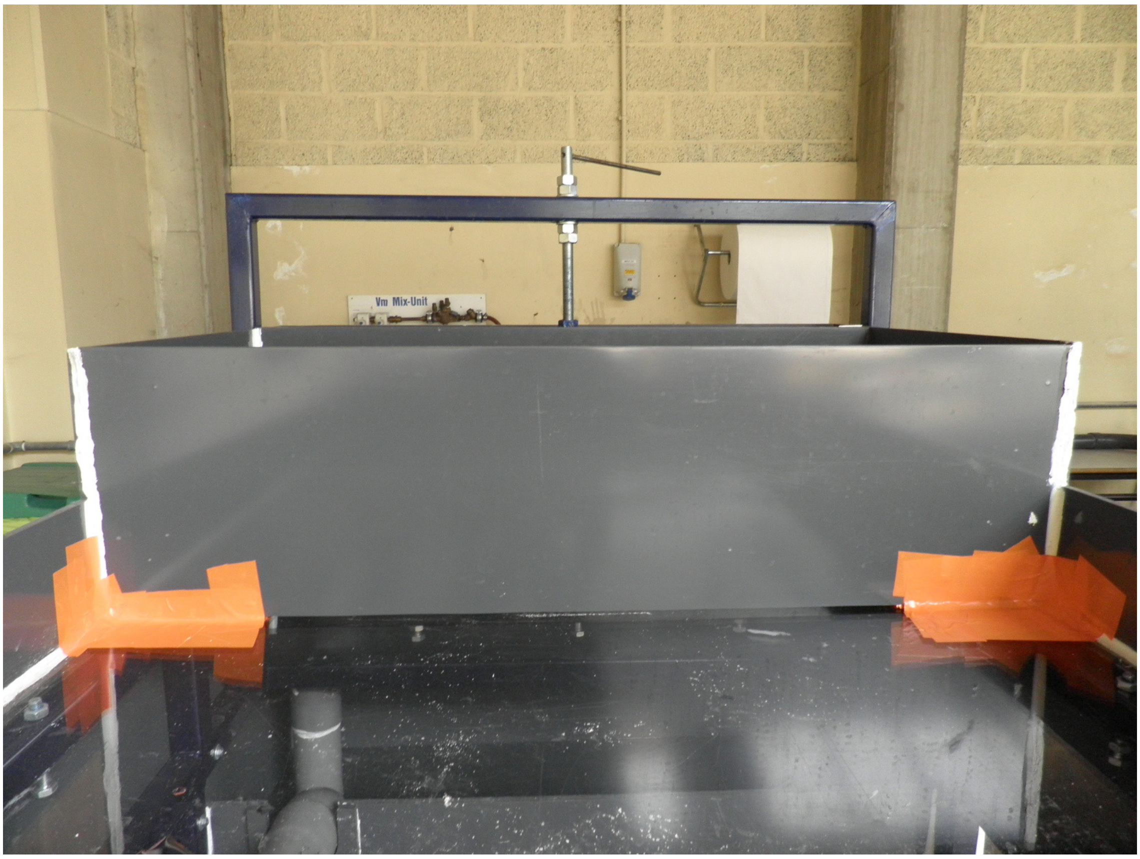
The level of the water before the entrance is 60 mm. high over the level of the table, which could be enough for our purpose. Actually if the adjustable opening is completely opened the height is 15 mm., so finally our range of variation on this respect is 15 mm. – 60 mm.

This range could be useful for the experiment 5.

Second part:

Despite this, if we need a higher level of the mass of water before the entrance we can reduce the section of entrance. If we reduce the length of the entrance the height of the water is going to be bigger and this could be interesting for us in the *experiment 5* as we have told before.

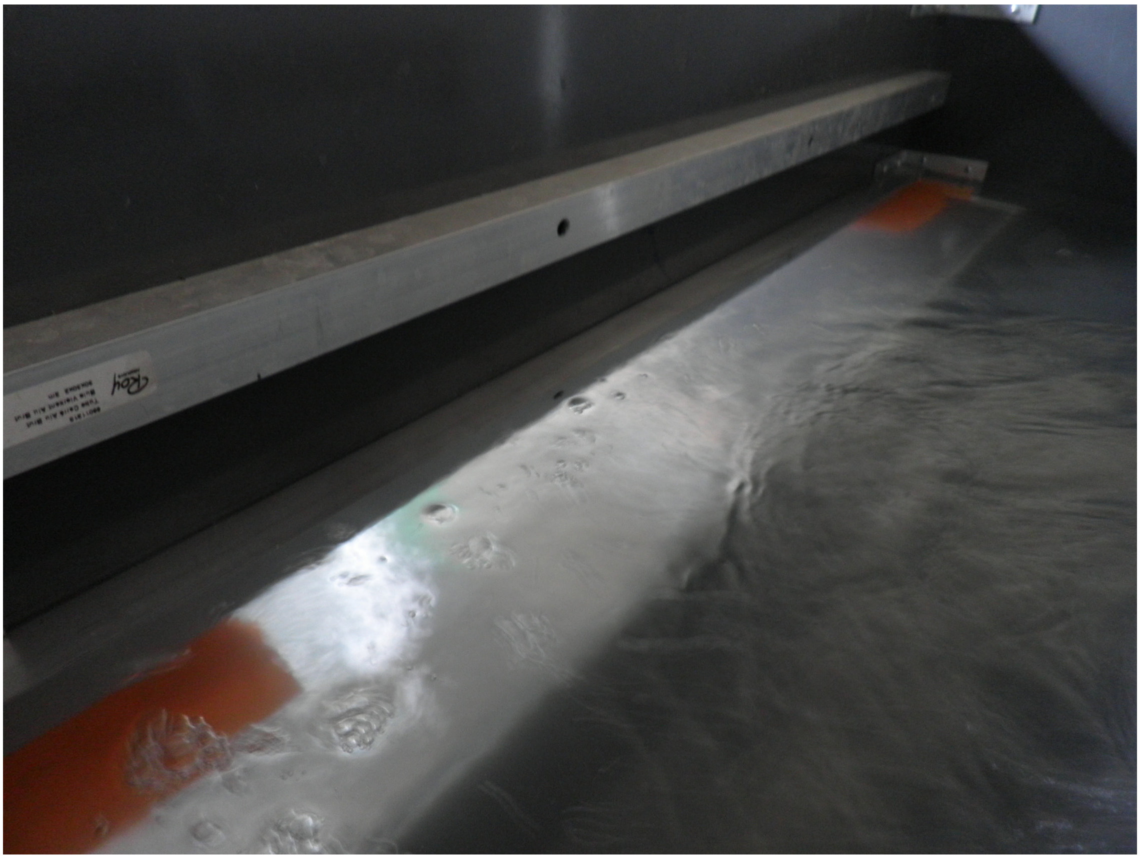
We are going to check it by reducing the section with 30 cm., so now the section is 70cm. We do this with adhesive tape because, although it is not a durable method, it works quite well and we only need to know if it is possible to increase the height; if in the future we decide to reduce it permanently we will do it in another more durable way.



Pic. 25 *The adhesive tape is at both sides of the entrance (15 cm. at each side).*

<u>Results (second part):</u>

Finally the level of water reaches 90 mm. with the opening completely closed. When it is opened the level of water is 15 mm. too, so the range is 15 mm. – 90 mm. with this smaller section of the entrance.

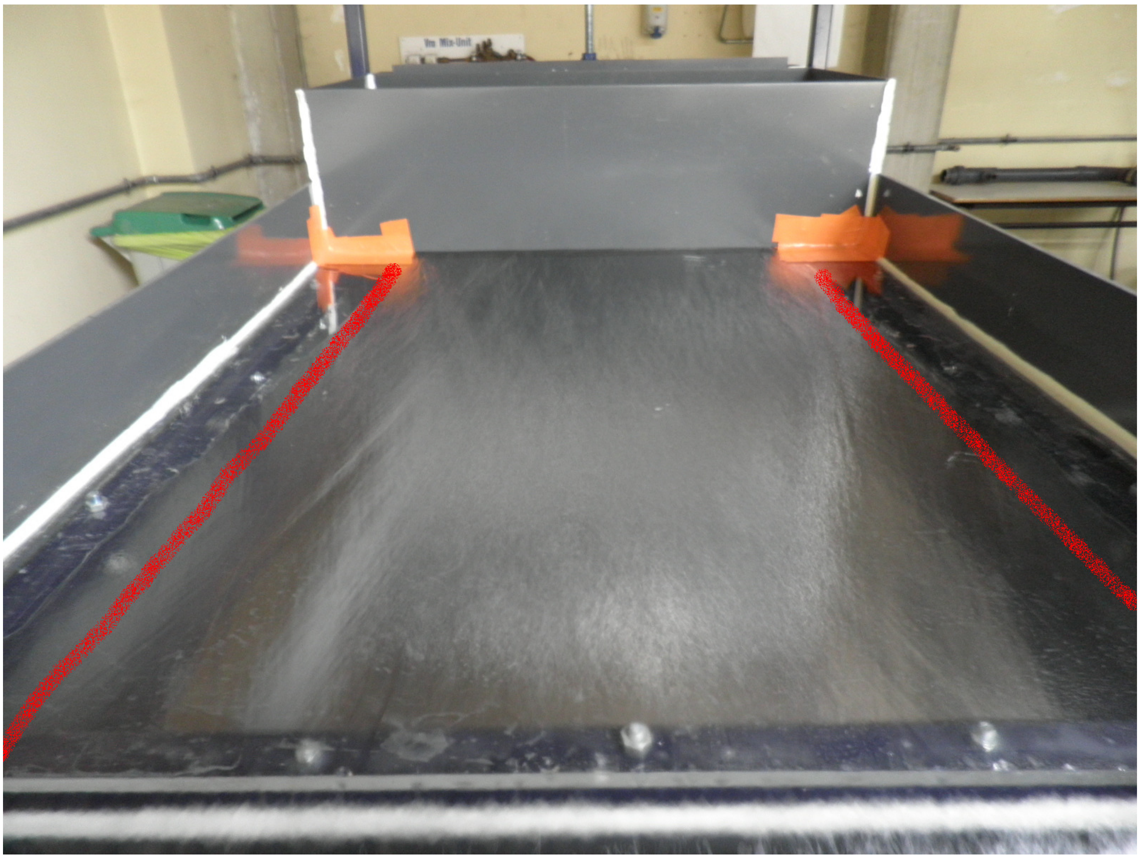


Pic. 26 *It reaches 30 mm. higher with this 70 cm. entrance.*

It is checked that we can change the height of the water by reducing the length of the entrance and this is very interesting for the fifth experiment.

To sum up, we can vary the maximum height of the level of the water before the entrance; if we need to do it in the 5th experiment. We can also increase the range of variation of the speed of the flow, as higher the water is, higher speed the flow has. The speed would be as controllable as in the past, but we could change the speed in a bigger way. We may not need a bigger range of variation of the speed of the flow.

*** Accidentally, this test has shown us also that the flow is more laminar after the third experiment. In the following picture can be seen that the flow follows a straight way on the table, without reflections against the walls.



Pic. 27 *The flow takes quite a straight way. The red lines are fictitious and they are parallel, 70cm. like the section of the entrance that is opened.*

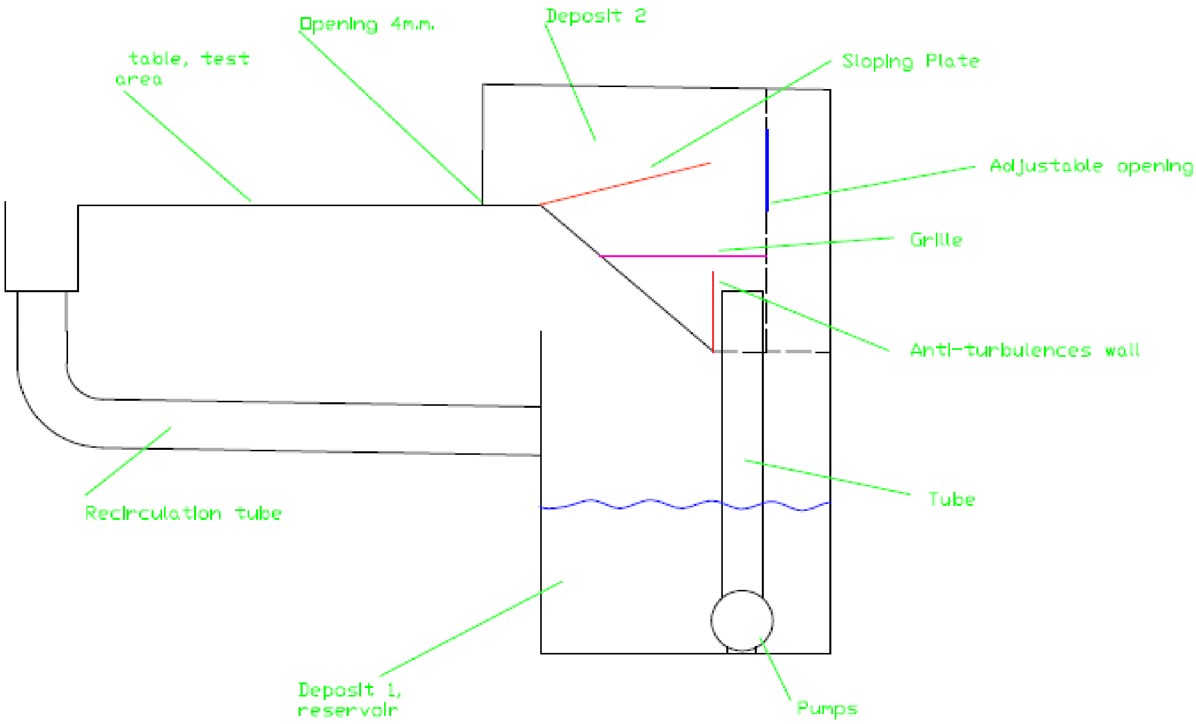
The flow could be affected by the turbulences in the second deposit and this could alter the straight way of it, but in the picture it is proved that it is following more or less the straight way that we mentioned. The flow is quite laminar because it has improved with the sheet and the grille as we thought after the experiment 3. The third experiment eliminated a lot of turbulences in the second deposit, getting us a good result on the test area.

4.5 INSTALLATION OF A SLOPING PLATE IN THE SECOND DEPOSIT WHICH CREATES A THIRD DEPOSIT

We keep on trying to get a non turbulent mass of water before the entrance to the table. Now that it has been checked that we can control the height in the second deposit, we make the fifth experiment and we can do it with different conditions (the water can be higher or less high), because it is easily changeable.

This test consists in displacing a sloping plate (orange line in the plane) that creates a kind of separate third tank where the water is supposed to be calmed. The plate has an inclination that in the future could be changeable depending on our needs. For now we place it with an inclination and in an easy way because this is just an experiment, depending on the results we can think about the possibility of making it adjustable.

To sum up, we want to let the water fall over the plate and this water is supposed to create a volume of water that it is wanted to be no turbulent before the entrance to the table.

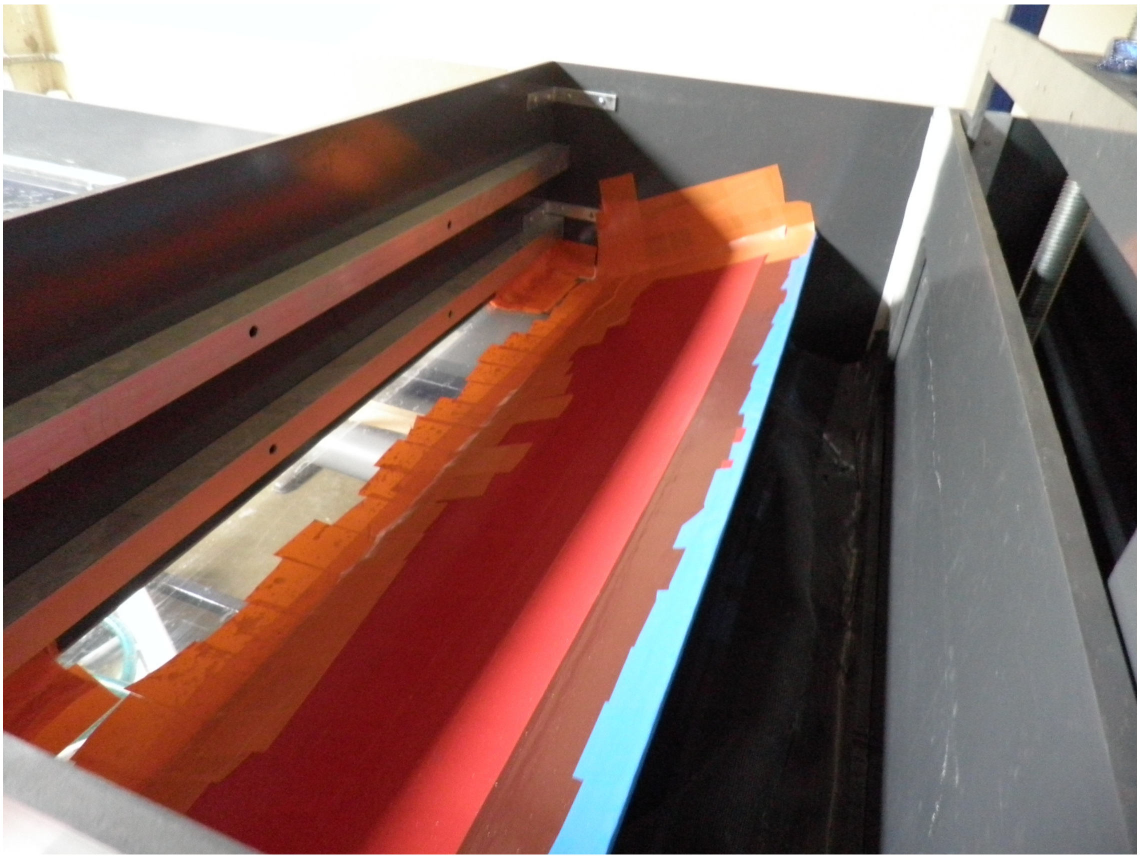


** In this plan it can be observed that we have kept the grille and the sheet. This is because they are working well, so it is thought that they can be part of the final solution and there is no need to take them out.

The sloping plate is made of wood (covered by adhesive tape to make it durable) and its measures are 29 cm. x 100 cm. Adhesive tape is chosen to fix the piece to the table, again an easy and cheap method. The inclination for this fifth experiment is 30 degrees.

First part:

Firstly, we do the experiment with the entrance to the table with an opening of 70 cm., just to reach a higher level of water in the new third tank that is supposed to eliminate the turbulences. The recirculation opening is also initially closed in order to reach the highest level of water.

