Student Beatriz García Navarro

«H-RISTA»

FISH FRIENDLY INTAKE FOR SMALL HYDRO

Trondheim, 16.06.2014

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NTNU
Norges teknisk-naturvitenskapelige universitet

Fakultet for ingeniørvitenskap og teknologi
Institutt for vann- og miljøteknikk

PROJECT WORK

Student: ***BEATRIZ GARCÍA NAVARRO***

Title: «H-RISTA» - FISH FRIENDLY INTAKE FOR SMALL HYDRO

1 BACKGROUND

In the current time Norway develops 30 - 50 small hydro power plants annually. This is due to markets situation and due to The rEnewable Directive from EU, which Norway has joined. For the next 10 years 50 – 80 small hydros have to be built. Many considerations have to be taken for a hydro power intake as operation, maintenance, investment costs, loss of water and generation, environment etc. Fish migration is among the most important issues related to the environment. In the north of Europe most attention is putted to migration of salmon and eel. Downstream migration of large eel is now heading up as the main research field in this aspect.

The newly invented small hydro intake «H-rista» (Horizontal trash rack) is being tested in the hydraulic laboratory at NTNU in 2013. The intake concept is based on a back flushing procedure of the trash rack during operation of the intake. The concept is very efficient for flushing of debris, leafs, moss etc; but in the same time this concept seems to be promising to prevent fish and other species from reaching the conduit and in the end the violent (from the fish point of view) turbines. Spacing in the range of < 10 – 16 mm between the bars is estimated to be sufficient to prevent fish to enter the conduit. Such narrow spacing between the bars will in many cases introduce a severe blocking of the trash rack but with a frequent flushing of debris and fish, this will probably cause minor problems.

The scale model «H-rista» will be available in the hydraulic laboratory at NTNU during the spring semester 2014.

2 MAIN OBJECTIVES

The project work will include:

1. Review of Spanish literature in the topic of fresh water fish migration related mainly to a) downstream migration of eal and salmon and b) different types of intakes for small hydro.
2. To be familiar with the H-rista model.
3. Running of experiments with the H-rista to verify velocity, depths, acceleration etc; given by the review of the literature relevant for migration of fish.
4. Review of results.
5. Reporting.

The content of this project work may be adjusted during the period.

3 GUIDELINESS, DATA AND INFORMATION

Main supervisor at NTNU will be Professor Leif Lia and co-supervisor will be Hanne Nøvik (until February 28.). Cooperation with master student Mari Wigestrand is recommended and required.

The candidate is encouraged to search information through colleges and employees at NTNU, SINTEF, Energy Norway, NVE and other companies or organizations related to this topic. Contributions from other partners must always be referred in a legal way.

4 REPORT FORMAT, REFERENCES AND CONTRACT

The project report shall be in the format A4. It shall be typed by a word processor and figures, tables, photos etc. shall be of good report quality. The report shall include a summary, a table of content, lists of figures and tables, a list of literature and other relevant references and a signed statement where the candidate states that the presented work is his own and that significant outside input is identified and referred.

The report shall have a professional structure, assuming professional senior engineers (not in teaching or research) as the main target group. The thesis shall be submitted no later than 16. June 2014.

Leif Lia.

***Professor*.**

Abstract

Environmental concern is a highlighted topic which arose some years ago; as a consequence of its importance, it has extended and developed. This concern has impregnated most of the anthropological actuations, and even more those which affect directly the environment.

The construction of Small Hydropower Plants has become a normal practice in the last years. Once this technology has been implemented, some negative impacts have been detected, and among them, the problematic of the downstream fish migration.

This report aims to be a part of a wider investigation that is taking place in the hydraulic laboratory of NTNU. It consists on the evaluation and observation of some parameters in a scale model representing an intake for small hydro.

Further in depth, the repot focus on the functioning of the guiding system for the downstream migration of the fishes which are more affected in rivers at the moment: the salmon and the eel. The model and its possibilities of change are explained; previous conclusions on the model are shown as basis, and the most relevant parameters of the study, the kind of racks tested, are presented.

Tests consist basically in the measurement of the velocities in the chamber previous to the rack for each rack proposed. At the same time, the head loss will be compute to estimate the viability of the installation. Secondly, among the results, the velocity fields and some comparisons between the velocities are shown in order to observe if the hydraulic behavior near the rack is adequate.

In the last pages, all the results from the tests are collected in tables and graphs in order to ease the task for further studies related to the model.

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1. Introduction

The needed of a huge availability of energetic resources is the headline requirement to maintain and develop our consumption and welfare system. Day to day the consequences for the environment derived from the economic growth are becoming a more important concern. Consequently, the renewable energies are playing a bigger role in the energetic system in order to obtain a sustainable growth. Among them, the hydrogenation of energy can be found, as a clean and local energy source.

These renewable energies are not expensive and minority anymore, on the contrary they have become competitive and efficient to cover the energy demand. China is the leading hydropower producer, followed by Brazil, Canada, the United States, and Russia. Hydropower represents the largest share of renewable electricity production. Only wind power was leading for new-built capacities between 2005 and 2010.

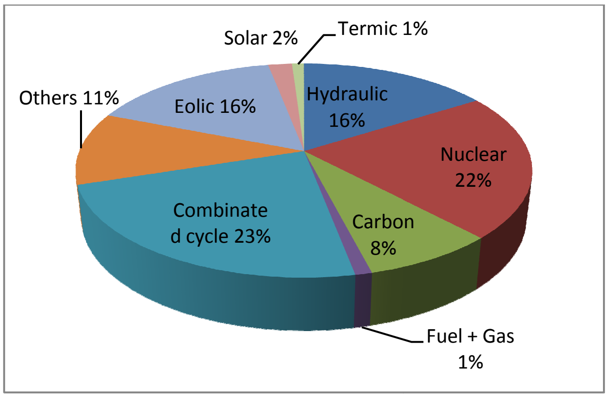

Figure 1. World distribution of energy production.

National policies, agreements, and international treaties include as primordial objectives a sustainable development which does not threaten natural resources for future generations. For this reason, measures and objectives are trying to be accomplished not only cooperating among the countries, but in their national policies as well. Furthermore, researches and new technologies are being developed in order to reform the ones which are already implemented and improve them for the following new implementations.

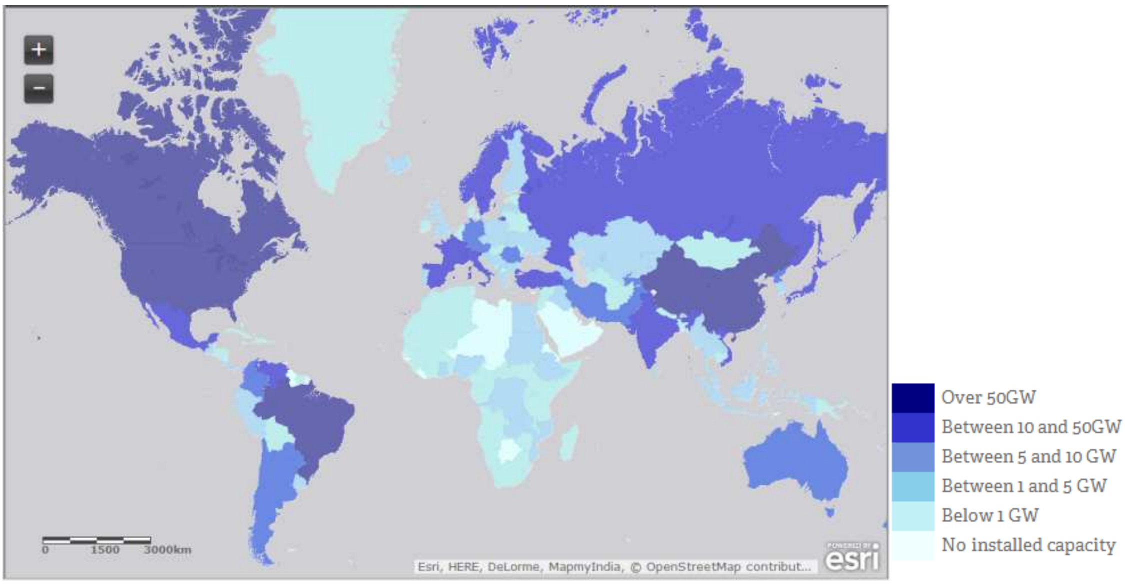

Figure 2. Installed hydropower capacity.

For instance, the Renewable Energy plan in Spain (PER) following the guideline of the Community Directive aims that at least 20% of the gross final consumption of energies in Spain will come from renewable energies. Plans establish a production of 97,121 GW and 146,080GW for the years 2015 and 2020 respectively.

Other example can be contemplated in Norway. Norway is in a unique position as regards renewable energy. Unlike most other countries, nearly all of Norway's electricity production is based on hydropower. Norway has a share of renewable energy that is much higher than in all EU countries. In 2011, renewable electricity production was about 124 TWh. According to the National Renewable Energy Action Plan under Directive 2009/28/EC; the renewable percentages in electricity was 97.0 % in 2005 and 96.9 % in 2010[1], and for 2020, a renewable percentage of 113.6 per cent has been calculated for electricity.

At the same time, the environmental and social effects of hydropower projects need to be carefully considered. Countries should follow an integrated approach in managing their water resources, planning hydropower development in co-operation with other water-using sectors, and take a full life-cycle approach to the assessment of the benefits and impacts of projects.

After the development of high hydropower plants, their environmental impacts were trying to be reduced by a new concept of energy hydrogenation given by the small hydropower plants. At the first point, they seemed to be much less aggressive environmentally, than the conventional, thanks to some facts like the minimum volume of storage, without a new flooded area, and then not resettlement of the population or disappearance of habitats, with all the consequences involved.

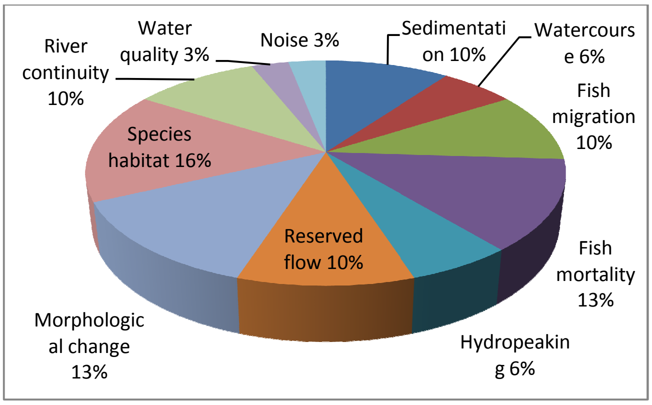

Figure 3. Identified hydropower impacts.

There are several issues that make small hydropower plants a kind of hydroelectricity production much more accessible to plan. More details about small hydropower facilities will be shown in the following chapters.

[1] The declined, was caused because 2010 was a cold year with high electricity consumption in Norway.

2. Background

2.1. Small hydropower plants

Run of river power plants (ROR) are those which use the water during their normal flow in the river. They may have little or no capacity for water storage, and the energy produced has to be consumed immediately; according to the European Union standards, their installed capacity is usually less than 10 MW.

Regarding their dependency to the variance of the water flow during the different periods of the year in the river, they are considered a non uniform source of power, and hence it is more difficult to coordinate the output of electricity generation to match the consumer demand. Nevertheless the right location (rivers with a minimum dry weather flow or those located downstream a much larger reservoir) favors a constant discharge which leads to an effective productivity and ensures a certain power over the year.

The operation of these installations is simple. A small dam retains water increasing its level to ensure the one required for the turbine; at this point, a determinate amount of water is conducted through a pressure pipe or a parallel channel (depending on the geomorphology of the place) to the turbines, while simultaneously a parallel conduction is diverting the corresponding environmental flow. Immediately after, the water is back to the main river. During the high level episodes, the water which cannot be retained by the dam goes above it, being spilled.

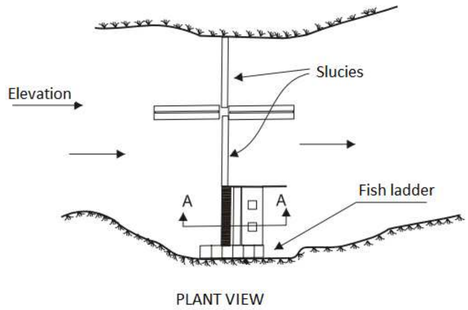

Figure 4. Plan view of ROR facility. Parts.

Those installations capable to keep water usually retain it for generating energy during the peak hours of the consumption, obtaining more benefits than others which are connected with the general electric network any time.

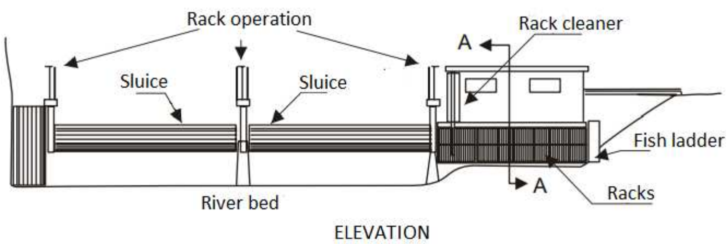

Figure 5. Elevation view of ROR facility. Parts.