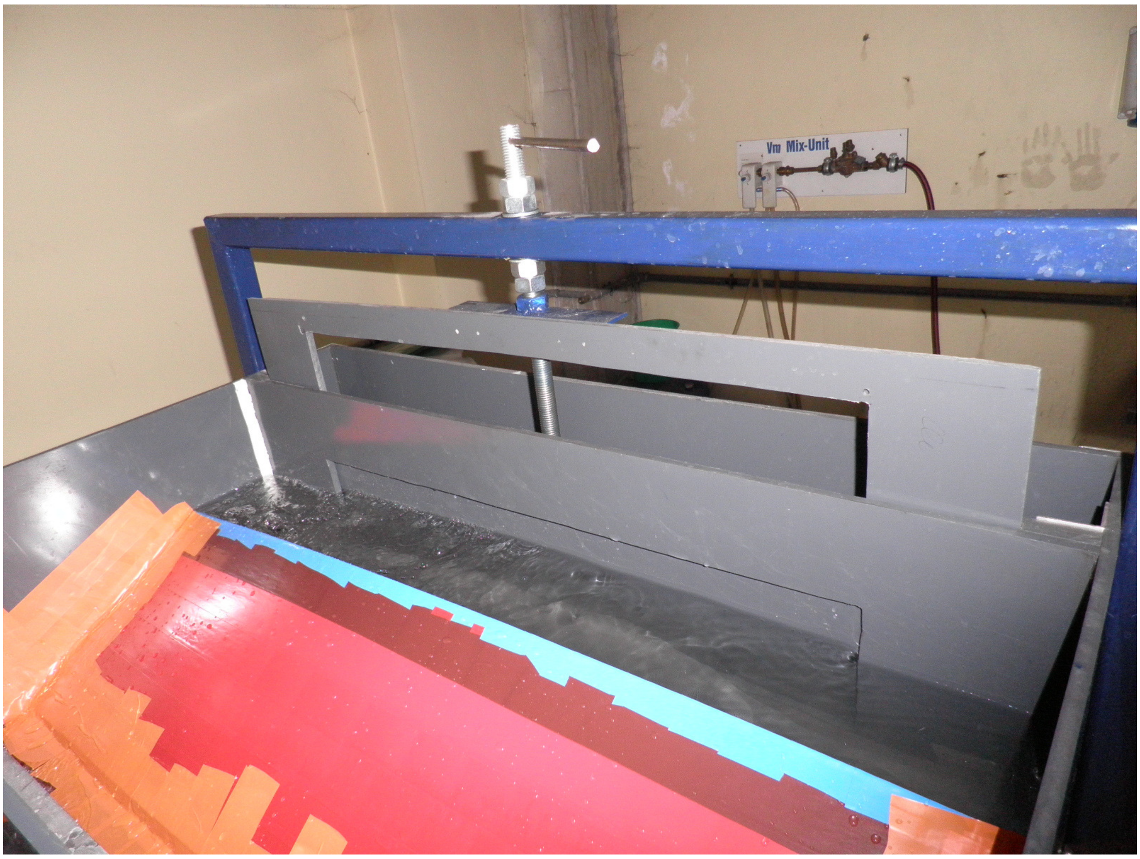


Pic. 28 *Pre-experiment situation; with the opening closed, the entrance with a width of 70 cm. and the sloping plate fixed with an inclination of 30º.*

When everything is ready we turn on the table (two pumps working) and we observe the results.

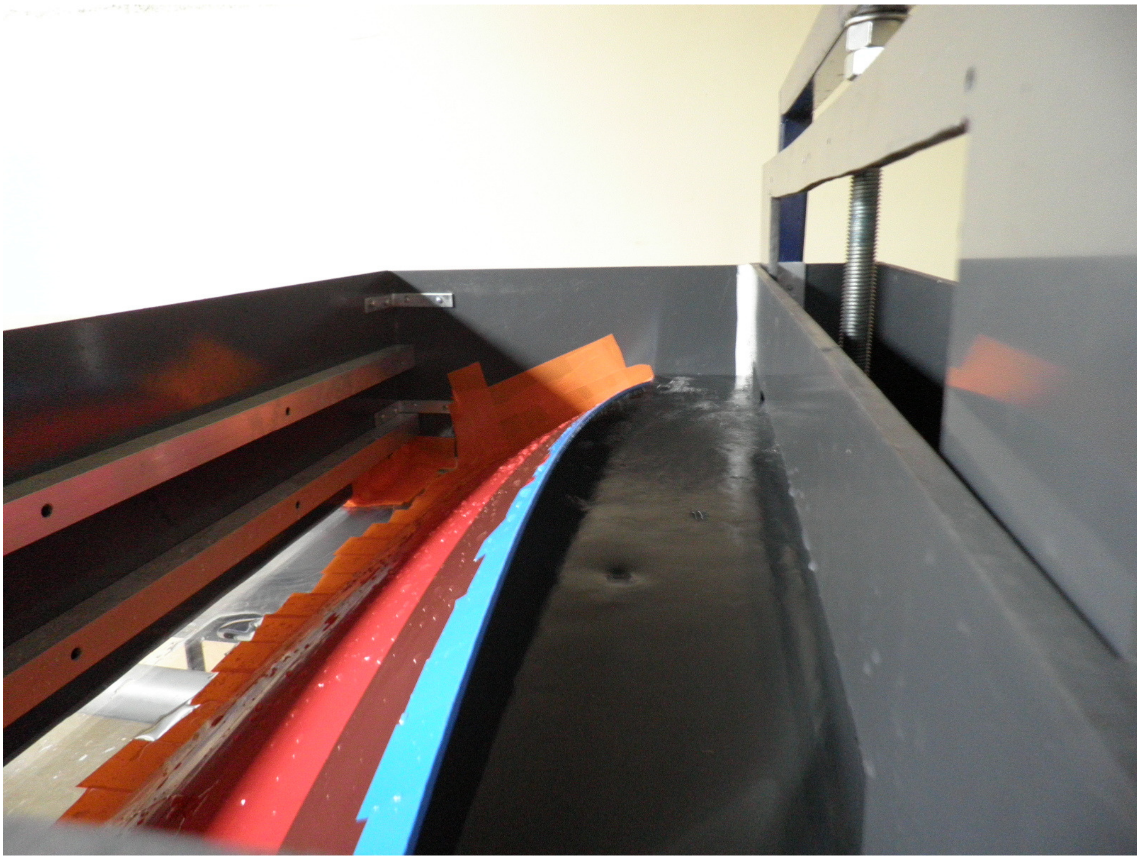
Results (first part):

When it starts working the second tank begins to fill and the water reaches rapidly the top of the plate. Then, the sloping plate begins to flex and the third tank does not receive water at all, so all the volume of flow goes back by the recirculation opening despite this one is closed (there are gaps in the sides). It flexes because the pressure of the water below the plate generates a force in a direction perpendicular to the plate.



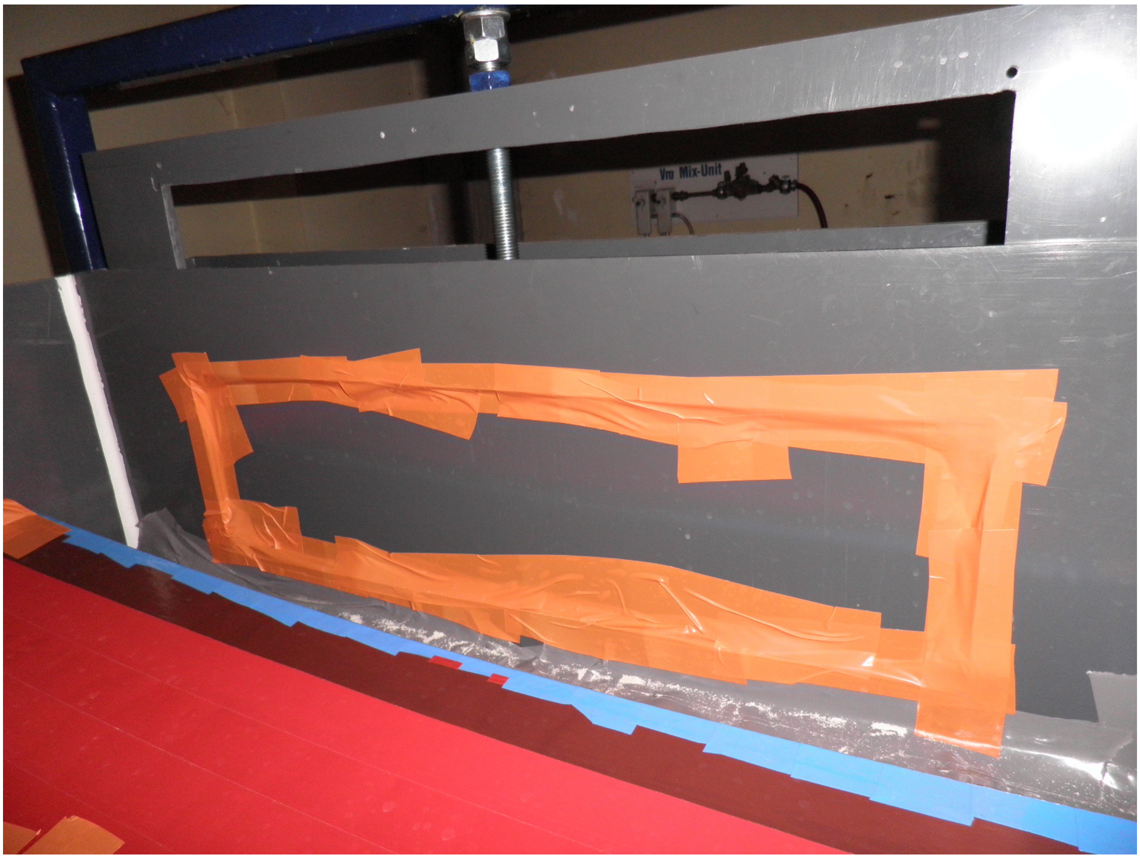
Pic. 29 *The plate begins to flex.*

By the effect of the pressure the water gets access by the sides of the recirculation opening and the plate keeps flexed. Another thing that this experiment has shown us it is that the recirculation opening is not hermetical and the water, in a situation like this one, can go back to the reservoir by its sides.



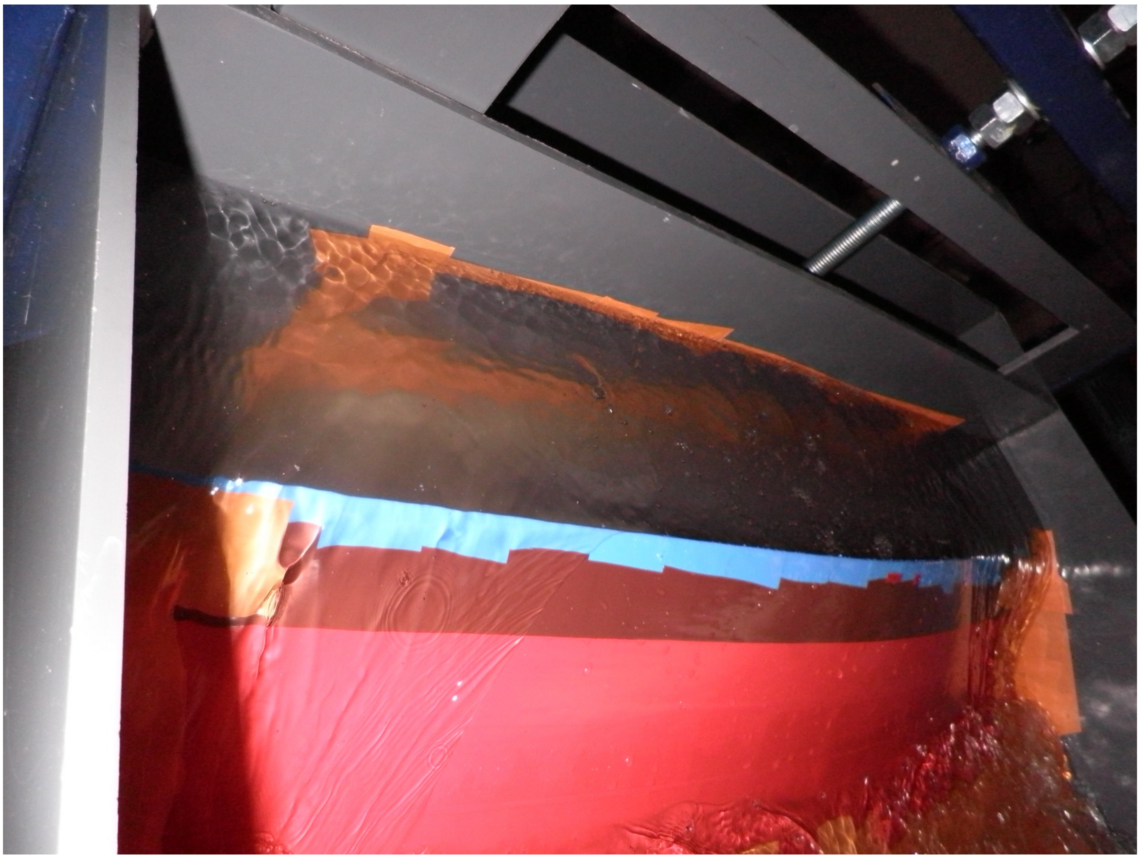
Pic. 30 *As can be seen, the third tank is dry and the water goes back to the first deposit by the opening not hermetically closed at the right part of the picture.*

After this bad result we do a simple adjustment to the test; we make the recirculation opening hermetical by displacing adhesive tape. With this it is expected that the water reach the height of the top of the plate and then, the plate could be straight again; we want to check it.



Pic. 31 *The adhesive tape does not let the water gets by the sides of the opening.*

After displacing this we turn on the table again and the water initially makes the plate flex. The question is whether or not the plate will straighten up once the water starts flowing.



Pic. 32 *The water is going down by the sides of the sloping plate.*

When we reach this point of the experiment, the water starts to go down by the sides of the plate while it is still quite flexed. The turbulences are enormous and the flow is worse than ever. It is still not extremely worrying because it is obvious that it is happening because of the flexibility of the plate.

By now, this experiment does not show too much because the bad results are due to the bad choice of the material. As we want to get more conclusive results we keep on using this test to get relevant information.

Second part:

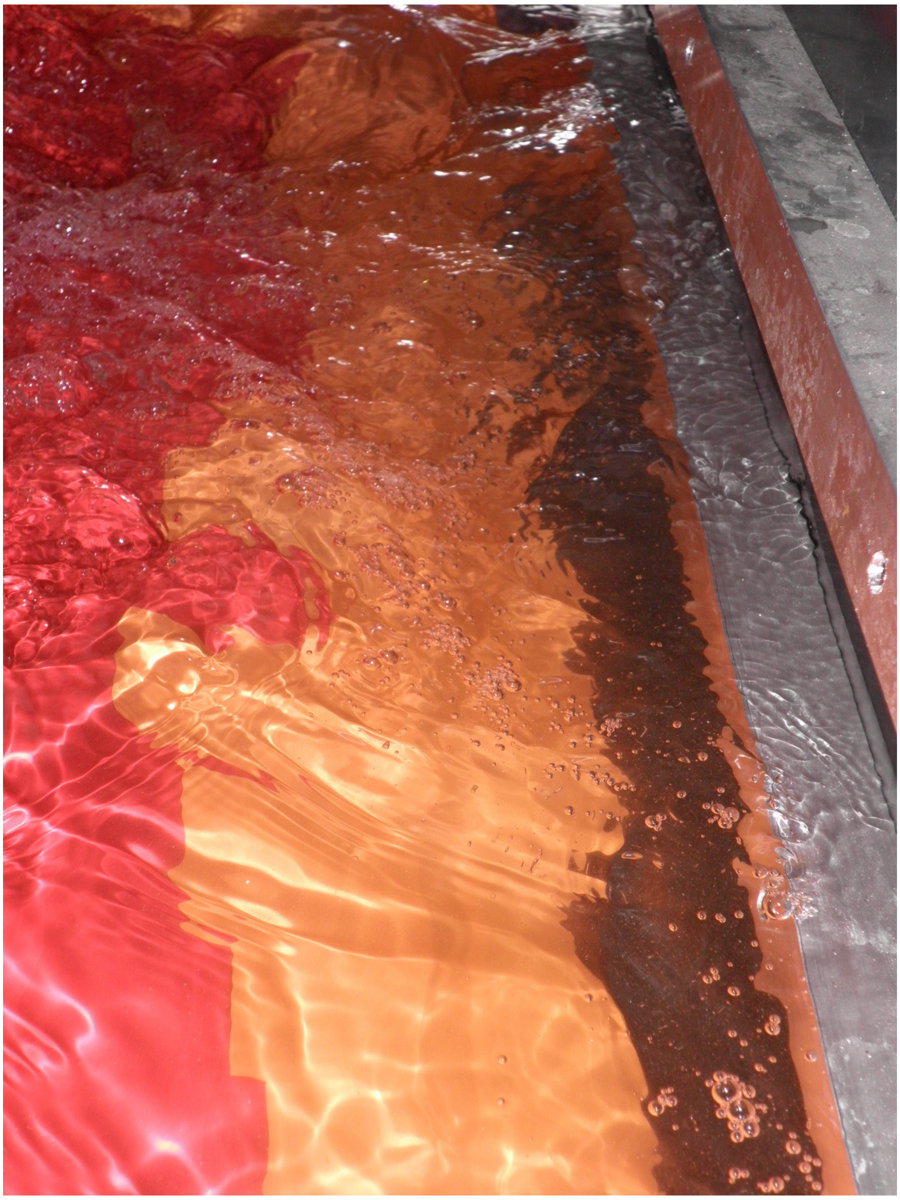
We want to know if it is worth to install a rigid plate or if in contrary, it would not work in our table.

To check if it would work with a rigid plate we press the central part of the plate and the water starts to go down by the entire surface of the plate. When we press this part the plate becomes straight and it works, more or less, as a rigid plate. This test can be good enough to get some valuable conclusions and show us again a way to go on.

Now we can check if the turbulences would be anyway, with a rigid or flexible plate.

Results (Second part):

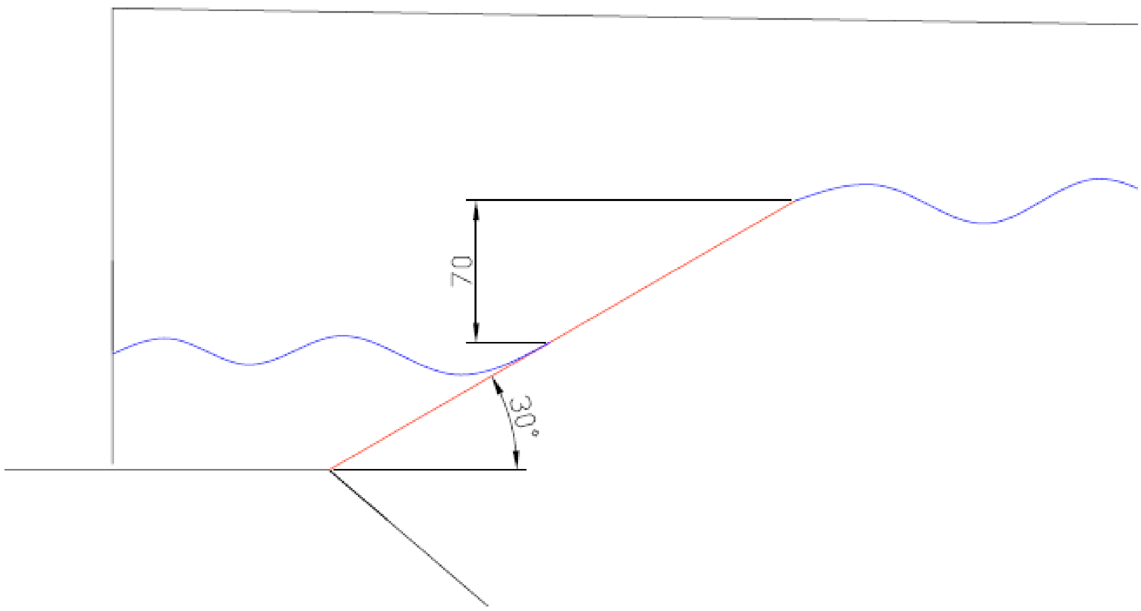
When the flow covers all the plate we can see that the turbulences are still there and they are not caused only due to the flexibility of the plate.