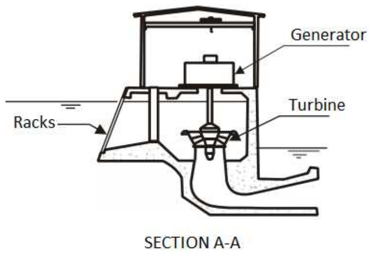

Figure 6. Detail from the power house.

100% of the questioned experts agree that small Hydro has an impact on the environment. Most of them suggest that there is no real difference between the small or large Hydro when speaking of impact, since according to them, all hydro plants affect and change different aspects of the environment. Indeed, each hydroelectric facility is unique and its effects vary depending on the different ecosystems, design and management of the plant.

Despite this, in general terms it can be said that the most noted impacts for small Hydro are those related to the aquatic species, the sedimentation, and the modification of the river continuity. Aquatic species are affected in terms of mortality, migration and change of the conditions and quality of their habitat. Some of these impacts on the fish species, more specifically, the downstream migration of the Atlantic salmon and the Eel will be developed in the report.

For instance, a research done in 63 run of river power plants in the Rivers in Guipuzkoa, show that most of these installations are not well prepare to deal with the fish downstream migration, in addition the installation of any fish passage would be really complicated.

2.2. Affected Fish species

In general terms, these are the five most relevant threatens to any fish population:

- **Overfishing**, that reduces populations above its critical levels.
- **Dams** and other constructions that become obstacles and difficult the migration.
- **Fluvial engineering projects** that degrade the biotope and alter the natural ecological processes.
- Agricultural and industrial **contamination**.
- **Aquiculture**, that provokes the crossing between species which escape from the fish farm.

2.2.1. Situation of the eel

Among the species and subspecies from the *Anguila* gender around the world, *Anguilla Anguilla* and *Anguilla rostrata* can be found in the Atlantic Ocean. The hypothesis of pan-mixing implies that the European eel constitutes one population which reproduces in the Sargazos Sea, but recent research established that not only they have different genetic features, but the *Anguilla Anguilla* form different groups (depending on the geographical, ecological and biological specifications). They are the Mediterranean, the North Sea, and the Atlantic group. This diffusion phenomenon is explained by the scarce swimming capacity of larvae. Most of these larvae migrate to the East, in the middle part of the Gulf Stream. And afterwards, the North Atlantic Drift or the Azores current allow some of them to reach the Northern or the Mediterranean parts, respectively.

Reviews of the available information on the status of the stock and fisheries of the European eel supports that the population, as a whole, has declined in most of the distribution area; that the stock is outside safe biological limits, and current fisheries are not sustainable. Recruitment is at a historical minimum, and most recent observations do not indicate recovery. Both populations, European and American, show a similar decrease in the abundance from the end of the 1970. Obviously, the situation is different in each catchment, and each one can represent the object of study of a report with own its characteristics.

It has to be considered that human constructions have provoked the catchment fragmentation and restricted the accessibility to countless habitats located in medium and high zones of the rivers, much less degraded, resulting in a diminution of the distribution colonization area. This effect has been more noticed in the colonization of peripheral areas, like the Scandinavian countries.

At the same time, the degradation of the habitat quality, like the increase of the contaminants as a consequence of the agriculture, has affected the situation of the specie in the last years. Indeed, the eel is a sensitive fish, which can accidentally accumulate these contaminants in its fat. A study in Belgium showed that the 80% of the samples exceeded the threshold of PCB above 75µg/kg (Goemans & Belpaire, 2002). And in 2008 in the Seine River, France, the high concentration of the same substance, provoke the forbidden of selling the eels captured in this catchment (Robinet & Feunteun, 2003; Thuillard *et al.*, 2005)

2.2.2. Situation of the salmon

A study about the evaluation of the Atlantic salmon explains how the number of individuals has decreased. Salmon was present in 2005 rivers on both sides of the Atlantic Ocean; nowadays the wild specie has disappeared in Germany, Switzerland, Holland, Belgium, Czech Republic and Slovakia, and it is near the extinction in some other countries as Estonia, Poland, United States and some areas from Canada. The 90% of the healthy populations are only in four countries: Norway, Ireland, Island and Scotland. In the rest of the areas it is considered as vulnerable, threaten or critic.

Cesar Rodriguez Ruiz, from AEMS-Rivers with Life, and scientific assessor from WWWF/Adena, ensured: “it will not be possible to safe our salmon populations if we only manage them in terms related to its capture, and not prepare a management action for its conservation”.

2.3. Downstream fish migration related to Small hydropower plants

The origin of the problems of migration is the modification in the environment needed to create the installation, which constitutes an obstacle in the natural river which has to be surpassed by fishes.

In the migration of the fishes to their new habitats it has been observed a delay of even weeks. Some causes are the time fishes need to find the passage which allows them to exceed the punctual installation and the decision to stop to rest during the migration.

In general terms the probability to pass by the turbines or by the dam depends on:

- The ratio which relates the turbine flow to the river flow.
- The configuration of the intake canal and dam.
- The migratory fish behavior.

The next paragraphs explain several manners how the obstacle the facility represents can be surpassed and its factors involved.

2.3.1. Crossing the spillway

It can provoke direct death of fishes as a consequence of injuries or collisions, or indirect as a result of the increase of the sensibility to the depredators after fishes become weaker and disoriented. Indirect death can reach 30% in some cases.

The situation which takes place when fishes traverse the spillway can be similar to the free fall. Fishes have a certain fall velocity depending on its size and the jumping height, this constitutes the limit velocity, which can be compared with a terminal velocity. Limit velocities according to the fish size are:

Table 1. Limit speed for different fishes sizes.

Fish size	Jumping height	Limit speed
10-13 cm	25-30 cm	12 m
15-18 cm	30-40 cm	15-16 m/s
>60 cm	>200 m	58 m/s

Smaller fishes will not reach a limit speed which can exceed the terminal speed independently the jumping height; and bigger will not be damaged while the terminal speed is not exceeded.

Some studies have revealed that the terminal velocity is 15-16m/s, independently of the fish size. It is consequence of significant damages in the animal vital organs: the gills, eyes, and intern organs.

Despite of the variability of the results, some conclusions were done:

Table 2. Percentage of mortality

Percentage of mortality	Height of the dam
0-40%	30 m
100%	60 m

2.3.2. Going through the turbines

The main reasons of the mortality in the turbines are:

- **Mechanical injuries**. They are a consequence of the collision and contact with turbine components. Hurts in bones, loss of eyes, abrasions, and cuts in the body are some of them.
- **Big pressure changes**. Changes in the hydrostatic pressure take place when water goes through the different parts of the turbine. They cause internal hemorrhages and changes in the volume of the gaseous bladder, which are impossible to control for the fish. The effects depend on the situation of the fish in the water column.
- **Hydrodynamic changes**. Turbulence of the water causes contusions, abrasion, lacerations, and cuts in their bodies. It affects the bronchus, and can cause fish decapitation. This factor causes more mortality than the changes in the pressure.

Some data have been collected about fish mortality depending on the different turbine types and the species object of the report. Despite this, some fish friendly turbines are being developed nowadays to reduce the mortality.

It can be observed that Eels have higher mortality rates than other fishes owing to its morphology, its relation between height and size that make them more vulnerable.

Table 3. Mortality based on the fish and turbine type.

Turbine	Percentage of mortality	
	Salmonids	**Eels**
Kaplan	5-25%	16-38%
Francis	5-80%	40-95%
Pelton	100%	100%

2.3.3. Deviations

Different system have been developed aiming to guide fishes to surpass the facility.

Positive barrier screens

The fish access to the dangerous areas can be avoided installing racks. They constitute physical impediments and should gather the following requirements:

- The spacing should be smaller than the smallest size of the design fish.
- It should be an alternative passage for the fishes continuing its itinerary.
- Water speed has to be small enough not to hamper fishes swimming during the necessary time for finding the alternative way.

There are several kinds of racks which can be more suitable in accordance to the installation conditions. Among them: the temporal racks, the rotating racks, the detector racks, the Eicher racks, the hydrodynamic screens and the static screens.

Behavioral screens

They are based on influencing the fish behavior and inducing its displacement. They are usually designed for small and fragile fishes that can escape the racks. They are bubble screens, illuminated screens, resonant screens and electric screens, depending on the basis of their functioning.

Their advantages are their low maintenance and cost requirements, but the big disadvantage is that they should to be tested for each situation to prove its effectiveness. Some examples of its functioning with salmon have been collected:

- 15% efficiency (8-28%) of an electric screen guiding smolts to a bypass with a 20 m long screen.
- 0% efficiency of an acoustic screen combined with an air bubble curtain to guide smolts to a bypass.
- 0% efficiency of an acoustic screen repelling smolts from an intake canal entrance.
- An increase of the efficiency by installing a night lighting device to attract the smolts. Very efficient on low velocity intakes.

Deviation systems

They can be located in different points of the installation. On the one hand a by-pass channel can be constructed to make the fish round the whole installation and avoid the entrance to the derivational channel in the direction to the turbines. On the other hand fishes can be allowed to enter into the derivational channel, and once in there, they can be derived through a special fish passage avoiding the turbines.

Among its requirements: their geometry has to minimize collisions which can damage the fish, turbulence and parasitic currents have to be reduced, and velocities should be moderated. Another challenge is avoiding the obstruction with sediments carried by the same flow. Its efficacy leads to the way it is installed and the hydrodynamic conditions of the placement.

2.4. Downstream fish migration and its environmental factors

The conclusions about the downstream migration of the eel have been picking up from a research which was made in a run of river power plant in the Urola River (Altuna Txiki, Guipuzkoa, 2013).

PIT divides were installed in 89 eels and only 12 of them were radio marked. Marking and following the eel allowed them to study its behavior as well as the characteristics of the migration period and the instantaneous migration peaks. Observations led to the following conclusions:

The migration of eels can be considered a phenomenon which happens when some environmental factors occurs at the same time. Depending on the frequency and the duration of these favorable conditions for the migration, the distance to the sea, and the presence of obstacles, eels can finish its itinerary in a different time; some of them can even stop its migration and wait until the next year (more common in long rivers)

Among these environmental factors: an increase in the discharge and in the water turbidity, as well as a decrease in the water conductivity and temperature, (which means low luminosity), are considered the most relevant. Contrary it was believed, the full moon periods seem not to be as relevant, and they are only associated due to the photophobic character of the specie.

The delimitation of the migration period was being done between October and January, with a maximum peak in November. Also the 91% of the migration took place with a discharge which has the 27% of probability to be exceeded during the period. These limitations match with other studies made in other rivers with similar latitudes.

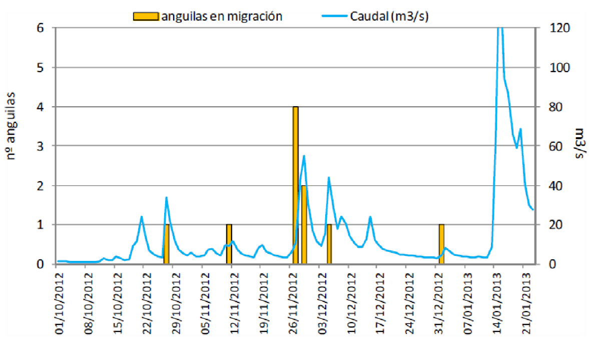

Figure 7. Water discharge and eel migration.

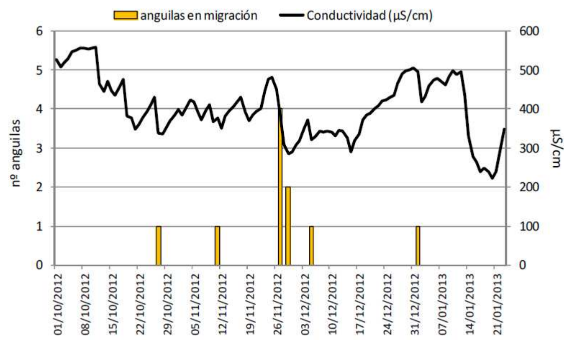

Figure 8. Hydraulic conductivity and eel migration.

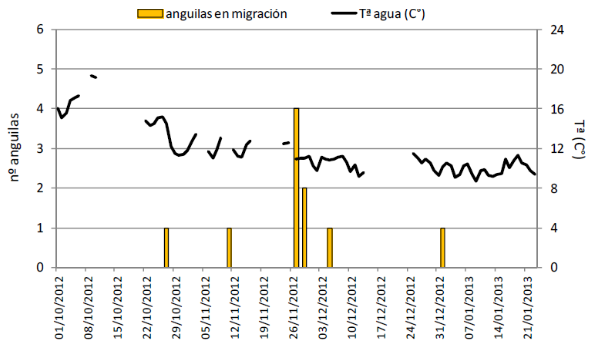

Figure 9. Water temperature and eel migration.

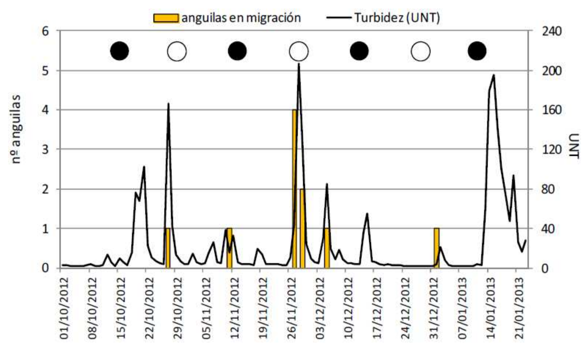

Figure 10. Water turbidity and eel migration.