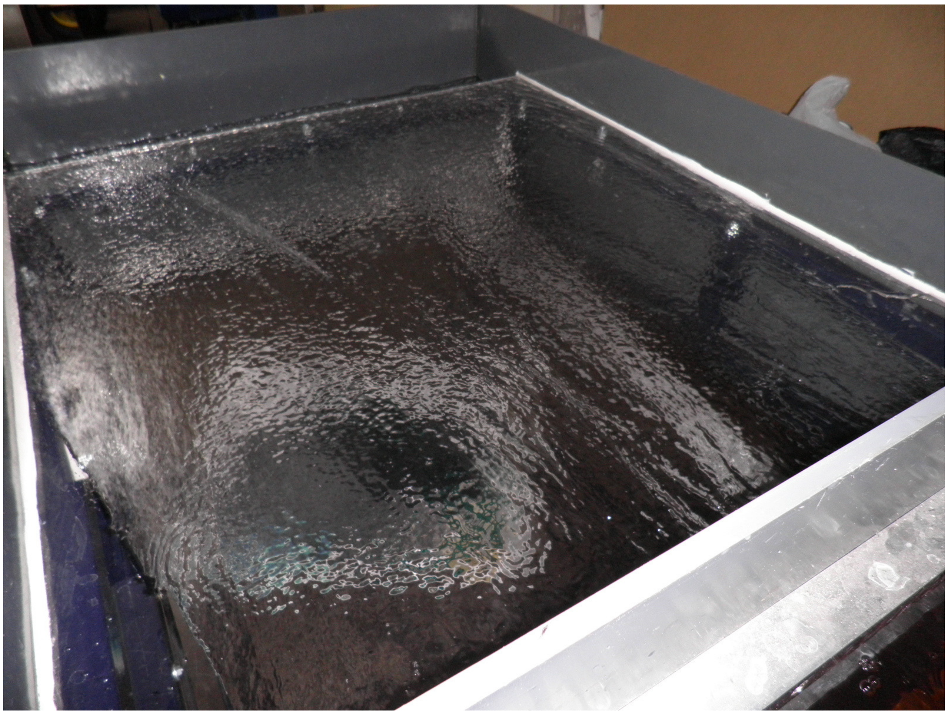
Pic. 33 *Turbulences in the low part of the plate before the entrance ("third deposit").*

These turbulences are created mainly because the water that goes down the plate crash on the mass of water that is wanted to be calmed. We have created a fall of water that is giving us very bad results.

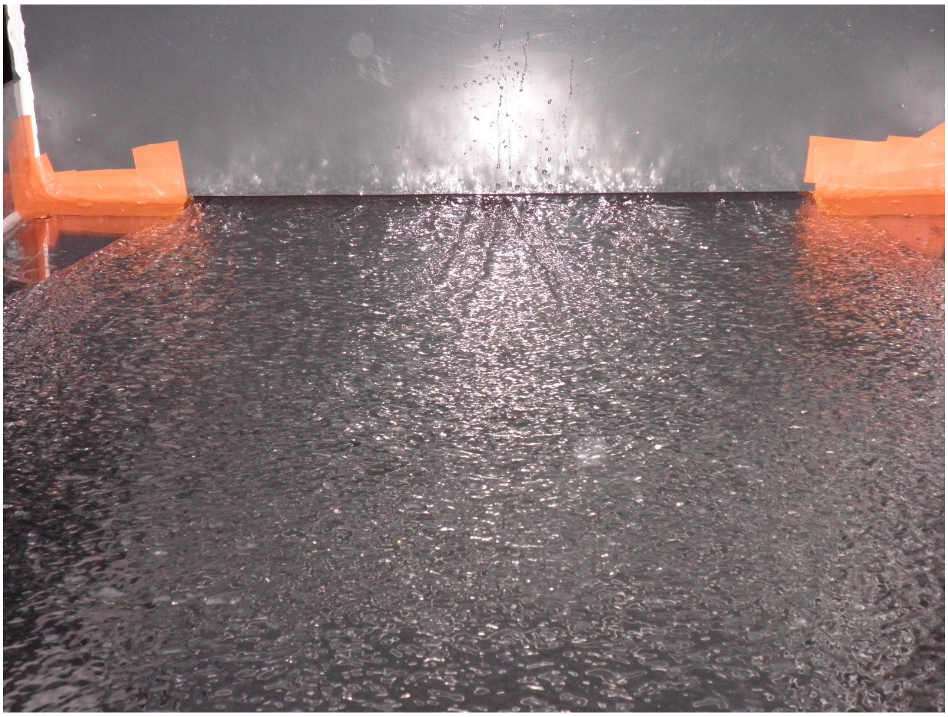
In the plan below it can be seen that the fall of water (of about 70 mm. in this case) creates a turbulent mass of water before the entrance.



With the sloping plate placed in this way the flow is even more turbulent than in the past and it is completely non laminar; it is the worst result of these five experiments.



Pic.34



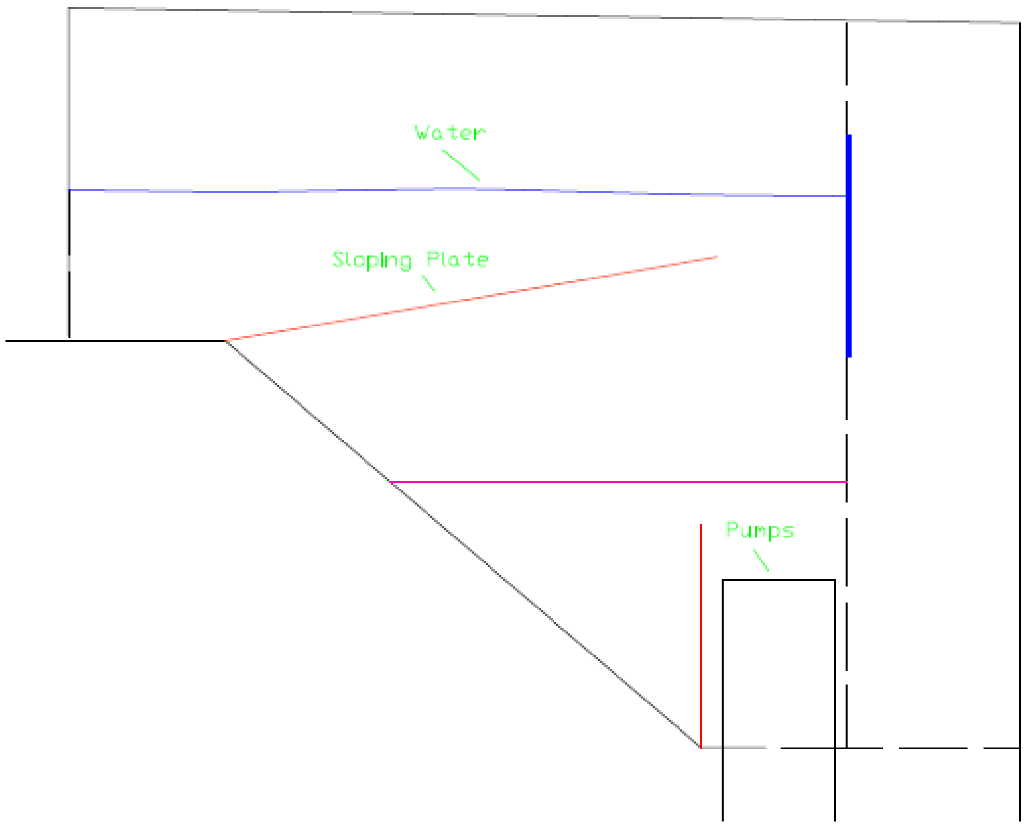
Pic. 35 *In this both pictures a lot of turbulences can be appreciated.*

It is checked that a rigid plate displaced in this way will be also inefficient, because the turbulences are caused by the fall of water. We cannot work with such a big fall because it originates too many waves and shocks before the entrance.

We do not try this experiment with one pump working because the fall would be even bigger and the result would be worse.

To sum up, it is checked that it is not worth to place a sloping plate with this inclination to create a third deposit with calmed water. The fall that is created makes all the previous efforts to make the mass of water calmed useless. The turbulences before the entrance have made decrease the speed of the flow, but with a lot of turbulences and reflections; this make this achievement not useful at all.

But what is learnt in this experiment is always useful and it can help us in the future. For example, we can still place a sloping plate with a lower inclination that does not create a big fall or even with the level of water above the top of the plate. If this is done we do not create a third deposit but the turbulences can be also reduced. This is verified in the *6th experiment*.



If we want to place this sloping plate in the future this experiment has shown also that the materials and the finish should be of a higher quality.

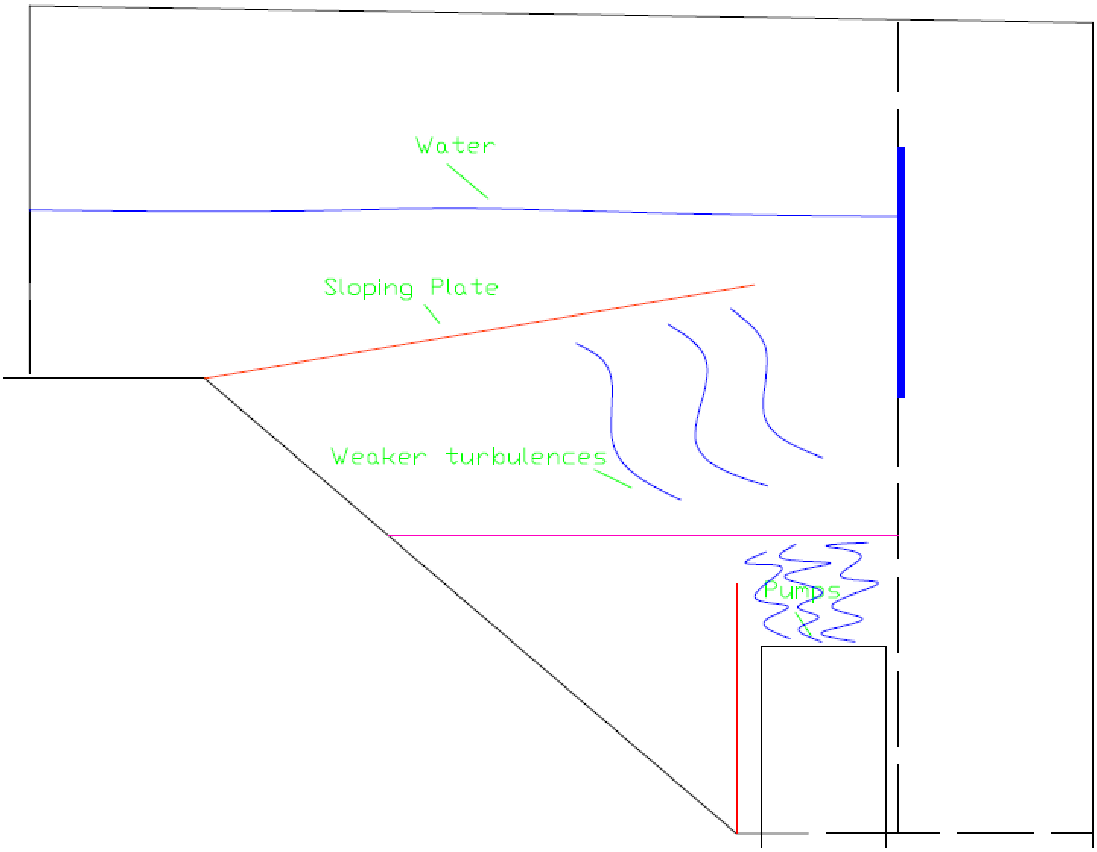
4.6 INSTALLATION OF A SLOPING PLATE MADE OF A RIGID MATERIAL IN THE SECOND DEPOSIT UNDER THE LEVEL OF THE WATER

This experiment is based on the results and conclusions of the fifth experiment. The fifth experiment showed that, first of all, we have to use better materials and a higher quality finish in the placement of the sheet (sloping plate). Secondly, we must eliminate that fall that creates so many turbulences before the entrance.

So this experiment is not focused on creating a separate and calm third deposit, but in placing another element, like the grille and the plastic sheet, that contributes to eliminate the turbulences in the second deposit. Following with the intention of the last experiments what is tried is to get a laminar flow by making the turbulences caused by the pumps disappear before the entrance to the table.

As it is done in the fifth experiment the grille and the plastic sheet are not removed from the table because they are working well.

The idea is that the turbulences that are still in the deposit after passing through the plastic sheet and the grille will find the plate and it will reduce them letting a calmer mass of water before it goes in the table by the entrance.



Schematic plan of the second deposit: The turbulences are less powerful after the grille and the sheet and then, they find the sloping plate.

The sloping plate is made of a piece of rigid wood that cannot flex with the pressure that is supporting. It was seen in the fourth experiment that, without reducing the section of entrance, the height (from the level of the table) of the mass of water before this entrance has a range of variation of 15-60mm. According to the purpose of this experiment and the condition that it is mentioned before (to eliminate the fall of water by the plate) the top of the plate cannot be much higher than the mass of water, so we have to take this into account to place the piece of wood

Finally, due to the conditions imposed, the piece of wood is going to have the dimensions of 452 mm. x 1000 mm., placed with an inclination of 3º so the top of the plate is 25 mm. high from the level of the table (Pic. 36). As it is only this high, the biggest fall that we can have with the regulated opening completely opened is 10mm. and it is not enough to create important turbulences. When the regulated opening is closed a little bit, the fall of water disappears and the level of water is above the top of the sloping plate.

Pic. 36 Sloping plate in the second deposit

In the following plan what has been mentioned in the last paragraph can be observed for a better comprehension.

PLAN

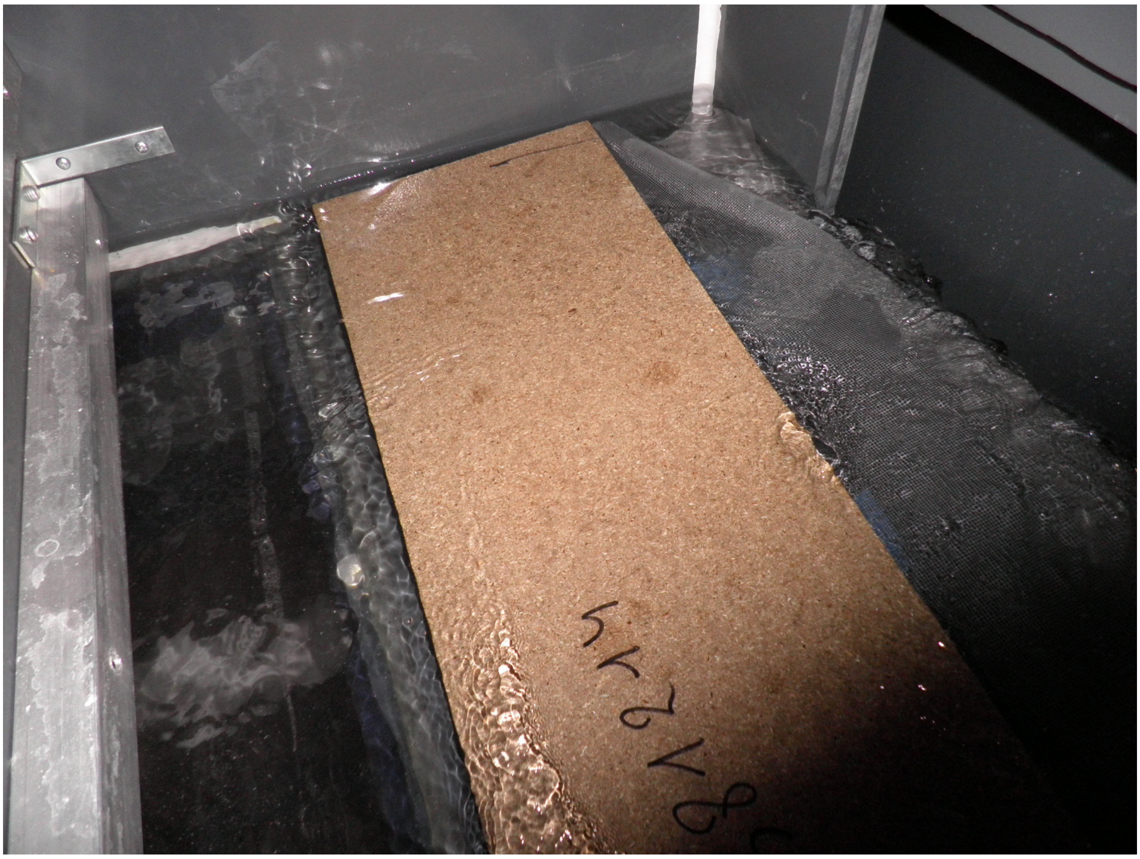
Water Table experiment 6 pdf.

After displacing all as it is showed in the last plan, the table is switched on and we observe the results to check if our predictions (the turbulences are going to decrease) are correct.

Results:

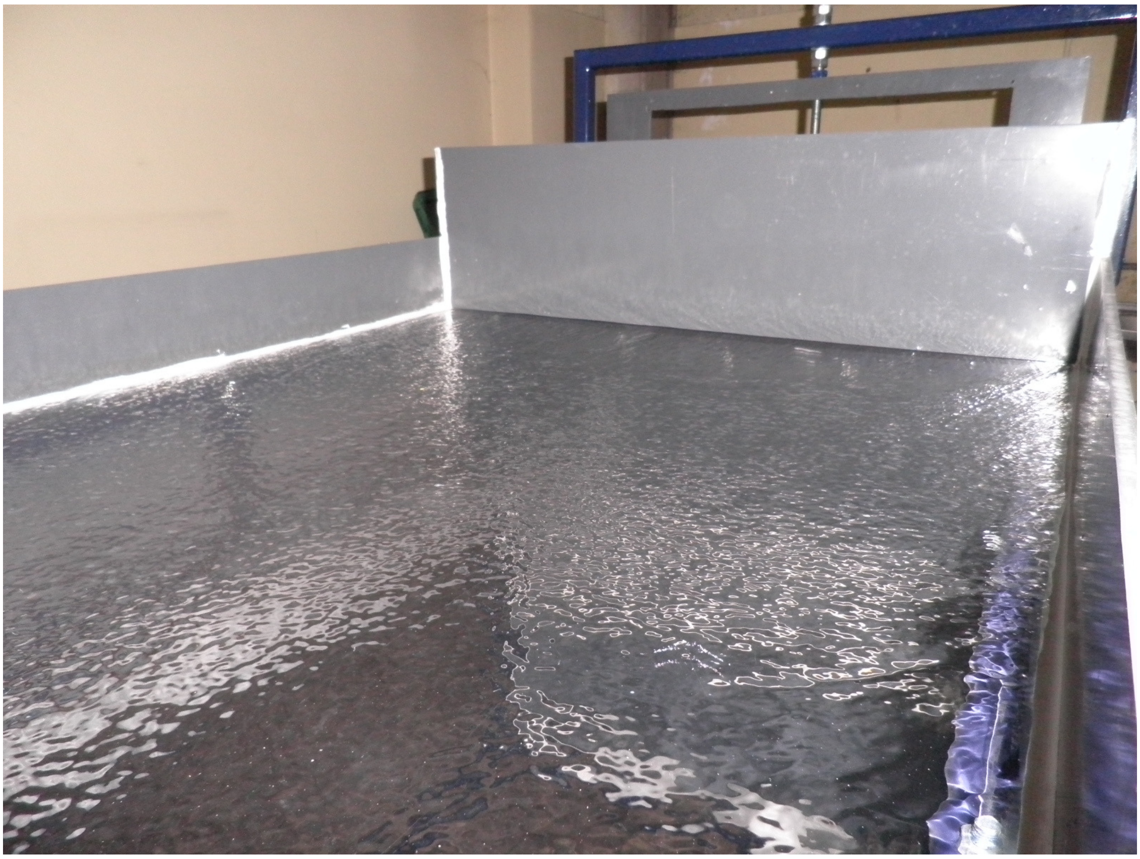
All the materials are supporting the efforts in a correct way and the experiment works without any inconvenience related with them.

Both pumps are switched off and we do tests at 15mm high, 30mm and 60 mm. high. It has to be underlined that the fall of 10 mm. that is formed when the level of the water is 15 mm. high does not form significant turbulences before the entrance.



Pic. 37 *The 10mm. fall does not create big turbulences before the entrance.*

In all the cases the flow has been quite laminar; but we do not find a big difference between this result and the result of the *experiment 3*.Anyway, as it can be seen in the picture below, the result is quite good.