2.5. Intakes in ROR power plants

Intakes are the parts of the hydropower installation designed to divert the water from the natural catchment to generate electricity. They act as a transition zone between the natural river, which can be quiet or really turbulent, and the derivation channel, in which water has to be controlled quantitative and qualitative.

2.5.1. Intake design criteria

It has to be designed according to geomorphologic, hydraulic, structural and economic considerations; these measures will avoid the operation and conservation problems during its useful life. Intake design usually follows 3 criteria:

- **Hydraulic and structural**: common for all the intakes structures.
- **Operational**: discharge control, debris elimination, deposition of sediments. Specific for each case.
- **Environmental**: fish protection to the turbines and fish ladders. Specific for each case.

2.5.2. Functioning intakes requirements

To ensure an adequate functioning it is necessary to gather some requirements:

The uniform production is one of the most relevant concerns in the viability of a small hydropower project; hence the importance of minimizing the head loss caused by the diversion of the water.

For instance, the transition of the water profile should reduce the separation of the water veins, aiming to obtain an even acceleration. Then it is necessary to pay special attention to areas in contact with the walls and the bottom, as well as in the points where direction changes.

Vortex can be formed as a consequence of the change in the cross section, from the rectangular one of the rack to the circular corresponding to the pressure pipe going to the turbine. They increase head losses and decrease turbine efficiency; in fact, manufacturer only ensure the efficiency of their turbines if the water flow distribution before the turbine is uniform.

There is not a formula to avoid turbulence in the flow, but the right submergence of the pressure pipe and a symmetric water current helps to avoid it drastically. Additional avoidance of vortex formations can be achieved through inhibitors.

2.5.3. Intake elements

Intakes are composed of several elements with different functions. Among the most important it can be found:

- **Racks**. These are located to avoid the debris carried by the flow as well as the animals going into the turbines. The spacing among the bars is decided depending on the size of the particles expected or the maturity of the fishes to protect (normally between 3 and 20 cm). The cleaning of racks can be done by several methods, automatically or manually, and obviously, it has to be adapted to the kind of rack and its characteristics.

- **Desanders and flushing system**. Its mission is to achieve the highest settlement of the suspended particles carried by the flow in order to avoid them going into the installation, and to flush them afterwards. In some places this can be an important issue if the particles carried by the water can induce high wear in the turbines.
- **Sluices**. They control the water discharge going through. Normally one is located upstream to stop the flow in maintenance cases; and other downstream for the normal operation tasks.
- **Fish ladders**. A channel in one of the margins of the installation in order to communicate the levels downstream and upstream and allow fishes to migrate.

2.5.4. Types of intakes according to its position

The location of the intake can be influenced by many factors as the river geometry, the geotechnical conditions, environmental concerns, sediment exclusion, and ice conditions (where required). Not only the location, but the orientation related to the flow is crucial: it is important to avoid locating it in a dead area where the deposits will probably gather, and it is recommendable a parallel location to the spillway.

It is important to recognize the kind of intake which is needed in each situation. There are three different types found:

- **The lateral intake**: in the out part of the river bend, avoids the entrance of bed and suspended material carried in the flow.
- **The front intake**: built in countries where there is a big sediment yield to deal with, it is provided with an appropriated flushing system which is frequently operated.
- **Mountainous or Tyrolean intake**: as its name says, it is located in steep rivers usually found in its initial parts in the mountains. It is formed by a rack in a cross section on the bed of the river.

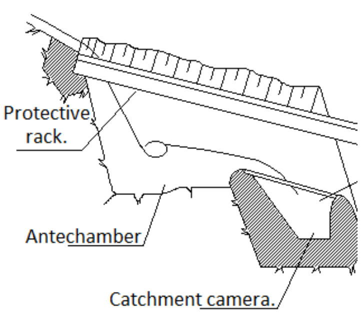

Figure 11. Tirolean intake.

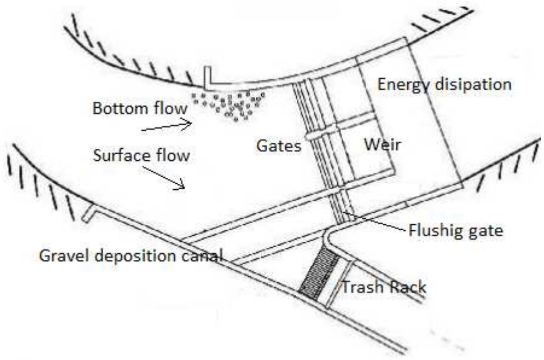

Figure 12. Lateral intake.

2.6. Fish passages

Fish passages are hydraulic structures that break the discontinuity caused by the construction of the run of river power plant in the natural river. They consume water volume, and this volume is added to the one which is spilled, representing the environmental flow.

The efficiency in the fish passages is regarded as the fish proportion able to go through the system with respect to the amount of fishes which try it.

The design of every fish passage should take into consideration these four requisites to succeed:

- **Adequate capacity**: coherent dimensions for the size of the river, its fish populations, and the flow. Migration can occur massively in little time, and it should be able to manage it.
- **Adequacy to fish swimming capacity**: rewarding the swimming speed and the jumping skills. The design should be thought for the less capable.
- **Permanent functioning**: for all river discharges.
- **Correct position**: it should be easy and fast to find for the fishes.
- **Adequate design and outlet.**

More studies about upstream migration has been done than rewarding downstream migration, but since some fish populations have decreased in the recent years, this topic has became more prominent.

3. Theoretical Background.

In this chapter, the more specific knowledge that can support the assumptions in the report is gathered together. Firstly, the one related to hydraulics is explained as the basis of the test and results, and secondly, a section with more specific considerations and conclusion about fish migrations and intakes.

3.1. Intake hydraulics

3.1.1. The Head loss

Run of river hydropower plants can assume less head losses, as a result all the parts that compose the model has to be carefully studied in order to minimize it. The total production of the plant is calculated with the power equation.

$$P = \rho \cdot g \cdot \eta \cdot Q \cdot H \quad \text{(Eq. 1)}$$

while:
P is the total production in Watios.
ρ is the water density (kg/m^3).
g is the gravity acceleration (m/s^2).
η is the efficiency of the system.
Q is the discharge through the generation group (m^3/s).
H is the height (m).

In addition the punctual head loss occasioned by the parts of the model can be also estimated:

$$\Delta H = k \cdot \frac{v^2}{2g} \quad \text{(Eq. 2)}$$

while:
ΔH is the head loss caused (m).
k is an empirical coefficient.
v is the velocity of the flow in this point (m/s).
g is the gravity acceleration (m/s^2).

Depending on the element or part of the system, the value of k will be determined in a differently. In this report, Kirschmer's formula has been used. This formula allows to computes k as a function of the rack characteristics:

$$\Delta H = Kf \cdot \left(\frac{t}{b}\right)^{\frac{4}{3}} \cdot \left(\frac{v^2}{2g}\right) \cdot \sin\alpha \cdot K\delta \quad \text{(Eq. 3)}$$

while:
Kf is a coefficient depending on how the flow attack the bars.
t is the thickness of the bars (m).
b is the spacing among the bars (m).
v is the velocity of the flow through the rack (m/s).
g is the gravity acceleration (m/s^2).
α is the angle between the rack and the horizontal (º)
$K\delta$ is a coefficient depending on the oblique flow to the rack.

3.1.2. Turbulence in a flow

A turbulent flow is characterized by a chaotic movement of the flow that makes it at some point unpredictable. In it, particles move disorganized and forming non periodic swirls. It usually occurs with high flow speeds or in low-viscous flows. A good example is normal courses in rivers.

Reynolds number combines three physical parameters of the flow conditions and constitutes the criteria to delimit the occurrence of this phenomenon:

$$Re = \frac{u \cdot L}{\nu} \qquad \text{(Eq. 4)}$$

- **The length of the flow of the study (L):** The longer is the length the easier is the flow to become turbulent.
- **The velocity (u):** A high velocity helps the turbulence to form.
- **The cinematic viscosity (ν):** Low values promote turbulence.

Flows, for our field of study, are considered to be turbulent for Reynolds numbers above 4000 (Moody diagram).

During velocity measurements, the total velocity of a point of the flow can be described by its decomposition in two different values: mean velocity and the velocity fluctuation. These two respond to the Reynolds decomposition of a flow

Reynolds decomposition stands that the velocities measured over time can be divided in two: the mean velocity, which is determinate by long-time averaging; and the velocity fluctuation which contains all other components of smaller time-scale.

$$u(t) = \bar{u} + u'(t) \qquad \text{(Eq. 5)}$$

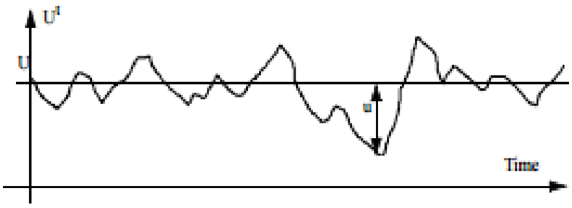

Figure 13. Reynolds decomposition.

In cases where the turbulence is expressed in the three main directions, the intensity of turbulence, the Turbulent Kinetic energy (TKE), can be calculated following the formula below.

$$k = \frac{1}{2} \cdot \left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right) \qquad \text{(Eq. 6)}$$

3.1.3. The continuity equation

This formula will provide the relation among discharge Q in m^3/s, the velocity v in m/s and area A given in m^2.

$$Q = v \cdot A \qquad \text{(Eq. 7)}$$

3.2. Hydraulic parameters of the migration

When studying the flow near the rack parameters in relation to the head loss and the obstruction have to be considered, but much more requisites have to be handled when fishes are involved.

First of all, there is a limitation of the velocity in the area nearby the rack due to the fishes swimming capability. It is proved for both the eel and the salmon, that this velocity (in a normal direction to the rack) is 0.5m/s. This maximum speed sets the minimum rack surface for a given turbine discharge.

At the same time, inclined racks are proved to obtain tangential velocities able to guide the fishes to the desired point. With a minimum inclination of 26º, tangential velocities can be twice the normal velocities motivating fishes to change their position in the flow.

Another significant factor of the rack is the spacing among the bars. At this point both species have to be analyzed separately. The eel tend to go in contact with the rack and force their way through it, while on the other hand, a larger spacing rack has a repellent effect on the smolts. As a consequence, it is possible to install efficient behavioral spacing for salmons, but not for eel. As their physiognomy is different, the spacing values will not be common:

Table 4. Recommended spacing for the racks.

Specie	Maximum spacing.	Fish size.
Salmon	1 – 1.5 cm	10 – 15 cm
Eel	1.5 – 2 cm	50 – 60 cm

Conversely, with a decrease of the spacing, there is an increase of the head loss, as well as the amount of trash stopped. And the cleaning systems have to be adapted to the spacing chosen in terms of geometry and operation.

About the bypass, its minimal width and water depth recommended at its entrance is 0.5 m to limit hesitations of fishing to go through. Conclusions from a research quantified the eel crossing the facility, and the bottom passage was found to be from 3 to 4 times more used than the surface bypass.

It is relevant to remember that the flow through the bypass can be regulated to be variable during the year: higher during principle downstream migration periods, and lower during the rest of the year. This is a promising common point to ensure the migration and avoid elevated head losses, but the migrations peaks need to be further studied.

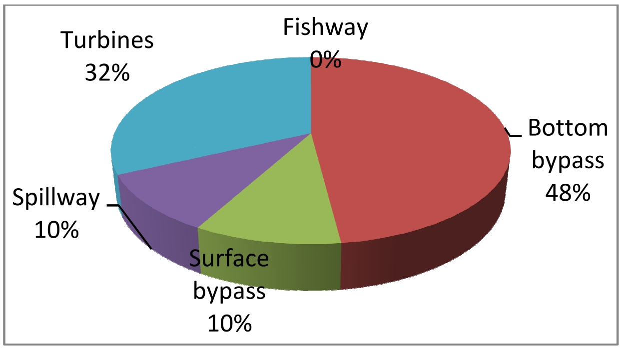

Figure 14. Probability and manners to surpass a hydropower facility.

4. The scale model

4.1. Proposal of the model

The H-rista model, whose name refers to the horizontal rack that characterizes it, has been built in the hydraulics laboratory at NTNU, Trondheim, Norway. It is expected to be a cost-efficient solution in terms of construction, operation, maintenance as well as a fish friendly solution able to ensure the species migration. Operationally, it is based on the flush backing concept to deal with the obstruction of the rack caused by the debris accumulation; and furthermore it tries to use the same process to induce the fishes to discover an alternative way to the turbines. It seems to be a promising intake method able to handle with several of the most important difficulties in the current intakes.

4.2. Geometrical description of the model

The overall model is contained in a 2.5 meter long, 1 meter tall and 0.35 meter width box. It is composed of two chambers situated consecutively. The first one is the tank where the water arrives from the intake pipe representing the intake discharge (Q_{in}). In addition, a spillway is installed in order to protect it from a flood.