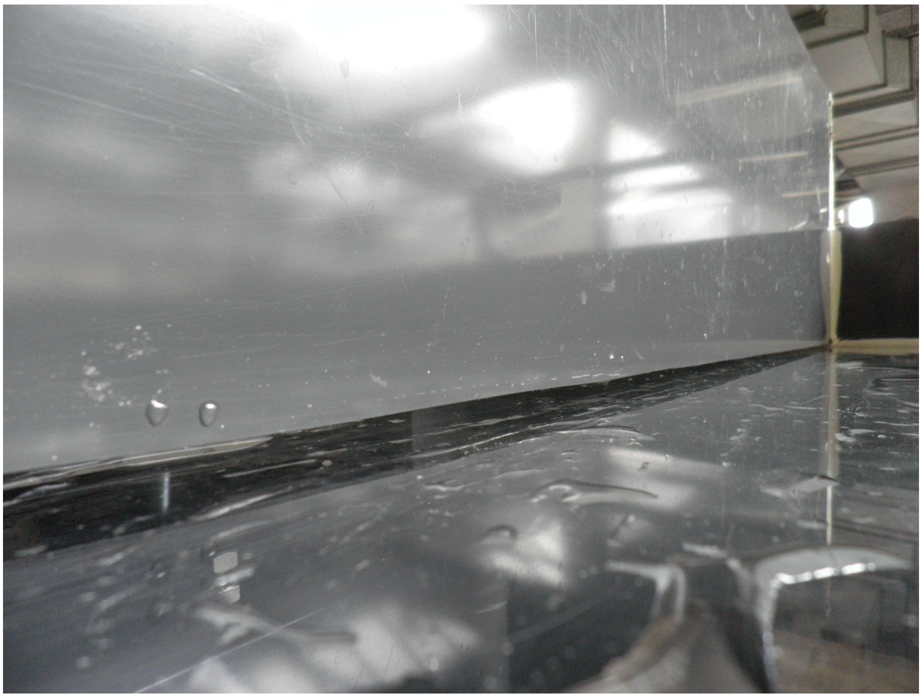
Pic. 38 *Smooth flow with both pumps working*

When only pump is working the result is also similar to the one after the *experiment 3*.

It can be concluded after this experiment that the sloping plate may help to eliminate the turbulences, but it is not decisive in the purpose of getting the laminar flow; with the plastic sheet and the plastic grille *(Experiment 3)* the same result seems to be reached. Anyway, we have a good result.

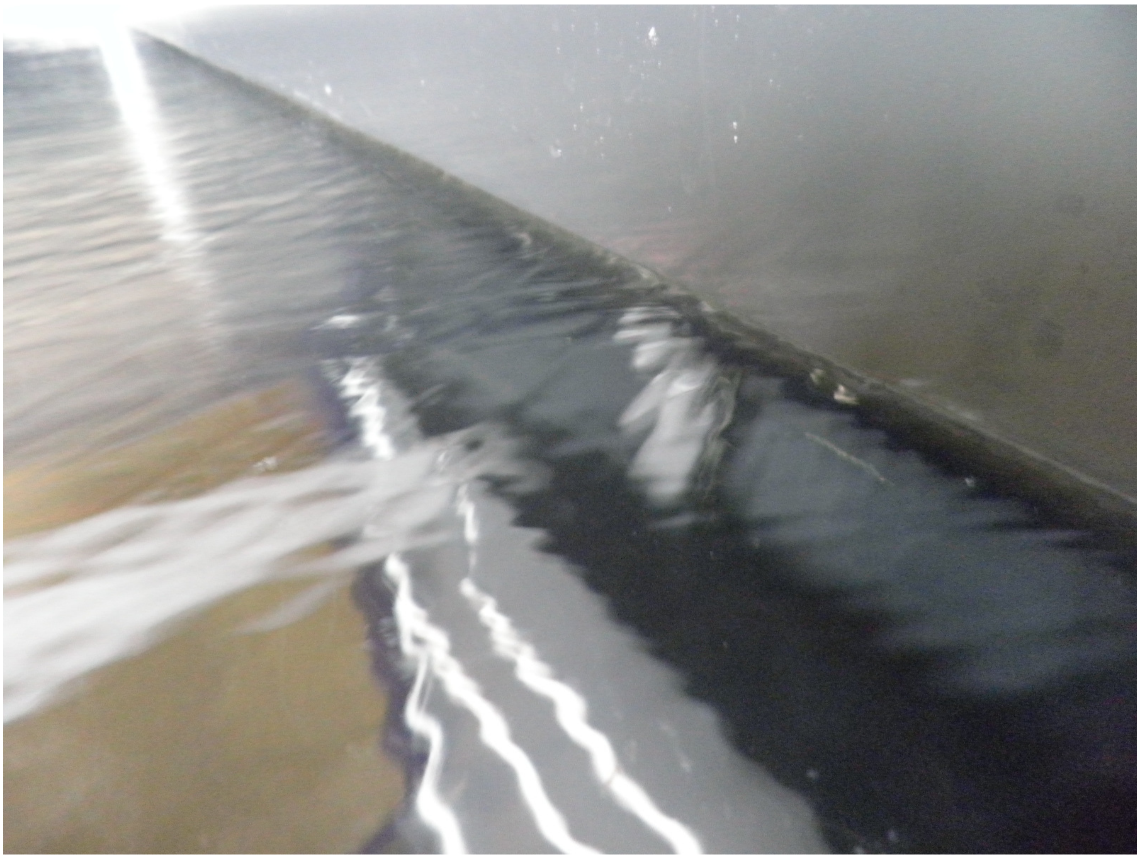
The result is quite good but, as it is mentioned in the conclusions (in the *results* part) of the experiments 2 and 3 , the space in the second deposit could not be big enough to make the mass of water completely still before the entrance and getting a perfect result. This experiment is going to be decisive in the election of the next test as it is going to be written in the introduction of the *experiment 7*. The result is good but another experiment *(experiment 7)* is made trying to check all the possibilities.

***There is another fact that is affecting our flow, the irregular section of entrance.



Pic. 39 *The entrance to the table is not completely regular*

Despite the entrance is supposed to be in all its extension 4mm. high, if this is checked carefully, in some parts the height varies, being even only 2 mm. high. Also the cutting that was made to create this entrance has not a well finish and some defects make the flow have some lines on its surface (small disturbances, see Pic. 40).



Pic. 40 *Some small disturbances appear after the entrance due to the bad finish of the cutting.*

This experiment has shown us another problem that may cause not to get a perfect laminar flow; but **it does not seem to be a big problem and there are minimum disturbances.**

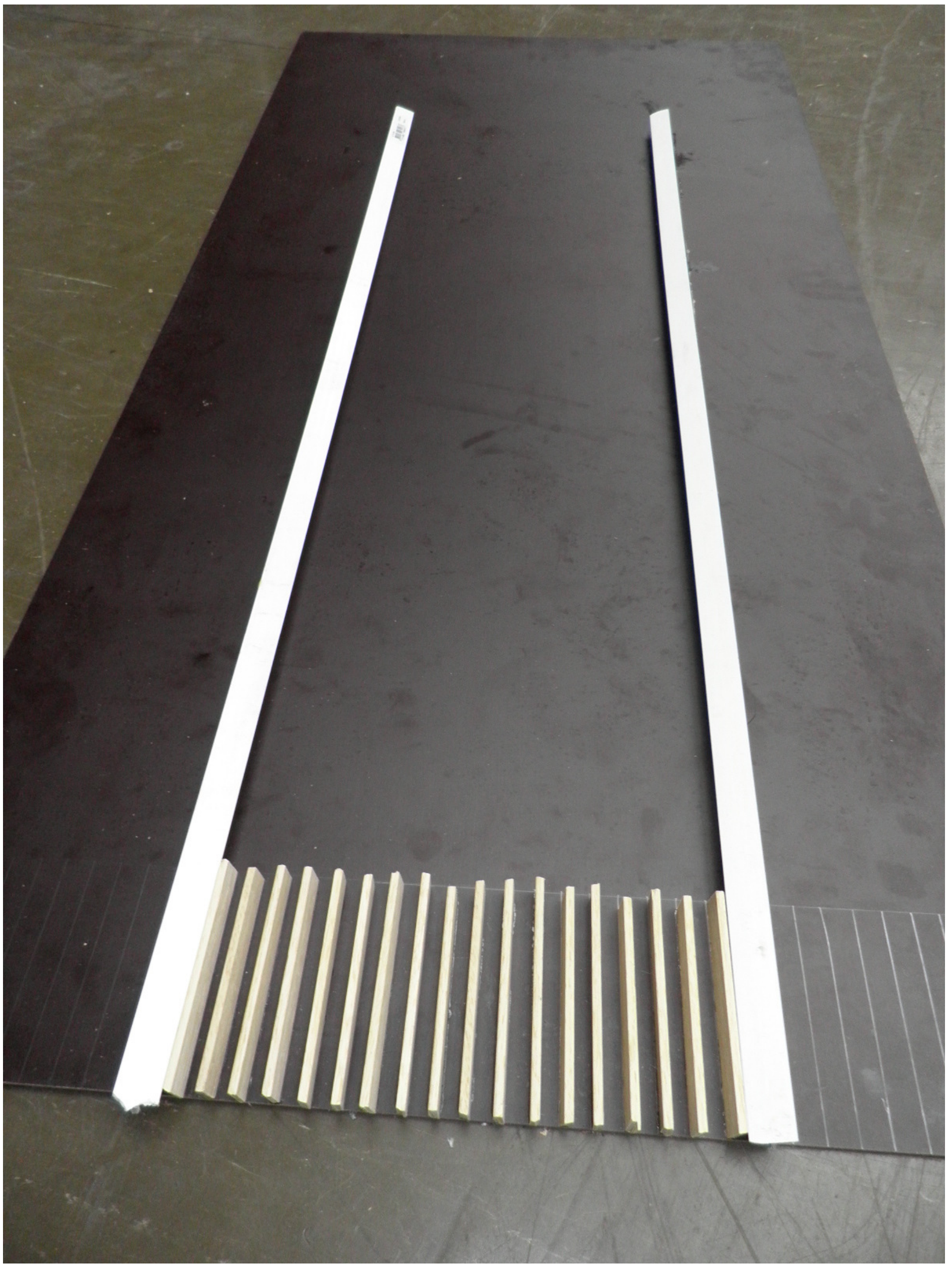
4.7 GETTING A LAMINAR FLOW AFTER THE ENTRANCE BY PLACING TRACKS TO GUIDE THE WATER

As we have mentioned in the conclusion of the *6th experiment* the result is quite good and the shock waves are well seen. But another system to get a perfect laminar flow and getting a clearer image of the shock waves is going to be tried. The space in the second deposit is almost over to place new elements and it is interesting to try something after the entrance.

It would be very interesting to get a smoother flow on the table than the one that is actually got with one pump; if the result after the *experiments 3 and 6* is good, the result with a smoother flow could be excellent.

Despite this, the new system is tried with one and both pumps working, just to check the results.

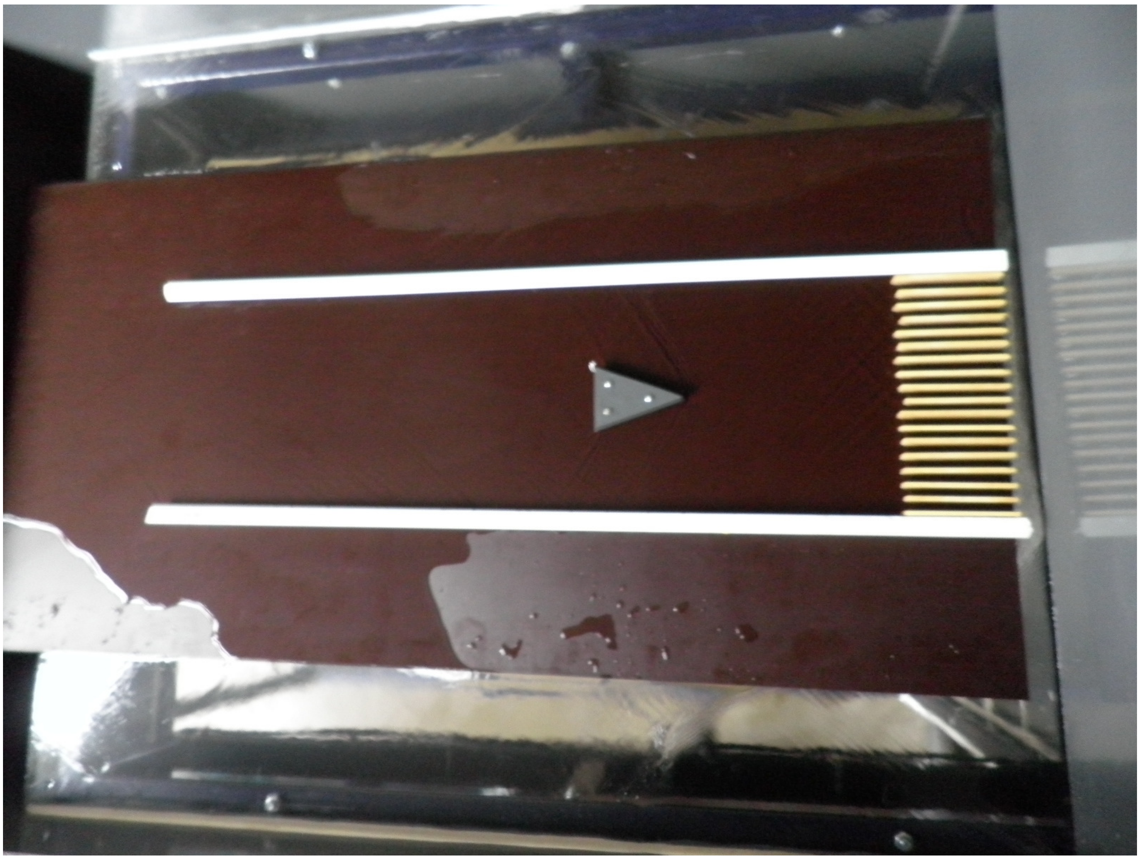
It consists in a very thin sheet of wood (125 cm. x 65 cm., thickness 2 mm.) that is placed on the table, This sheet is our new test area´s surface and the solid models will be placed on it. At the beginning of the sheet, rectangular pieces of wood (11 cm. x 2 cm., thickness 2 mm.) are placed creating between them tracks. With tracks it is meant a straight way by where the flow is going to pass through.



Pic. 41 *The test area is between the white plastic walls; the water starts to flow by the tracks and after, it gets into the test area.*

The distance between the rectangular pieces is 13 mm. and the length of the section between the white walls is 35 cm. The space between the white walls (plastic) is going to be our test area and the rest of the surface on the sheet and on the table is not interesting for us.

The sheet is placed on the table as it is seen in Pic. 42, just after the entrance of the table.



Pic. 42 *The water goes over the wood sheet and it finds the test area*

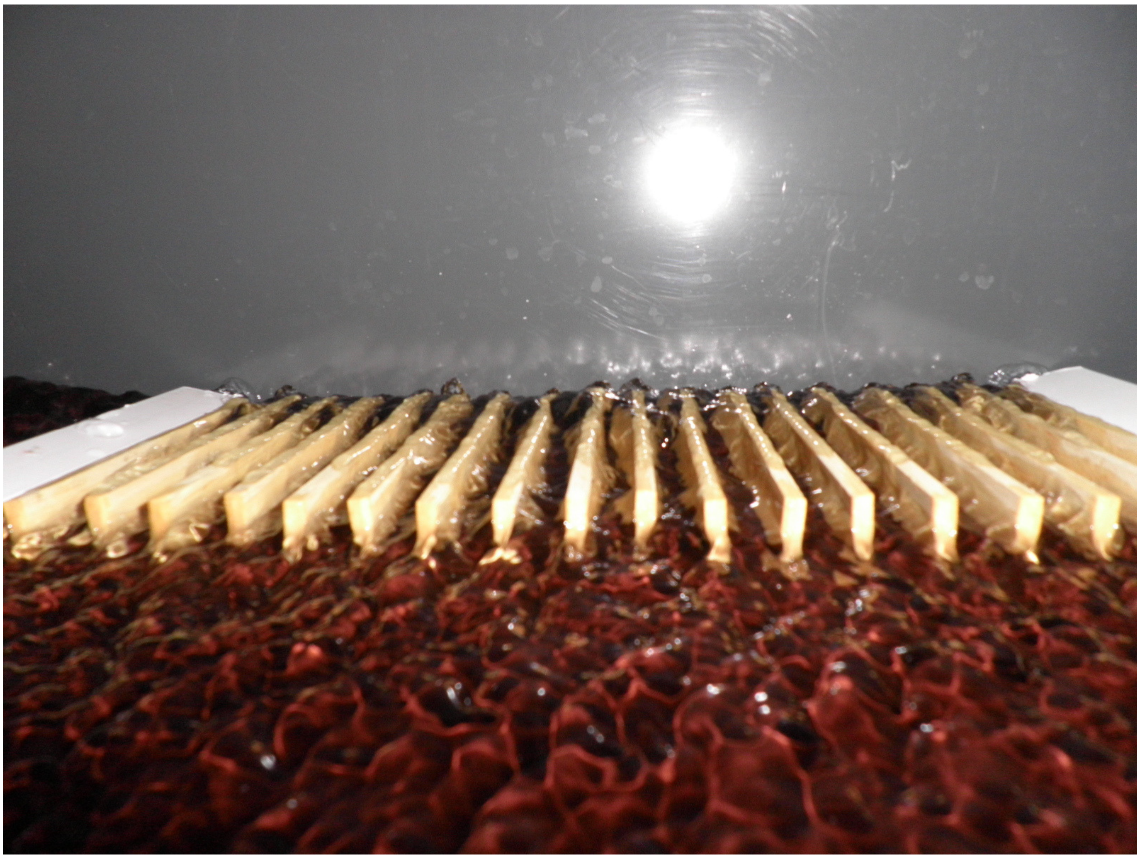
The purpose of this experiment is to check if the speed of the flow can decrease and if the tracks let a good laminar flow. The tracks are supposed to make the water go in a straight way.

When all is placed we switch on the pumps and the water passes by the tracks and over the sheet.

<u>Results:</u>

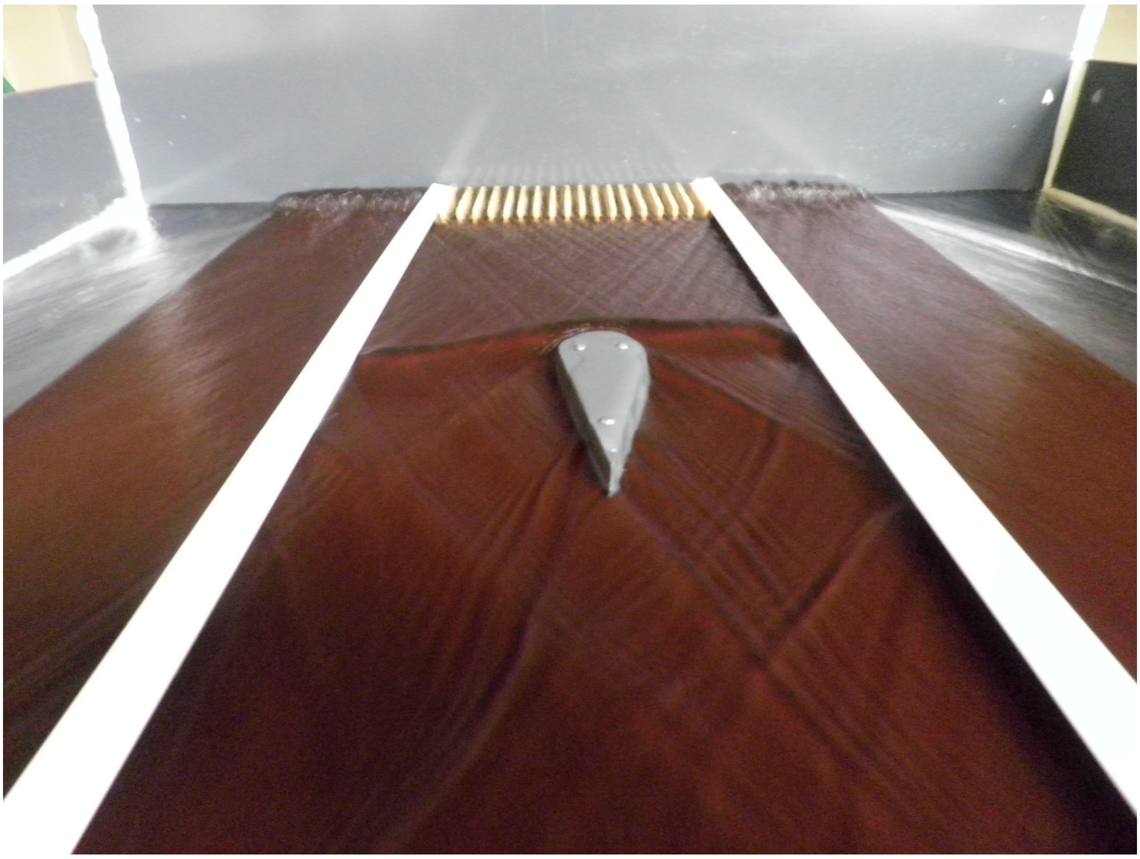
Firstly, **both pumps are switched on** and the water starts to pass through the tracks. The water goes into the sheet and when is in the tracks it turns into a completely no laminar flow.

As it can be seen in Pic. 43, the water goes over the pieces of wood because the volume of flow is too high, so a lot of reflections and turbulences come out from the tracks and go into the test area.



Pic. 43 *A lot of turbulences come out from the tracks.*

If the test area is observed there are a lot of reflections against the walls; and if a solid body is placed on the test area to see the shock waves, the result is horrible. The shock wave created by the model in the Pic. 44 is a sample of how the new system is working with both pumps working.

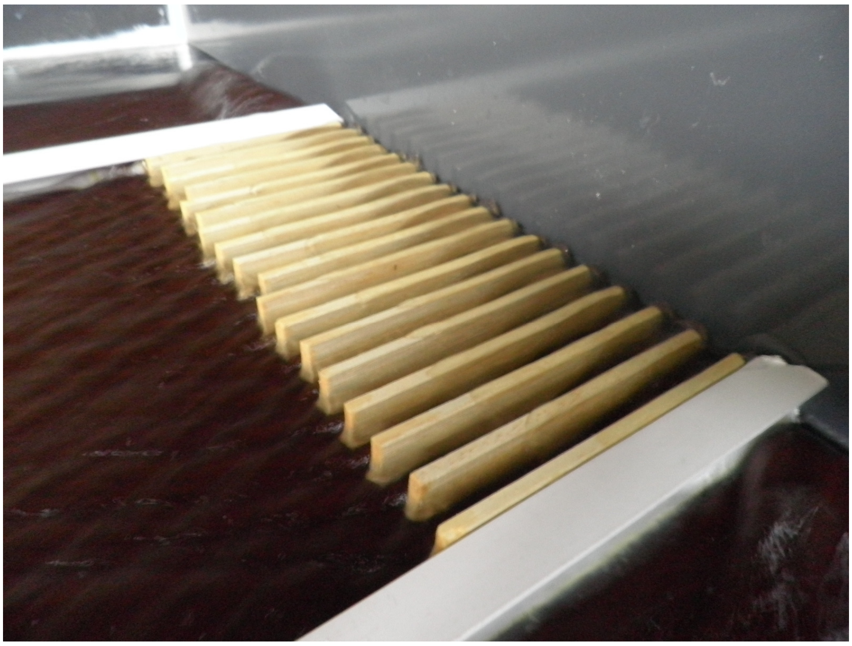


Pic. 44 The shock wave is not so clear and also the section is too small for the speed of this flow.

After this bad result one pump is switched off and the experiment is done with only one working.

When only **one pump is working** the result is very good. After the tracks the flow is the smoothest that we have ever got and the test area seems to be a good place to work.

Pic. 45 *The test area is free of important reflections. Out of the test area the water does not flow very well, but this is not important at all.*



Pic. 46 *After the tracks thin oblique lines appear in the water, but they are very soft and they do not affect the flow.*

If a solid body is placed in this smooth flow, the shock wave that is formed around it is very clear, so the result that we have got in the test area is very good.

Pic. 47 *Clear image of a shock wave in the test area.*

In conclusion, in this experiment it has been checked that this system is not useful if we are working with both pumps switched on. However, the result has been excellent when only one was working, being the best result ever. The shock waves are clear and their shapes are caused by the pass of an excellent laminar flow.

4.8 CONCLUSIONS

All these previous experiments done are focused on the goal of this thesis; *to optimize the water table to visualize shock waves and vortices in the water flow.*

So in this part of the thesis it is going to be explained the best way of reaching this goal according to the experiments made.

The best result with both pumps working is in the *experiments 3 and 6.*

The best result with one pump working and also the best result ever is in the *experiment 7*.

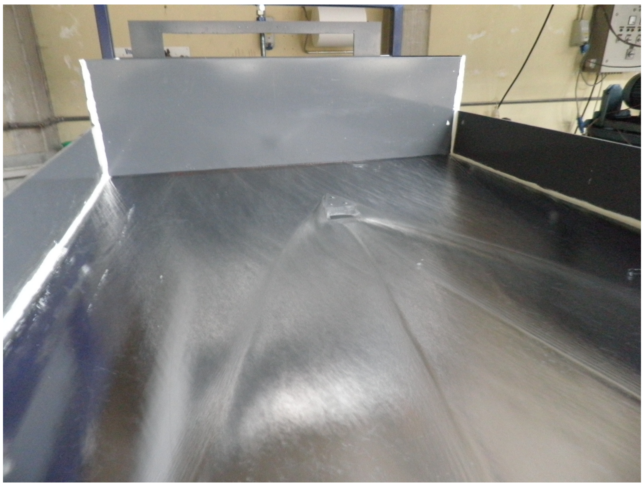
In both cases the table will be built permanently as it is shown in the plan *Design: Water table plan* (at the end of *Conclusions*), which is exactly the same as *Water table plan experiment 6.* The sloping plate can be maintained or removed because not big differences have been found; it is a matter of checking it during the definitive process of construction. In the definitive water table construction the plastic sheet and the sloping plate would be placed in the second deposit with silicon; the plastic grille would be rigid made of a metallic material (placed with silicon too).

The difference in the table between the both cases is that, when we work with only one pump, the wood sheet with the tracks will be placed on the table (Pic. 57 and 58 at the end of *Conclusions*).

Both pumps working:

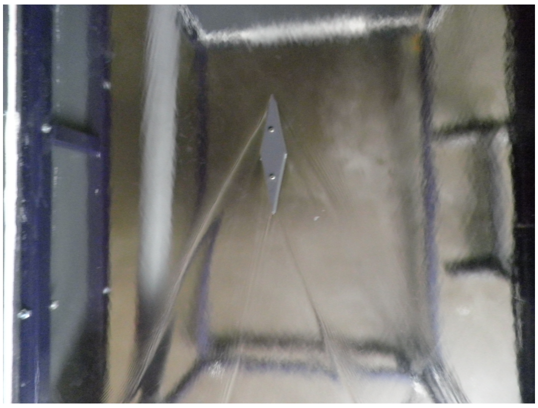
Even the result with only one pump is the best, it is important to work also with both pumps because the speed of the flow can vary by changing the height of the mass of water before the entrance (adjustable opening).

Solid bodies are placed on the table to see the shock waves, which are clear as it can be seen in the following pictures.



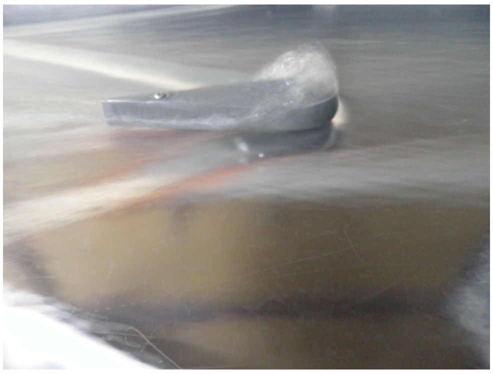
Pic. 48 Shock wave 1.

Pic. 49 Shock wave 2.



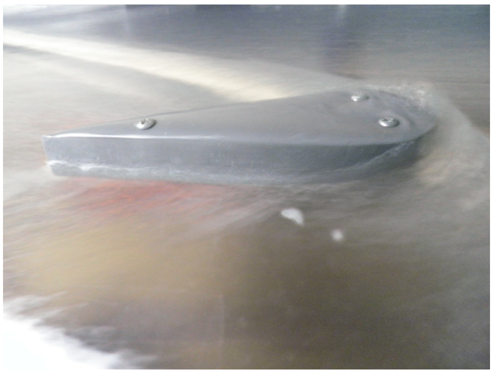
Pic. 50 Shock wave 3.

But the following pictures show that there is a problem caused by the high speed. A jump of water appears when the flow finds the solid body. Depending on the height of the water before the entrance (which controls the speed of the flow) this jump is bigger or smaller as it is checked in Pic. 48, 49 and 50.



Pic. 51 Height of the water: max, 60 mm.

Pic. 52 Height of the water: 37.5 mm.



Pic. 53 Height of the water: min, 15 mm.

This jump of water makes the shock wave less clear, despite having quite a good result.

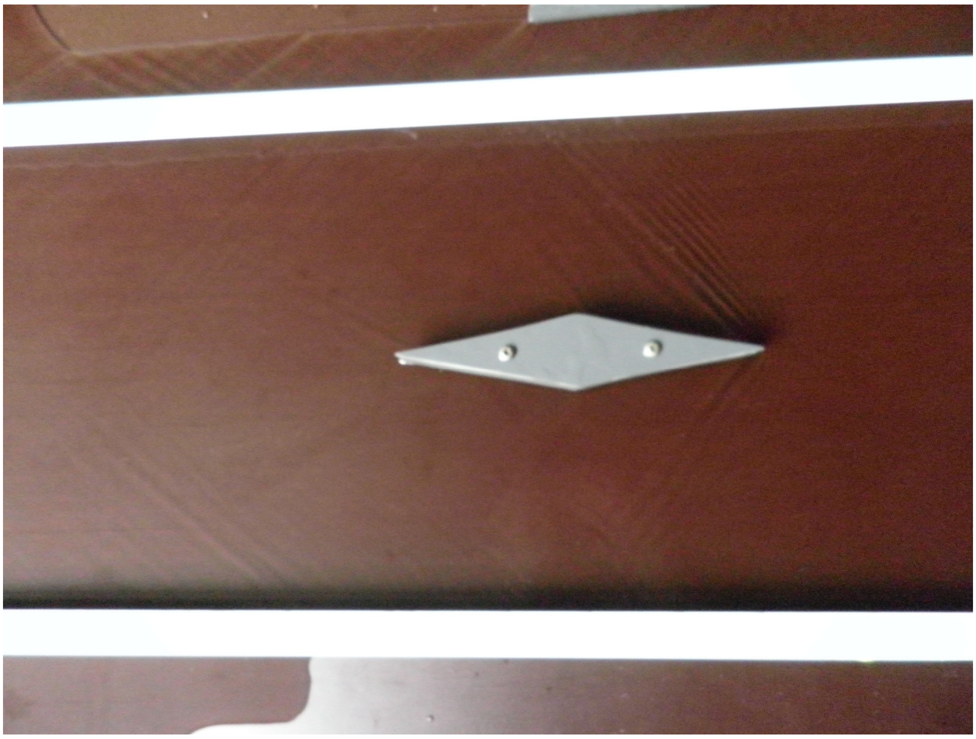
Both pumps working give us a good result, worse than with only one; but the good point is that the speed of the flow can be controlled by controlling the height of the water before the entrance of the table (adjustable opening). It is thought that a bigger range of variation of the speed of the flow is not needed.

<u>One pump working:</u>

The best result is when only one pump is working and the wood sheet is placed on the table.

When the solid bodies are placed on the test area the images got are very clear as it is seen in Pic. 51, 52 and 53.

Pic. 54 *Shock wave 1.*



Pic. 55 *Shock wave 2.*

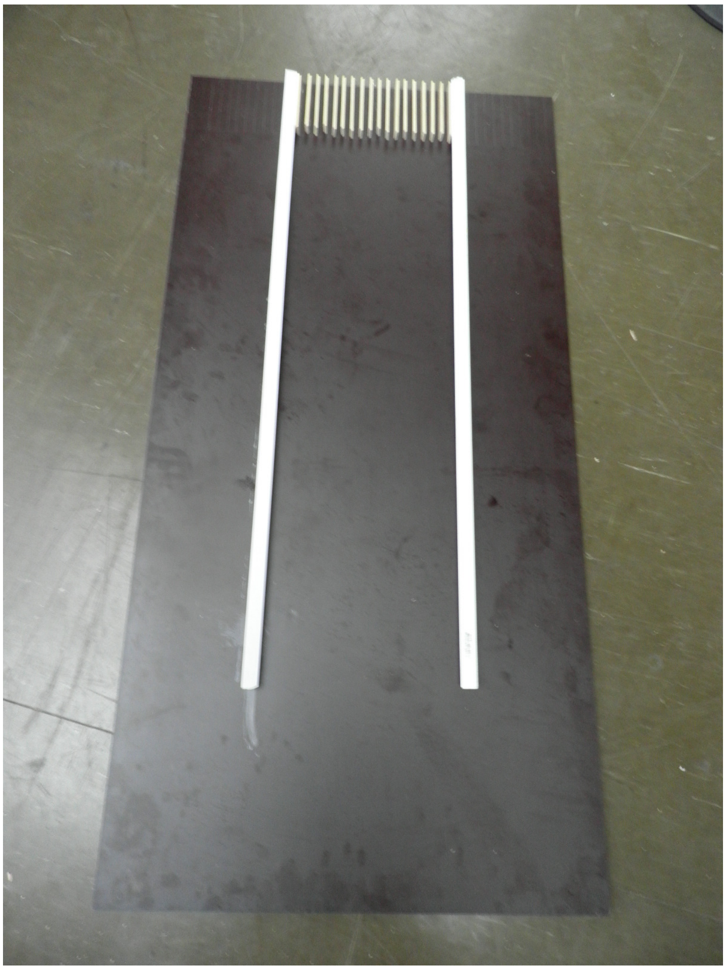
Pic. 56 *Shock wave 3.*

With one pump we obtain the best result and quite a smooth laminar flow. If the speed of the flow is not going to be varied, THIS IS THE BEST WAY TO VISUALIZE CLEAR SHOCK WAVES.

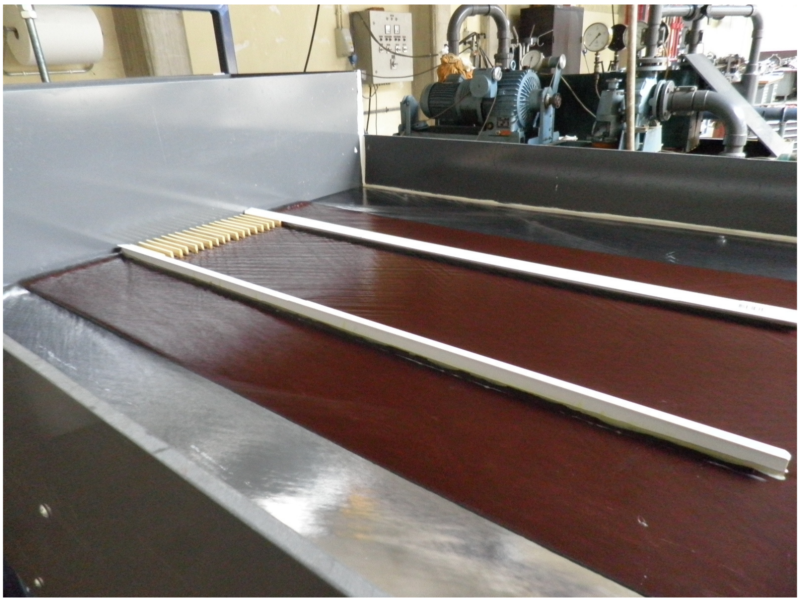
*****THE DEFINITIVE DESIGN HAS BEEN BUILT IN THE WATER TABLE.**

PLAN

Design: Water table plan PDF.



Pic. 57 *Wood sheet with the tracks and the separated test area.*



Pic. 58 *Wood sheet placed on the table.*

Chapter 5.

ALTERNATIVE DESIGNS

***In this part of the thesis some other solutions to get the purpose of a laminar flow are going to be explained. These solutions can be installed in the future but they mean very important changes in our table in comparison with the solutions given in the *Conclusions* of the *Chapter 4: Experiments*.

5.1 WATER TABLE WITH AN UPPER PLATE

In this table the main difference with our table is that the water flow would not go down the table in contact with the atmosphere. The main change would be the installation of an upper plate that would create a test area where only the water and the solid models that we placed for creating the shock waves would be. In other words, the test area would be free of air.

The speed of the flow would be better controlled than ever as it is going to be explained in the following paragraphs.

This system would create a good laminar flow and the changes that should be made in our table are detailed below.

Getting a horizontal test area:

First of all, it is important to explain that in this table the flow would go by the table not due to the inclination of the table. As the water goes by a closed way we can use the pressure that the height of the water creates, before and after the plate, to make the water go by the test area.

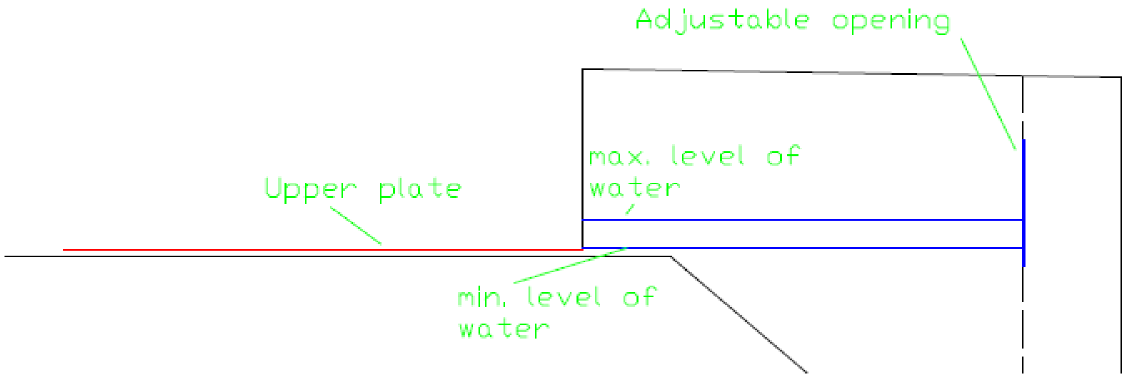
As we would use the pressure and not the inclination, our first step would be to change the inclination of our table from 0.62 º to 0º, so we get a horizontal test area. We could do this easily by increasing the height of the both front legs of the Water Table. If the height is increased 10 mm. the table is completely flat.

Pic. 59 *The legs are adjustable, so we can increase the height (10 mm.) easily.*

After the surface is completely flat the test area would be built.