An intake gate communicates both chambers. Some of its dimensions are constant, as the width 0.3 meters, or the initial point of its aperture from the bottom part of the model at 2.5 centimeters; nevertheless the main parameter is the height of the gate (Hi), which is variable. During the tests, due to the time availability, it has been considered to be a constant parameter, 0.21 meters.

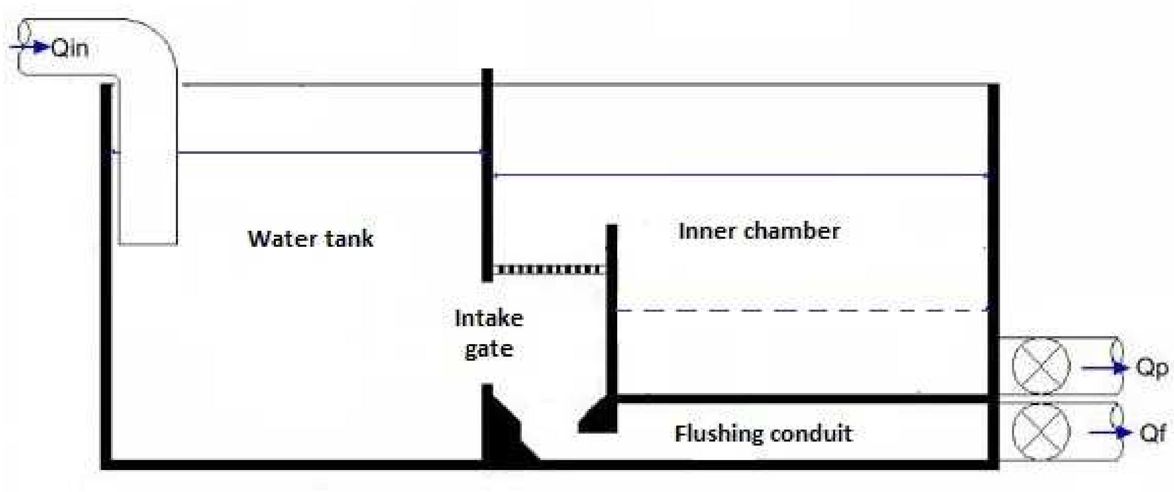

Figure 15. The chambers and the general water flow.

The second chamber is the inner chamber where the operational phenomena happen with a length of 0.5m. During the normal operation, water from the intake will flow through the horizontal rack to the inner chamber in order to reach the pipe, at its end part, which devices the water to the power house; this pipe represents the production discharge (Qp), the amount of water destined to produce energy. In addition, there is a long passage in the lowest part of the model, below the inner chamber, communicating both parts of the installation and constituting a flushing conduit through which the debris and fishes can be diverted to an alternative pipe. That one, will conform the flushing discharge (Qf), the water amount to be flushed and separated from the energy producing part of the model. Water, fishes and debris will flow into it during the flash backing process when necessary.

The racks are the most important elements in this model to consider. The dimensions of the horizontal rack are 0.28 meters long and 0.35 meters wide. Its bars are 3 millimeters of thickness (br) and 20 millimeters depth (pr), and the spacing between them is 8 millimeters (sr).

The inclined rack is used for representing two different situations adapting the angles of 38.9 and 28.7 degrees. Its main dimensions are 0.41 meters long and 0.35 meters wide. The bars characteristics are shared with the horizontal rack.

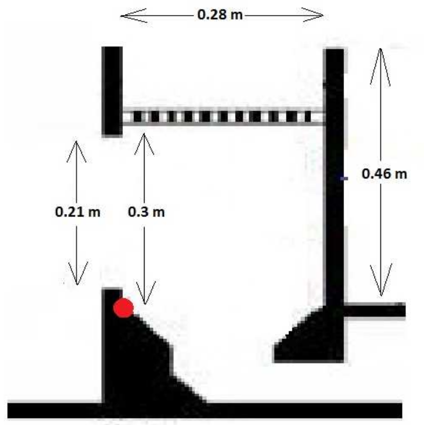

Figure 16. Measurements with the horizontal rack.

There is only one extra component needed for this new intake concept. A 0.46 meter wall constituting a weir is located perpendicular to the horizontal rack in order to separate the water up and downstream the rack, and subject the rack. With the inclined racks, this wall reduces or is not longer necessary.

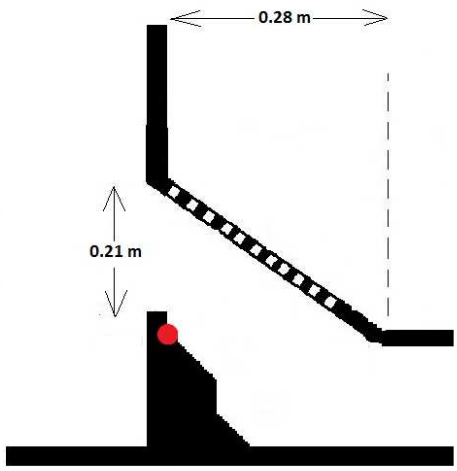

Figure 17. Measurements with 39º inclined rack.

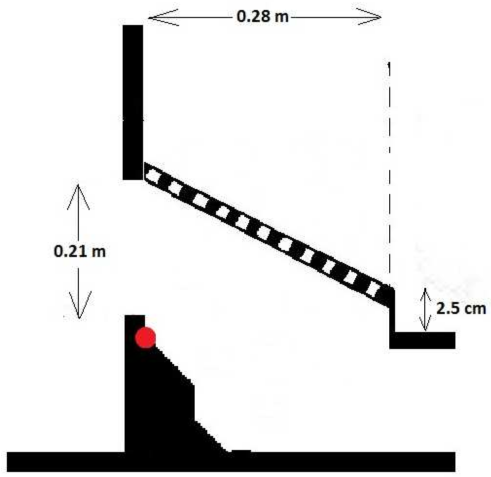

Figure 18. Measurements with 29º inclined rack.

A coordinate axis has been adequate to the model owing to ease the understanding of the situation of the parts during the report. As it has been seen in the figures before, a reference point has been selected as an origin of the coordinates for locating the points around the different racks during the most specific tests.

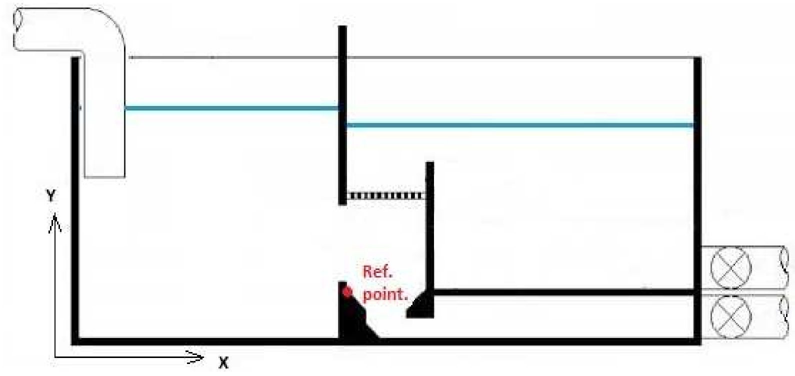

Figure 19. General coordinates of the system and reference point.