Walls to increase the range of variation of the pressure in the limits of the test area:

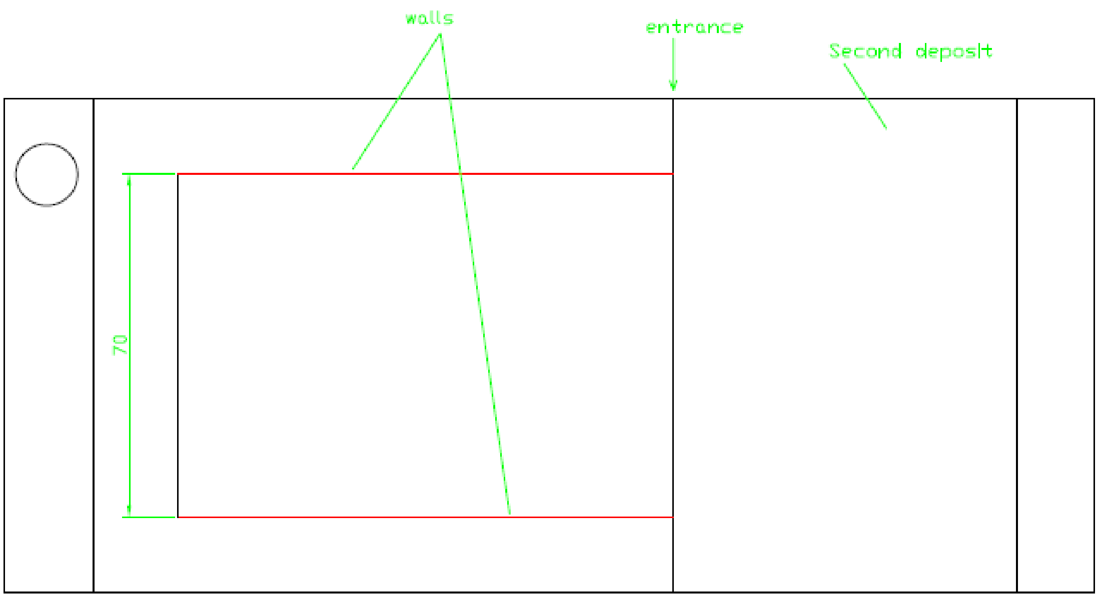
The amount of flow that goes by the test area wants to be controlled by the height of the water before and after the plate which will be installed at a certain height after the entrance. Actually, we could only regulate the height before the plate (by the adjustable opening).



The max. level of water and the min. level of water are 60 mm. and 15mm. respectively.

It would be more interesting if we could get a bigger range of variation, so the pressure would be able to change consequently in a bigger way. As we saw in the experiment 4 *(Experiments)*, by reducing the section of entrance from 100 cm. to 70 cm., we would get a bigger range of pressures before the entrance (the range of variation of the height would be, as it is mentioned in the experiment 4, 15 mm. – 90 mm.).

What would be done to get this section is to place two walls of the same material of the upper plate (laminated glass) on the table. They would have the same length of the upper plate, and this one would be leant on the walls. So these walls must have the same height that is desired for the test section and one is parallel to the other one with a distance between them of 70 cm. (like the section in the experiment 4).



Schematic overview of the table with the walls placed; the flow only goes between the walls.

The height and the length of the walls are defined in the next paragraphs where the installation of the upper plate is explained.

Installation of the upper plate:

The upper plate would be installed on the table, leaning on the walls. Its material would be transparent laminated glass and its dimensions would be 70 cm. x 97 cm. The upper plate would be against the entrance at a height of 4mm., like the height of the entrance.

It must be noticed that the dimensions of the walls have just been established 97 cm. x 4 mm.

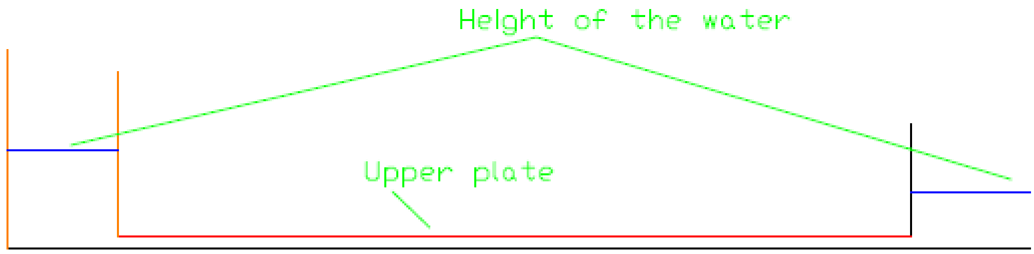
So the thickness of the flow of water would be permanently 4 mm., the distance between the upper plate and the table.

We could try to make this height adjustable; but for this test area we would have to create the solid models to create the shock waves, and if the thickness changes we would have to create new ones for all the thickness. Also more elements that are explained below *(elements to make the flow more laminar)*, that are placed between the upper plate and the table, should be made to fit with the different thickness of the test area.

The plate would be removable so we could change the solid bodies from one test to another.

Controlling the pressure before and after the test area:

Schematically the volume of flow that goes by the test area is going to be controlled as it is shown in the plan below.



Schematic profile view of the system to control the volume of flow in the test area.

By changing the height before or after the test area we would change the pressure and the volume of flow would be controlled.

The orange lines represent two walls that would not let the water (after the test area) to go directly to the first deposit by the recirculation tube.

The level of the water before the entrance is controlled by the regulated opening that is in the second deposit. However, after the test area we do not have a deposit like it is shown in the schema above. This deposit would be created by some plastic walls like the orange ones in the schema. Also a regulated opening would be placed in the left wall and the water would access by there to the recirculation tube. The adjustable opening is from 15 mm. high to 90 mm. high so the range would be 15 mm. – 90 mm. The opening is not closed in the highest part, so if the water reaches that high it would go back by the recirculation tube.

With this adjustable openings both pressures, before and after the test area, would be controlled, and the volume of flow would be adjustable. If we control the volume of flow in a constant section like in our design, we control the speed of the flow.

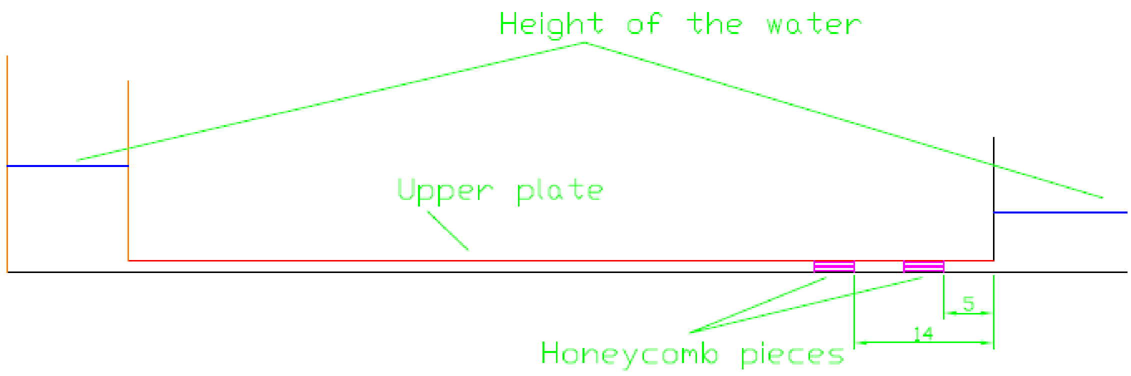
These openings are shown in the plan *(Water Table with upper plate)* at the end of this chapter.

Elements to make the flow more laminar:

Finally, to get a more laminar flow two pieces of honeycomb would be placed between the upper plate and the table to eliminate the turbulences that remain in the flow.

These pieces would be 4mm. high x 70 cm. wide (fitting with the test area) x 4 cm. in the direction of the flow.

The distance from the entrance, at which the pieces are placed, is shown in the schema below.



The flow is more laminar after passing through the honeycomb pieces

All the changes have been explained and we have to mention that the grille, the plastic sheet and the sloping plate explained in the experiments *(Experiments)* are still in the new plan of the table; because they worked in a good way and they would help to eliminate most of the turbulences before the entrance.

With this design the speed of the flow would be better controlled than ever by the adjustable openings before and after the test area.

In the plan below the new design is showed.

PLAN

WATER TABLE WITH UPPER PLATE

5.2 ALTERNATIVE WATER TABLE

In this part is going to be showed the plan of another possible solution for a water table. The structure of this water table would be different from our water table, but it is thought that is interesting to show another water table, with a different design. It is more interesting to work on our previous water table (money and time would be saved, and the result is good), but it is always good to see another ideas like this one.

(See the plan in the next page *Alternative water table*)The height of the water would be constant and it would not depend on the volume of flow provided by the pump. The speed of the flow is controlled by the adjustable opening at the beginning of the test area (connected to the atmosphere). If the opening is completely opened (biggest area of entrance) the speed would be the lowest possible; if it is mostly closed (smallest area of entrance) the speed would be much higher.

This is because (1) $Q = S \times V$; being Q = volume of flow , S = area of the entrance , V = speed of the flow.

As the Q would be mostly constant, what has been said before is according to equation (1).

The turbulences created by the pumps would be eliminated because the 1st entrance is well isolated by the anti-turbulences wall. The space between 1st and 2nd entrance is supposed to be always full of water, so new turbulences cannot appear.

*****With this design the table could work quite well, but the water table should be rebuilt.**

PLAN

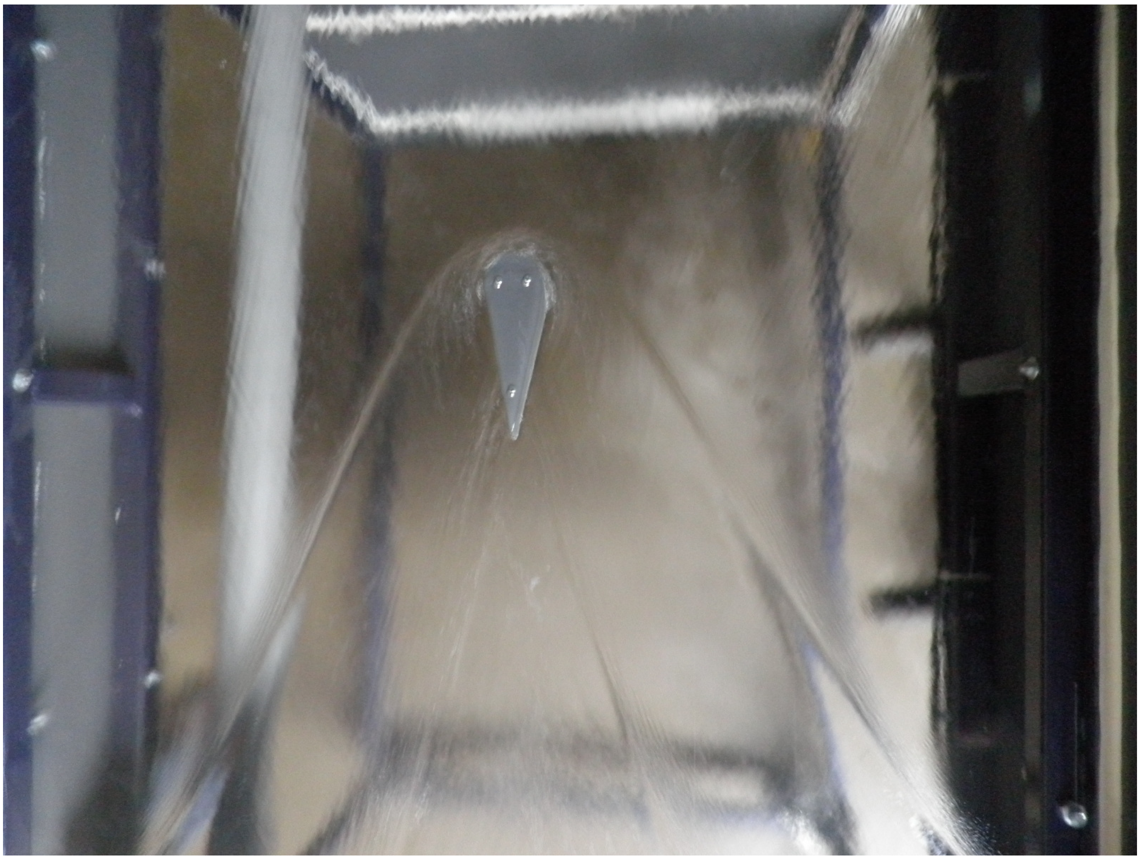
ALTERNATIVE WATER TABLE

Chapter 6.

VISUALIZATION METHODS

***As it has been mentioned before, some phenomena appear in the flow when an object is placed in it. In this part of the project different methods of visualization, that could be installed in the table to get a clear image of the laminar flow and these phenomena, are explained. This can be very useful because it is important to remind that **this water table was designed and built with docent purposes.**

After a solid body is placed in the way of the flow, immediately **shock waves** appear around it. Although these waves can be observed in quite a good way without any method of visualization, a lot of details of these waves are missed.



Pic. 60 *The shock waves can be seen without any method, but not in such a clear way as we would do it with any visualization method.*

It would be very useful that the future students could see these shock waves in a clearer way; that is the reason why these methods are studied in this thesis.

Also the phenomenon of the **boundary layer** is around the bodies that are placed on the table. It is impossible to see this phenomenon with the eye naked and to get a good image of it is much harder than to get the image of the shock waves. Despite this, also a method of visualization of the boundary layer is explained in this thesis. This could be very interesting for the docent purposes of this water table.

Some of the methods that are going to be presented would need important changes in the table. Four methods are explained in order to have different alternatives which the future user of the water table can study in this thesis. After having studied them, he will be able to choose the best option for his needs and budget.

6.1 DIRECT DYE INJECTION

The marking of lines or contours in a flowing liquid by means of dye can be achieved by introducing the dye into the liquid from outside (**"direct injection"**), or by generating it with an appropriate chemical reaction in the liquid. In the second case it is required that the liquid carries respective chemicals in solution, and that the dye-producing reaction is initiated at the proper location in the flow. The first method is more simple and easier to control, that is why the following explanation is focused on it.

The injection of dye has since long been a popular method for visualizing water flows. The dye is released either from a small ejector tube placed at a desired position in the flow field. One cannot avoid the fact that the main flow is, to a certain degree, disturbed by the presence of the ejecting device. The tube from which the dye is dispersed must be placed far enough upstream of a test model, so that interference of the tube with the flow pattern to be studied will be minimized. The released dye is contained in the wake of the tube, and one should prevent the wake of the dye ejector from becoming unstable or turbulent; this confines the technique to flows in which the tube wake Reynolds number is below the critical value. Tubes that normally serve as Pitot probes in air flows can be used as dye injectors. Such tubes are fabricated with an outer diameter of 1mm. or less; better **injecting devices for our Water Table could be hypodermic tubes or syringes.**

Dye syringes [18]

The rate at which the dye is released has to be matched with the velocity of our water flow. If the injection rate from the injector tube is allowed to become too large, the issuing dye might behave like a jet, and vortices appear along the interfaces between the jet and the main flow.

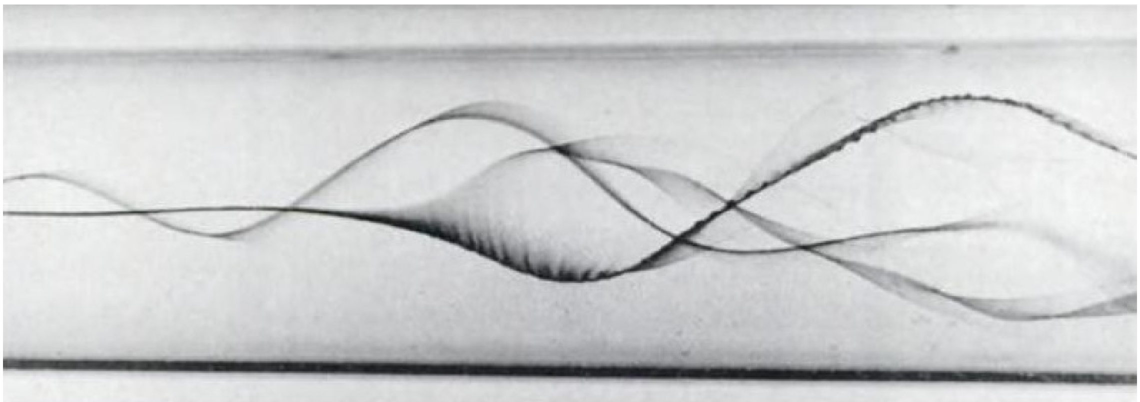
A dye suitable for the visualization of filament lines or flow contours has tu fulfill a number of requirements. Besides some general properties that apply to any foreign material used for flow visualization (e.g., nontoxic, noncorrosive) there are mainly three conditions the dye should meet, that is **neutral buoyancy, high stability against mixing, and good visibility.**

Neutral buoyancy:

A dye is neutrally buoyant if it has the same specific weight as the working fluid, in our case water. This value of the specific weight can be met by mixing the prepared dye with alcohol. Such a mixture is not a true solution, and, under the action of inertial or centrifugal forces, which act in different ways on the different components of the mixture, the dyed filaments will either decay or not indicate the true flow direction. **The latter problem is minimized if the dyed solution can be prepared by complete dilution of the dye (e.g., food coloring or ink) in the working fluid (water).**

High stability against mixing:

As the dye propagates along a line in the flow it will mix with the surrounding fluid, and the dye lines will lose their clarity and rapidly decay, particularly in a turbulent flow. The mixing also occurs at the interface of differently dyed flow regimes or contours.



At the right part of the picture the dye starts to mix with the water [19]

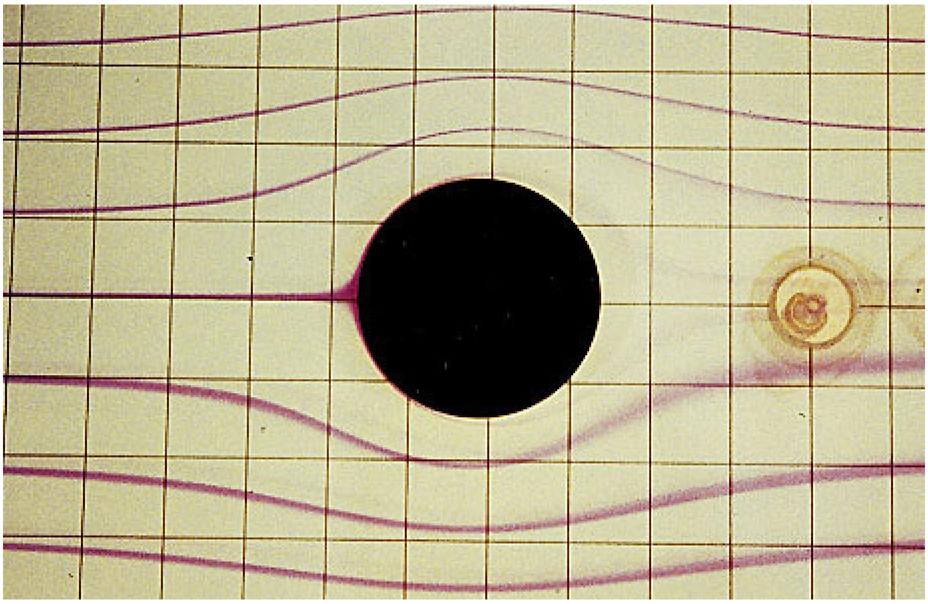
Therefore, this method of visualization is restricted mainly to laminar flows or low fluid velocities. The mixing or diffusion of dye in the working liquid is a fact hard to controll. But some ways **to increase the stability are known, as stabilizing the dye filaments by mixing the dye with milk** (Werlé, 1960; also demonstrated in many other publications of Werlé, e.g., 1973, 1976 (with Gallon), 1980).

Good visibility:

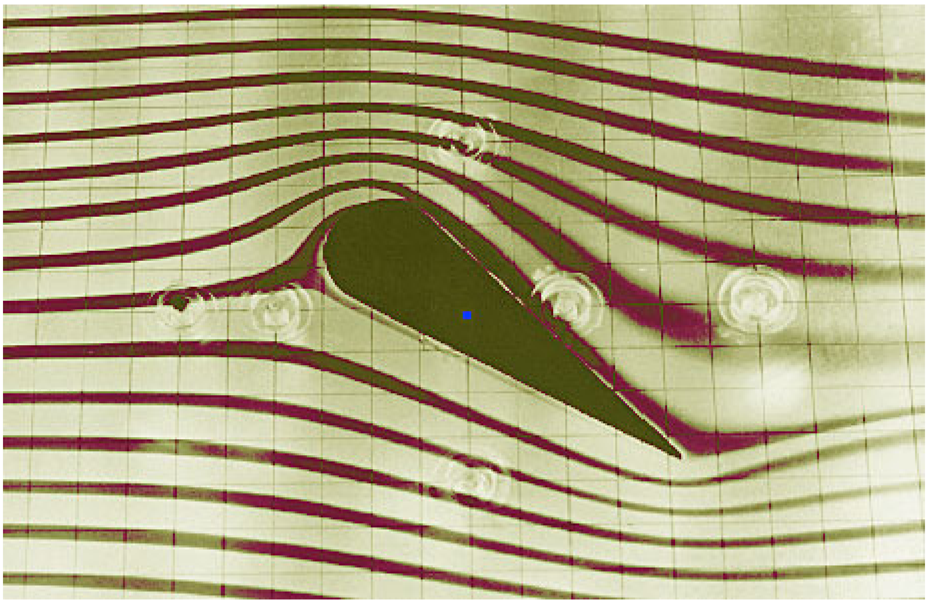
The easiest way to get a clear visibility is to use a dye of a color that contrasts a lot with the background of our table. Our table is transparent like the water; we could place under it a white sheet and then, we could use a black dye that contrasts highly with it. Another way of getting a good visibility is utilizing a fluorescent dye but it is much more complicated and much more expensive too. [11]

***With all this information we can think that in our table could be placed a system of visualization that would use this method (Direct dye injection). It should consist in a row of hypodermic needles placed at the beginning of the test area after the laminar flow is got. To visualize the flow of water dye is injected (the rate of injection should be studied previously) through the equally spaced needles. The characteristics and color of the dye should be the ones that we have explained in the three previous paragraphs.

If this system was installed and it worked perfectly, the laminar flow and shock waves would be clearly observed as it is done in the following pictures.



Shock waves created by a round body in a laminar flow. [20]



Shock waves created by an aerofoil profile in a laminar flow. [21]

With this method we would visualize the shock waves produced by the solid bodies that are placed on the table and the laminar flow. This method is not enough to see the boundary layer.

6.2 HYDROGEN OR AIR BUBBLES

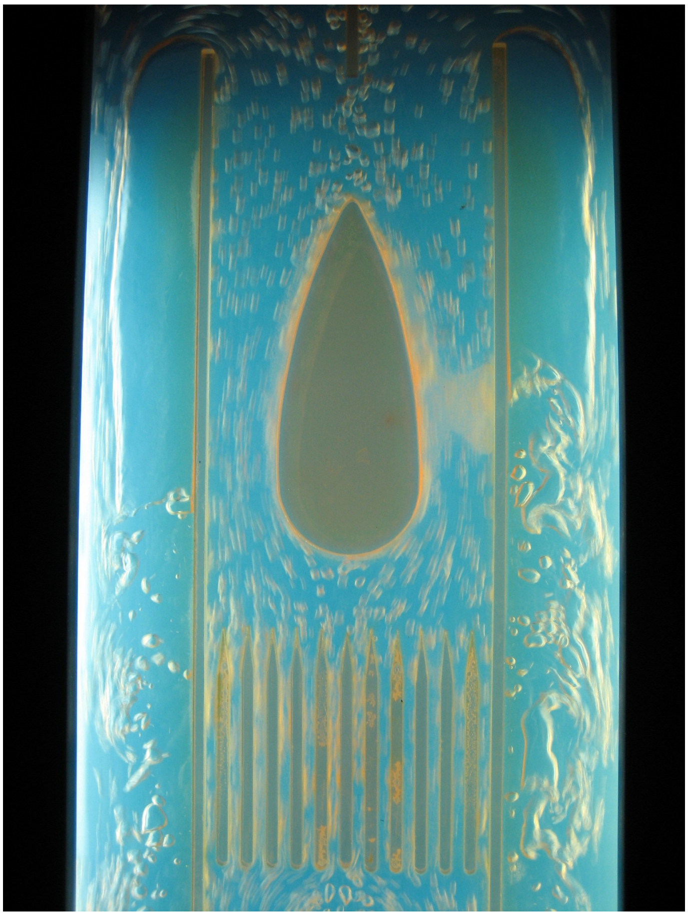
The injection or production of bubbles in the flow is another valid method of visualization.

The **hydrogen bubbles technique** is quite complicated and would require a deep study of our table.

Bubbles are produced at the surface of a thin (25-50 μm) platinum wire. The wire is used as the negative electrode and a positive electrode made of metal or carbon is placed nearby in the fluid. The positive electrode should be flat. DC voltage is applied to the wire, generating a current that passes through the water. Electrolysis at the wire surface generates bubble of hydrogen with diameters comparable to the wire diameter. The bubbles, which are very small, effectively follow the local velocity vector, allowing one to visualize the local flow structure.

The diameter of the hydrogen bubbles will be of the order of the wire diameter. The typical voltage range to generate bubbles is 50-70 V with currents in the range of one amp. An electrolyte must be added to the water to enhance bubble production. Typically 100 mgL_{-1} of table salt or sodium sulfate is used. With a steady power source, a continuous sheet of bubbles is released into the flow. Pulsing the power supply creates a series of bubble lines that allow quantitative analysis of the local velocity. Greater voltage may be needed for long wires or multiple wire arrangements. The right amount of electrolyte is important. If concentration is too low, bubbles are too diffuse; if too high larger bubbles are created, causing buoyancy problems. The technique is most effective only at relatively low flow speed - O(10 cms_{-1}). Finally, due to the high voltages used, great caution should be exercised when working with this technique. Contact with the wire, the positive electrode, or the water flow may result in an unpleasant electric shock. [9]

We could also install a system of **air bubbles injection**. It would consist in a number of syringes that would introduce air in the flow at a particular rate. This system would be simpler but also it would be harder to control. The bubbles should be preferably created in the flow of water before it turns into a laminar flow, in order to avoid the disturbing of the flow when it is laminar.



The bubbles are generated before the tracks that make the flow laminar in the low part of the picture. [22]

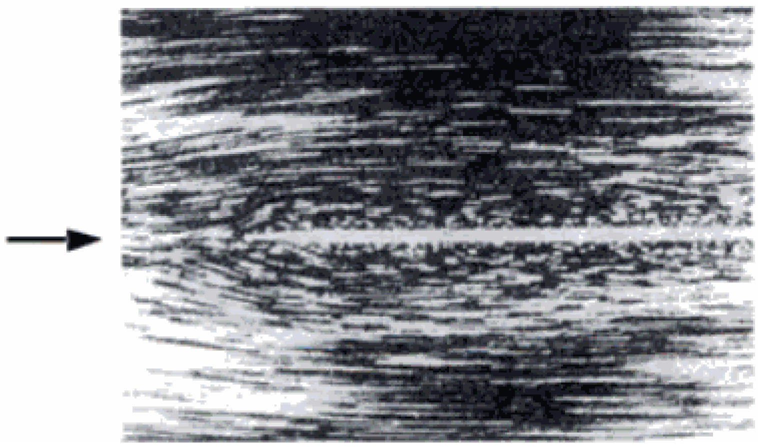
***To use this both methods in our table would make us **modify the structure of our table** installing an upper plate. This is because if we would not do it the bubbles would disappear rapidly mixing with the atmosphere. This upper plate would avoid this to happen, with the condition that the flow of water filled entirely the space between the plates**.** So these systems are more difficult to install than the previous ones. **With this method installed we could observe also the shock waves and the laminar flow on the table.**

6.3 ALUMINIUM PARTICLES (BOUNDARY LAYER)

The phenomenon of the **boundary layer** is almost impossible to be observed with the naked eye, as it is mentioned in the introduction of *Visualization methods*. This would be very interesting for the study of the effects of a solid body in a flow. The method that is explained in this part makes the visualization of the boundary layer possible, but not with the eye naked.

The method consists in sprinkling aluminium particles on the surface of the water to make the streamlines visible. But the particles are very small to see the streamlines clearly with the eye naked and logically, the boundary layer is not seen. What it is done to solve this problem is to install a high quality photographic camera above the table, focusing on the solid body on the test area and its surroundings. After the particles are sprinkled in the water and these ones are surrounding the solid body placed, a snapshot is taken.

It is known that the boundary layer has a lower speed than the rest of the flow, and now also the particles that are in the region of the flow that is boundary layer. If we take the snapshot with a particular exposure time the result would be as the one that is shown in the following picture.



Flow sprinkled with aluminium particles along a thin flat plate [23]

The length of each particle streak is proportional to the flow velocity. It can be seen that directly at the wall there is a thin layer (boundary layer) where the velocity is considerably lower than it is at some distance from the wall. The thickness of this layer increases along the plate from front to back. [10]

So with the image taken by the camera the student is able to see the boundary layer, which is in the region where the particles have a shorter streak, so they move at a lower speed.

***** To sum up, this system of visualization is more complicated and more expensive than the previous ones but it is the only one that allows the student observe the boundary layer. In the snapshot the shock waves and the direction of the flow can be observed too.**

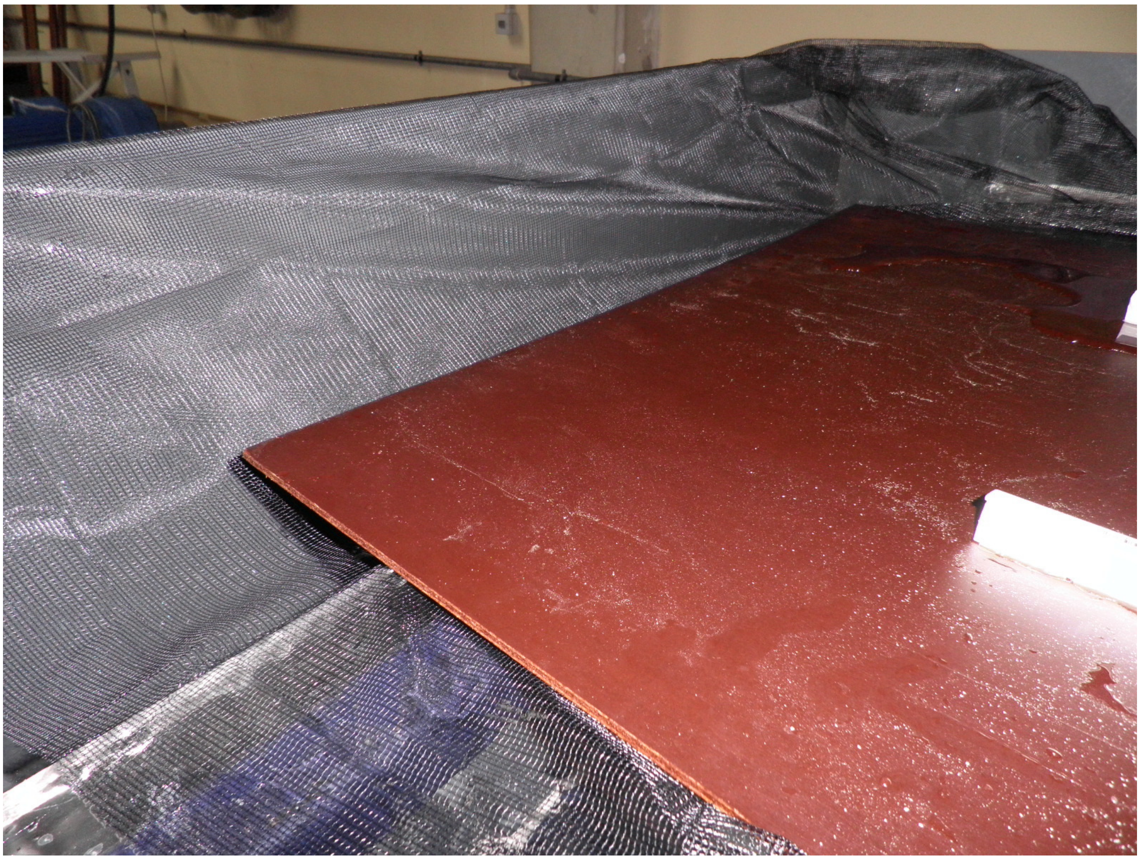
6.4 SOLID PARTICLES (EXPERIMENTED)

This is the only visualization method that has been experimented in the water table.

The system is quite simple and it consists in sprinkling solid particles on the surface of the flow just in the beginning of the test area. The buoyancy of the particles should be taken into account and the perfect material for them should have the same density to water.

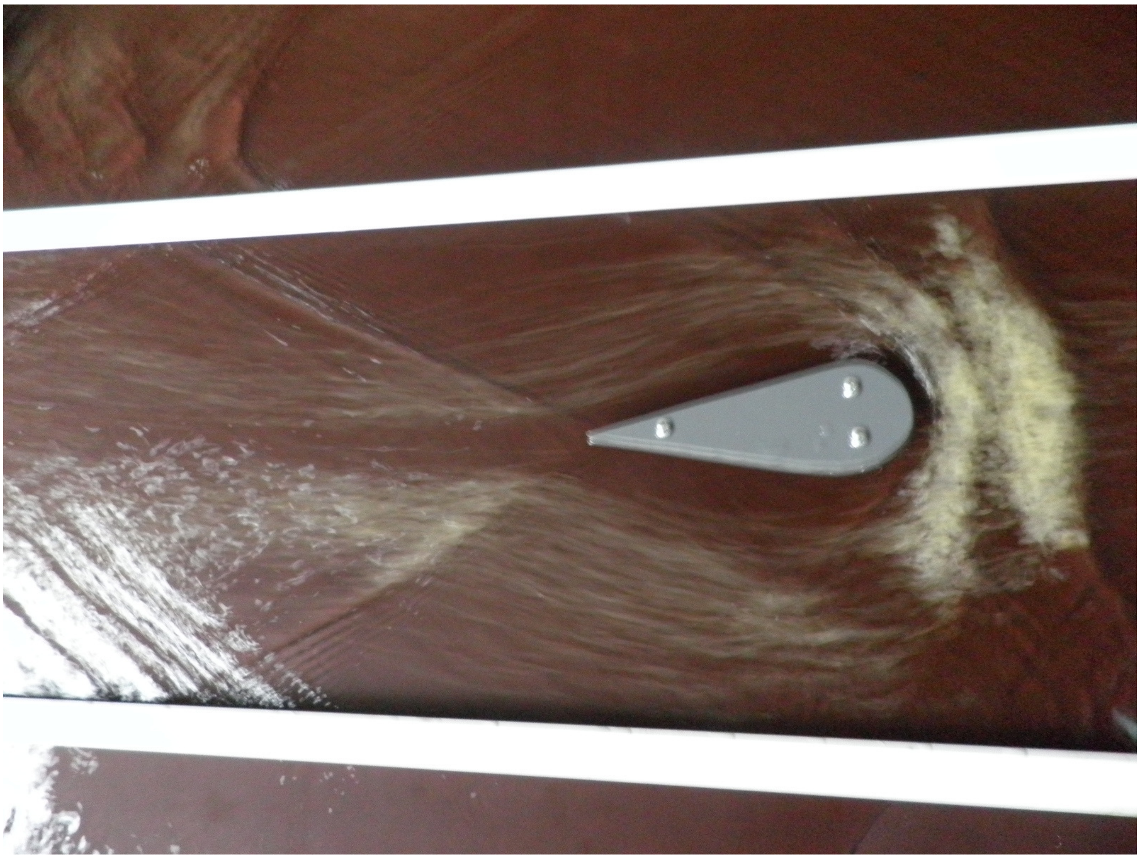
In our experiment we would use rice, it has a higher density than the water, but for one experiment is valid; it should show the streamlines.

The rice grains could block the tubes of the table, so we have placed at the end of the test area a grille to avoid this problem to happen.



Pic. 61 *The grille keeps the solid particles after the test area.*

When the pumps are switched on and the particles are sprinkled the image that we get from a shock wave can be seen in the Pic. 62.



Pic. 62 *The grains show us the shock waves and the reflections.*

The experiment is done with two pumps working and the sheet placed (turbulent flow), so we can see how the particles show us also the bad reflections and turbulences in the right part of the Pic. 62. The grains firstly follow the direction of the flow and when they found the solid body, they follow the direction of the shock wave. The method is good (the shock waves are shown by the grains) but the big density of the rice makes the grains be stopped in some parts of the test area.

This experiment has shown us that this method can be installed in our table, but the solid particles should be of another material with a density similar to water. With that material the result would be good and the shock waves and the laminar flow would be perfectly visualized.

6.5 CONCLUSIONS

Any of these four methods explained in this part of the thesis can be installed in the future.

The direct dye injection would get us the clearest image without using a camera while the aliminium particles method is the only one that could show us the boundary layer; but it is the most expensive to install.

The solid particles system is quite simple and the cheapest to install (our experiment shows us that it would be good with particles of a material of similar density to water), not as the hydrogen bubbles that would require the installation of an upper plate.

The election of the best method can be chosen by the future user of this table depending of his needs and budget. The user can use this chapter as a guide to install the best one according to his needs and budget.

Chapter 7.

CONCLUSIONS AND RECOMMENDATIONS

***The goal of this thesis is to optimize the water table to visualize shock waves and vortices in the water flow. To get this we want to get a laminar flow and a good control of the speed of the flow.

The final solution for this goal has been found after using the information provided by the experiments done and the information provided by the study of the important fundamentals that are seen in this thesis. **In this thesis is seen how the way of experimenting shows us ways to solve our problems**.

After seven experiments in the water table, the final design for the table is written in *Chapter 4, Conclusions.* These seven experiments have shown us the way to reach our goal; some of them had good results while other ones did not, but they also showed us a way to continue our work. The final design is deeply explained in this chapter; with one pump working and with both pumps working. These solutions have been installed in the water table.

An important recommendation for the construction of the solutions given in *Chapter 4* is that the grille in the definitive design should be metallic, and all the elements are better placed with silicon instead of adhesive tape. The adhesive tape is good when we want to install and uninstall the elements easily, but not permanently.

In Chapter 5 there are two alternative designs deeply explained; specially the first one *(water table with an upper plate),* because it is thought to be a very good possibility for the future. This thesis can be used as a guide for the future utilization of the water table; the future user can choose between the solutions explained in *Chapter 4* (which have been tried, installed and the elements have been built and placed) or the alternatives explained in *Chapter 5.*

In *Chapter 5* the option *Water table with an upper plate* is easier to be built than the other alternative. This solution would provide us an excellent control of the speed of the flow in the test area.

The *alternative water table* is a good idea that provides us an extra solution and it shows the future reader of the thesis a different way to achieve our goal. The problem is that it would need the construction of a new water table.

This thesis is also a guide to choose a method of visualization for the water table *(Chapter 6).* Four options are explained and the last one has been also experimented. Each option has some advantages and disadvantages respect the other ones. They are well explained in *Chapter 6*.

The *aluminium particles* system is the only one that would allow us to see the boundary layer and this is very interesting for the docent purposes of this water table.

The *direct dye injection* provides us a very clear image.

The *air or hydrogen bubbles* method needs the installation of an upper plate.

The *solid particles* system has been experimented with quite good results with the only inconvenience of the bad election of the particles´ material. If the material had a more similar density to water the result would be excellent.

Who wants to install a visualization method can use this thesis as a guide to choose it, depending on his needs and budget.

The designs, alternatives, solutions and methods are well explained in the chapter which they are contained.

To sum up, the best design of this water table to achieve our goal has been defined after doing seven experiments in the water table *(Chapter 4, Conclusions)*.

With both pumps working the second deposit has a grille and a plastic sheet; the possibility of a sloping plate is up to the election of the future user of the table. The flow is laminar and the shock waves are on the test area after placing a solid body on it. The speed of the flow is controllable by the adjustable opening.

With one pump working the wood sheet with the tracks on it is placed on the test area (the water table maintains all the elements installed: plastic grille, plastic sheet…), getting the best result ever. The flow is smooth and laminar and the shock waves are clear in the test area. The disadvantage is that the speed of the flow cannot be controlled and it is fixed (low speed).

The solutions given in *Chapter 4, Conclusions* have been installed with good results as it is showed in this part of the thesis.

This thesis is also a guide which contains alternatives designs for the future (*Chapter* 5) and different methods of visualization (*Chapter 6*) which can be installed according to the needs and budget of the future user of the water table.

Finally, with the design of the water table explained (Chapter 4, Conclusions) and installed, the goal of this thesis has been reached. This thesis can be used also as a guide to keep on improving the water table.

Solutions installed:

One pump working: The laminar flow is got, the shock waves are clearly seen and the speed of the flow cannot vary. The shock waves have always the same size and shape.

Both pumps working: The flow is laminar but not so smooth, the shock waves are correctly seen and the speed of the flow is controlled (adjustable opening). We can change the size and shape of the shock waves by varying the speed of the flow.

Chapter 8.

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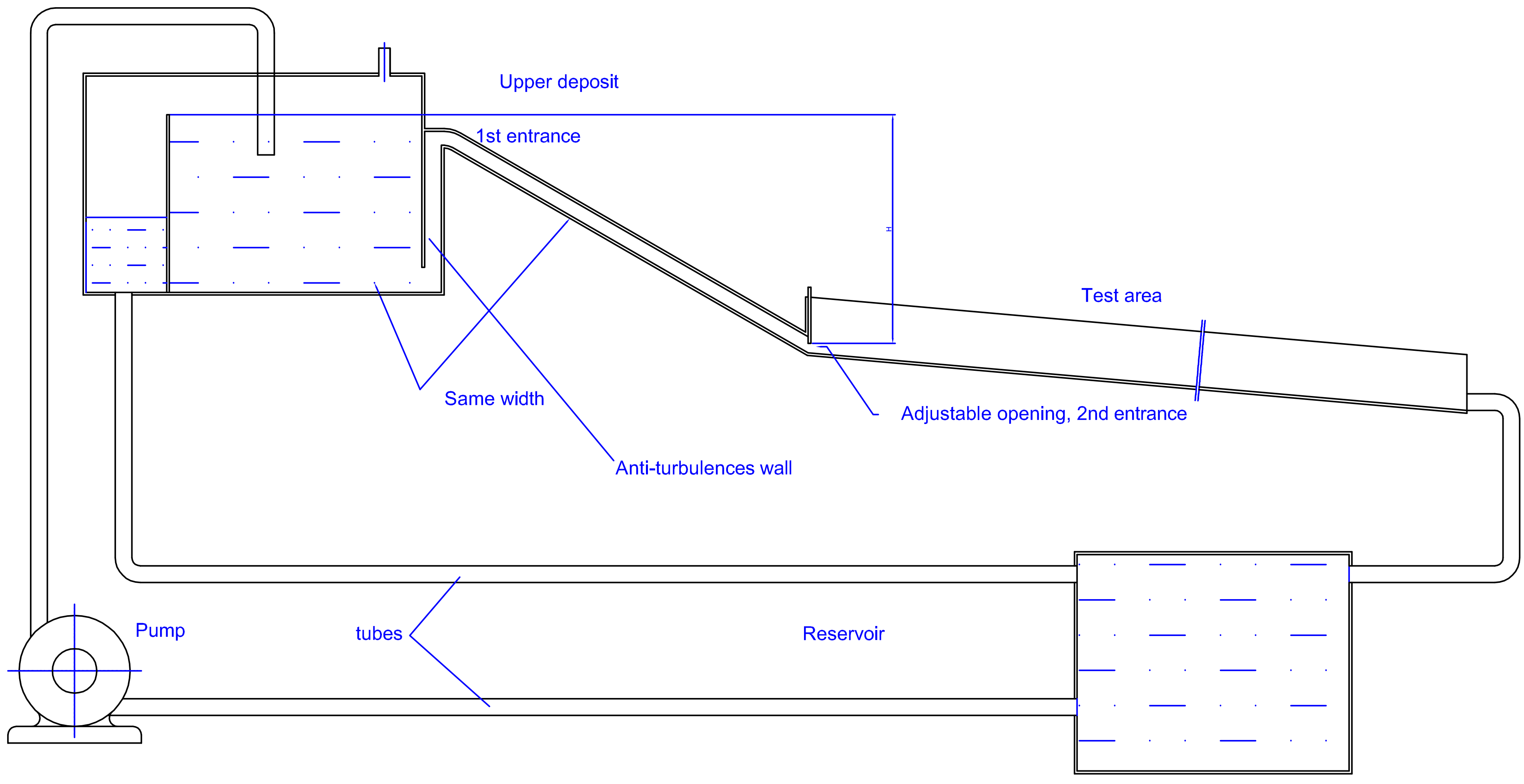
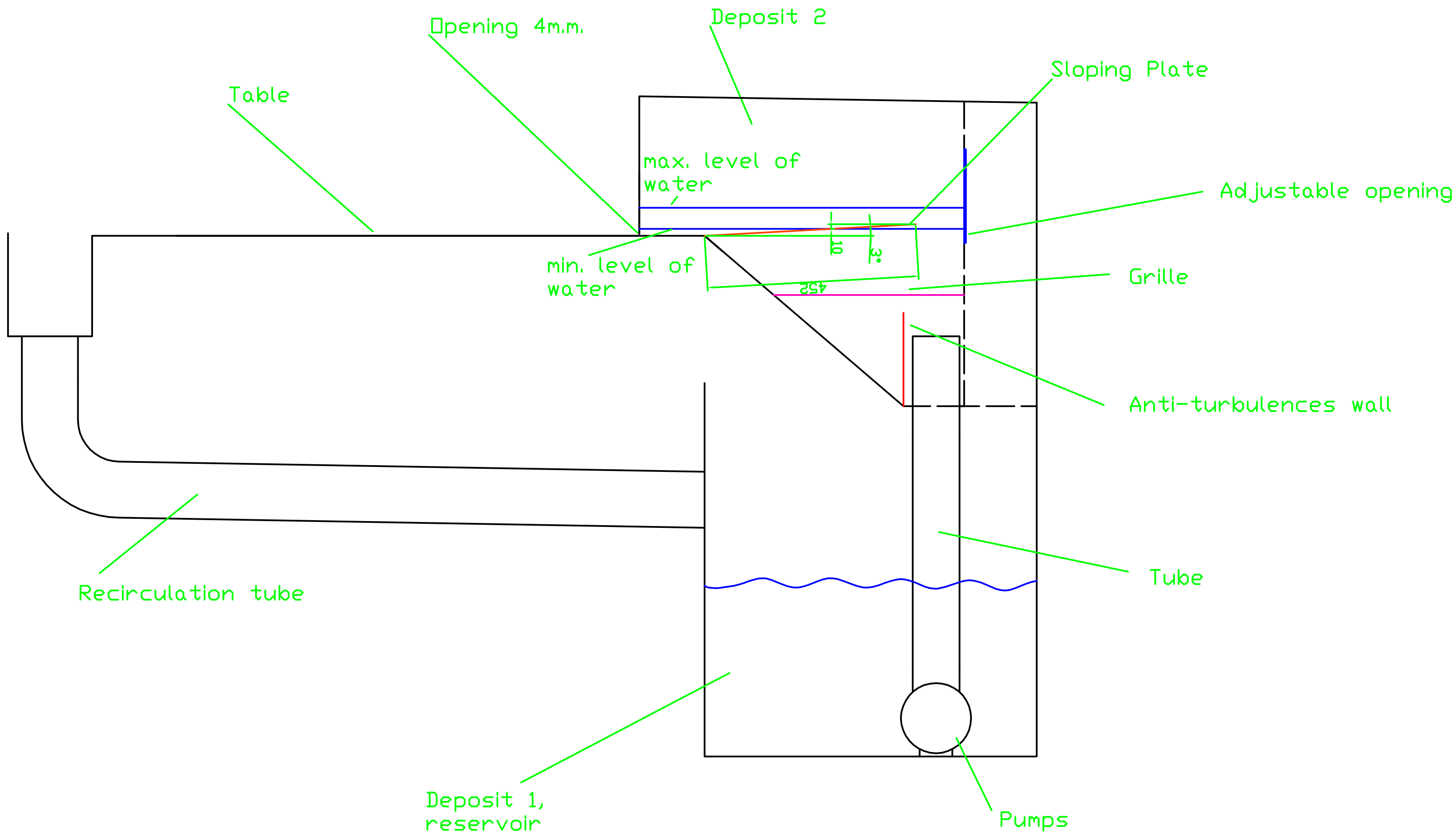
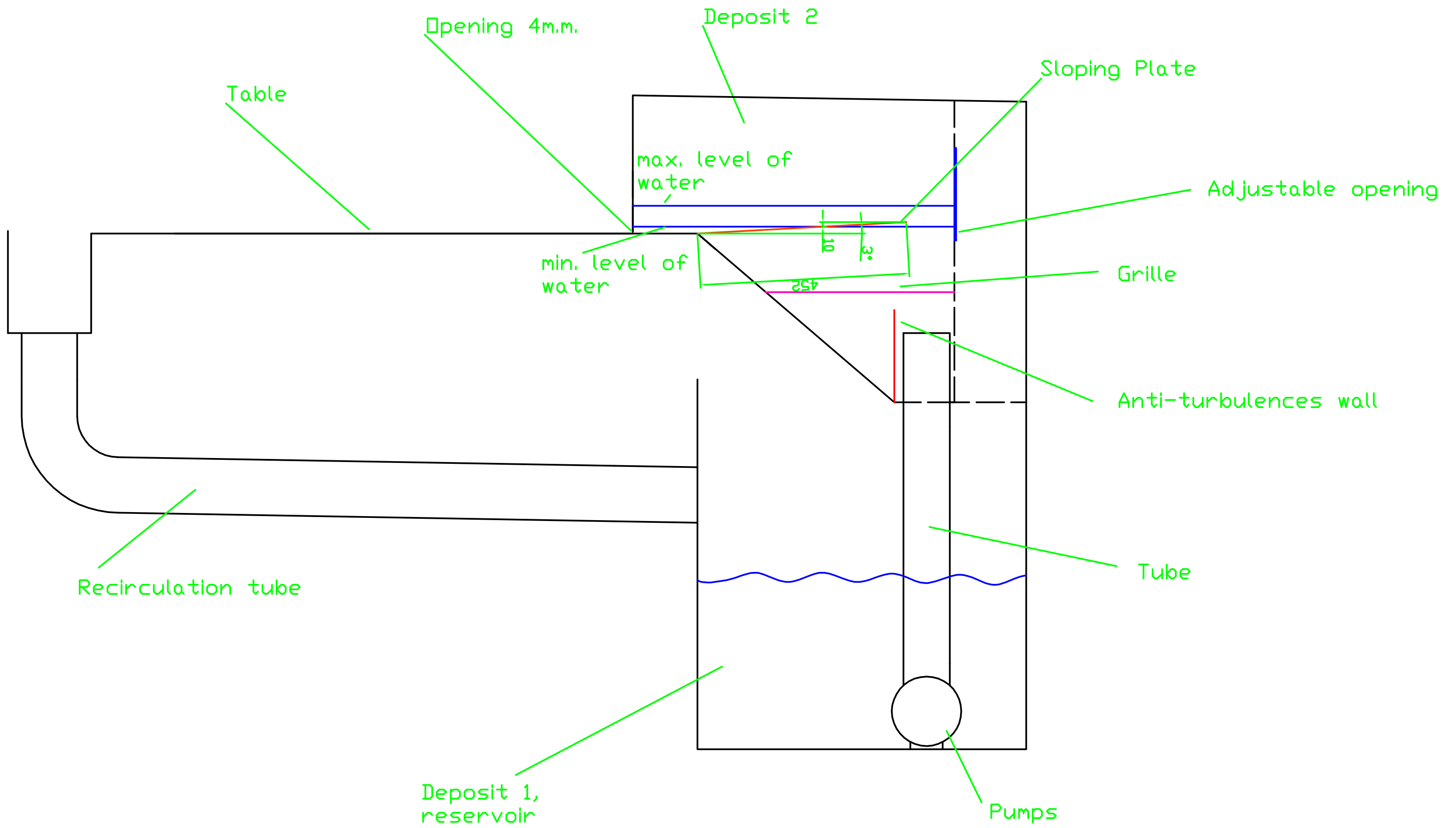


Alternative water table		
Measures	Date	Barcena, J. Bosco
changeable	1st of June, 2010	



Design: Water table plan		
Measures	Date	Barcena, J. Bosco
mm.	1st of June, 2010	



Water table plan Experiment 6		
Measures	Date	Barcena, J. Bosco
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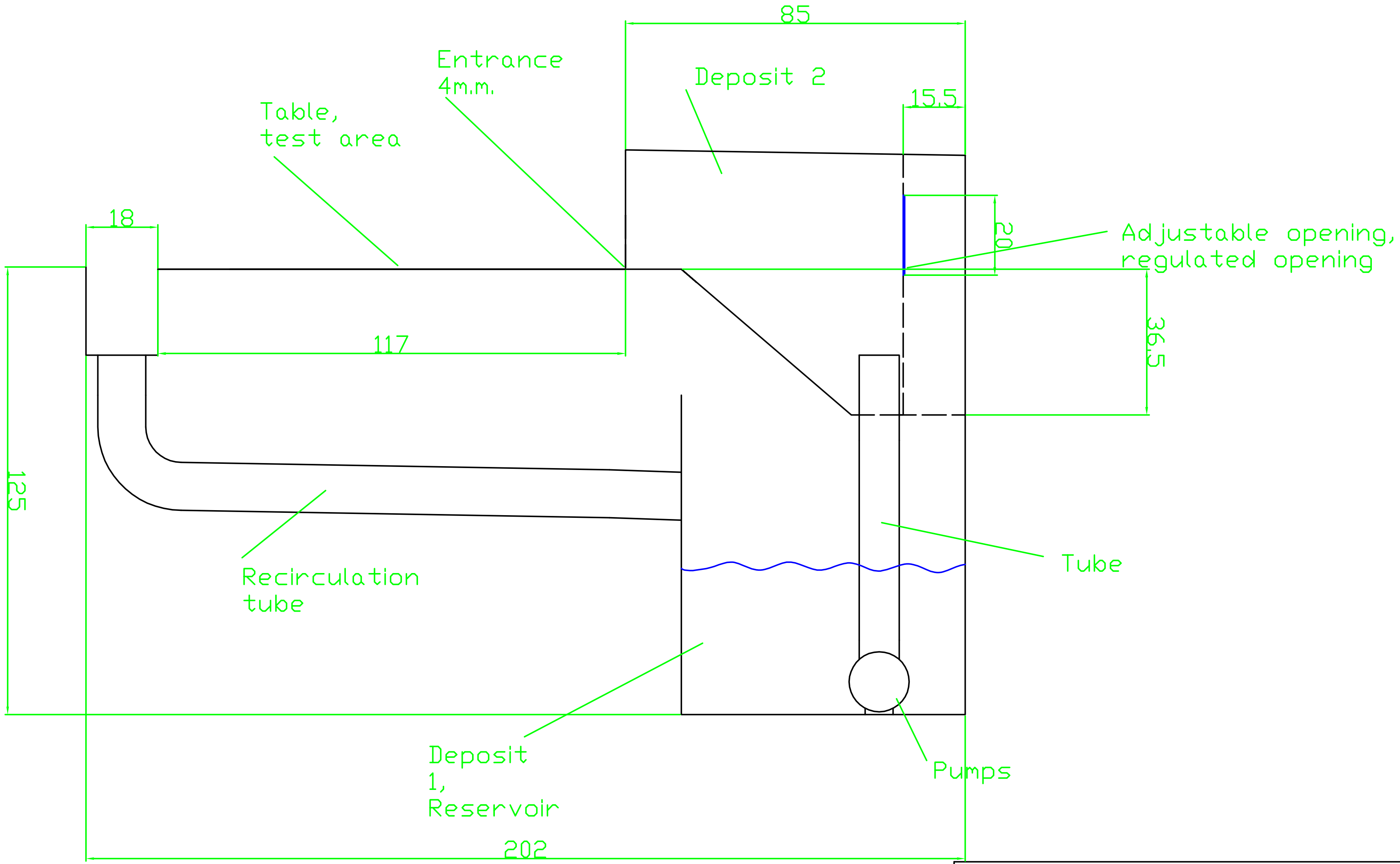
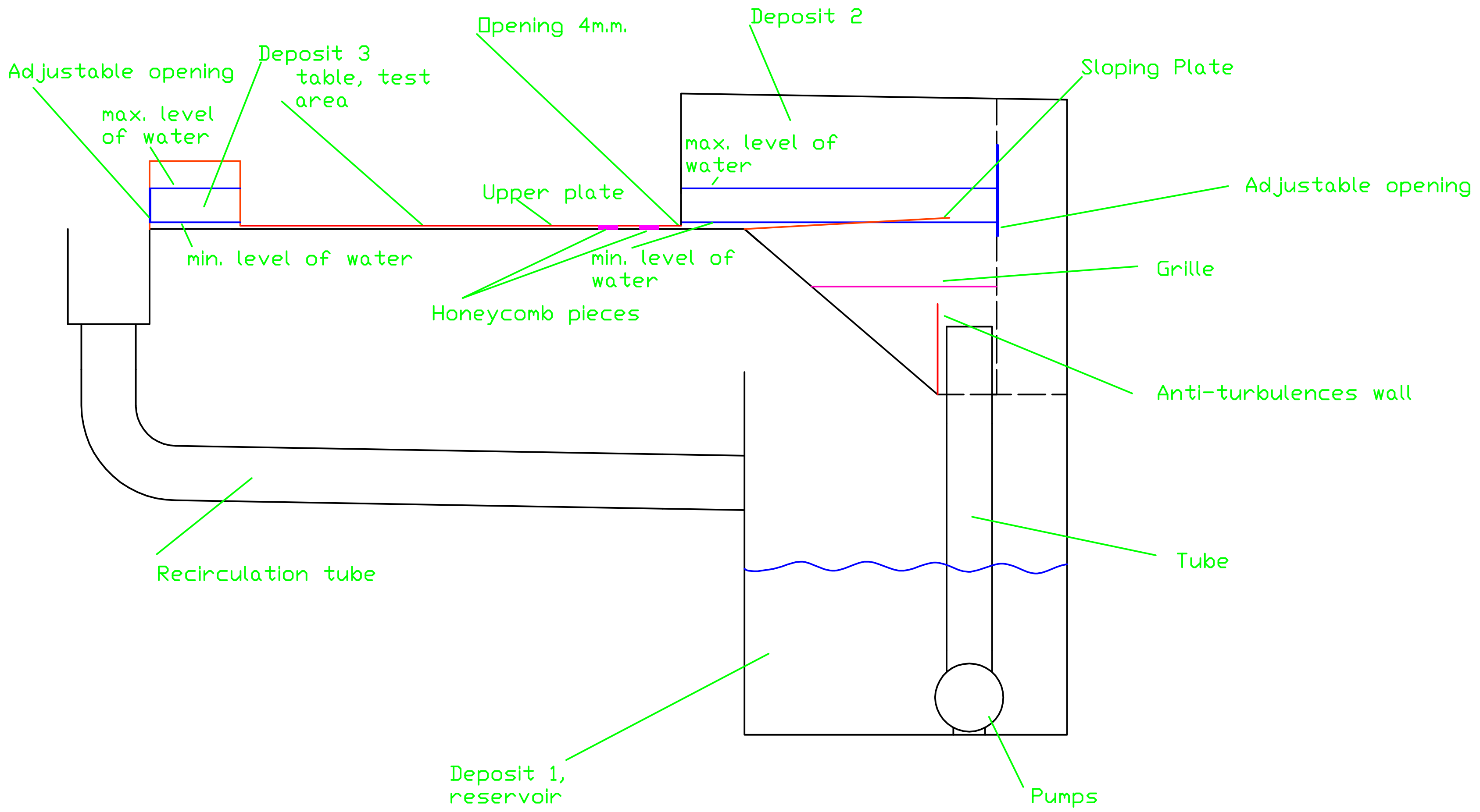


Water table plan		
Measures	Date	Barcena, J. Bosco
cm.	1st of June, 2010	



Water table with upper plate

Measures	Date	Barcena, J. Bosco
cm.	1st of June, 2010	