4.3. Hydraulic performance

4.3.1. Operational processes

Two operational processes govern the hydraulic performance of the intake. Despite they are opposite phenomena, both can occur at the same time. The difference resides in the predominance of one above the other, allowing an environmental flow while production, as well as, a continue production while flushing.

The operational process aim is obtaining a cost-efficient energy production. During this process the most of the water will flow from the intake through the rack along the inner chamber in the production pipe. At the same time, debris and fishes will not be able to access to the inner chamber remaining upstream the installed rack. The environmental flow, necessary to maintain the adequate conditions in the natural river downstream, will be a percentage of inflow water of the intake (between 5 and 20%).

On the other hand, the back flushing process occurs in order to eliminate the possible debris which can obstacle the rack during the operational time, as well as provide an alternative main flow which can be followed by the fishes which swim in the area before the rack. It represents a decrease in the efficiency of the model.

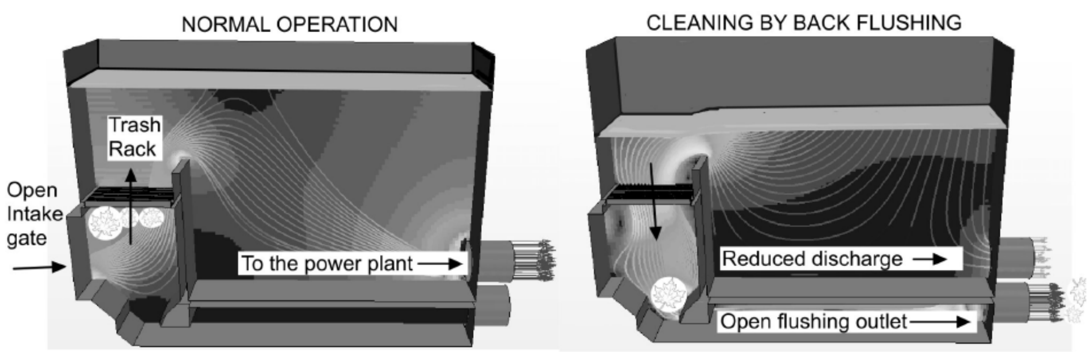

Figure 20. Operational phases of the model.

4.3.2. Back flushing

A specific flow pattern should be obtained to achieve all the requirements explained before about the back flushing. This flow is characteristic because it goes in the opposite direction that the normal flow does. Water from the inner chamber will be induced to go back through the rack and down to the lower passage until it reaches the flushing pipe. In this itinerary, the water flow will carry with it all the debris obstructed near the rack, and influence the fishes swimming in the surroundings to follow this main flow which devices them outside the energy generation part.

This phenomenon was studied previously in the same scale model reaching some conclusions that will ease to describe the operation phase in more detailed.

Back flushing variables

There are several methods the flushing can be done depending on the decision of how much the control sluices, the intake gate and the production pipe, should be closed.

Firstly the production pipe and the intake gate can be shut while the flushing pipe opens; consequently a free surface flow will be really efficient in cleaning of the debris. However a high pressure difference will be caused on both sides of the intake gate, and during the reopening, a jet will occur endangering the neighbor components durability. This jet hits the rack and the weir.

An open or partially open intake gate during the flushing will increase the water volume for flushing, although it will reduce the efficiency of the back flushing.

Figure 21. Jet while reopening of the intake gate.

Back flushing efficiency

There are 3 criteria that have been identified as the most relevant to affect the flushing operation: the velocity distribution, the average flushing velocity and the pressure difference over the rack at the initiation of the back flushing.

- The velocity distribution over the rack is required to be as uniform as possible to eliminate the clogged materials in the same way along the entire length of the rack.
- The average flushing velocity over the rack, should accomplish:

$$\frac{\overline{v_{r,f}}}{\overline{v_{r,max}}} > 0.4\ m/s$$

  while $\overline{v_{r,max}} = 0.5\ m/s$, is the average velocity through the trash rack for the design of an intake structure for a small hydropower plant, (Jenssen at al. 2006).
- The pressure difference at the initiation of the back flushing should achieve the relation given by Nøvik *et al.* (2014).

$$\frac{\Delta p}{Hr} > 0.1$$

The criteria above are influenced by the operational strategy, governed mostly by the intake opening; and the design of the structure. At the same time, the most important design parameter affecting the efficiency of the back flushing system is the capacity of the flushing (Q_f). A certain capacity of the flushing system is required in order to obtain a sufficiently high flushing velocity over the trash rack. Q_f/Q_{max} should be larger than 1.0 in order to obtain both, a high enough flushing velocity and rapid pressure difference.

Flushing duration

Most debris will be removed at the initiation of the back flushing, however a definition of back flushing duration has been developed to define the total time needed to convey the debris out of the flushing gate, Nøvik (2013).

The duration will be limited by the critical height that can be reached in the inner chamber in order to avoid air entrainment in the pipe. This critical height depends on the submerged of the production pipe. Formulas provided by Knauus (1987) facilitate its calculations.

In previous reports a 6 seconds flushing duration was the limit time to maintain all the criteria explained in the previous section and ensure the flushing efficiency. (Nøvik *et al.* 2014)

4.4. Theory of physical models

Physical models are within the numerical methods, the most recent tools used to investigate the water behavior. They try to represent the real hydraulic situation to find a technical and economic solution for an engineering problem. Scaled models are physical representations of a particular hydraulic structure; while numerical methods are mathematical representations of a physical system which governing equations are solved using a computer.

4.4.1. Advantages and disadvantages of physical models

Some of the advantages of physical models are that they give an immediate visual feedback, and then full fluid physics can be observed directly. This helps to understand the phenomena that occur at the moment, even for those who are not experts on the topic, like stakeholders around the project. Simplifying assumptions can be avoided; improvements in the reliability of the solution occur, and what it is more, measurements can be obtained for extreme conditions.

The most remarkable disadvantage is the existence of the some inaccuracies when the model tries to represent the prototype. First, the scale effects appear as a consequence of the inability to simulate all the relevant forces in the model at the proper scale. They would be always present in the most of the scaled models, but in a different magnitude. And secondly the laboratory effects; they are those differences that arise from the limitations of space, model construction, or instrument and measuring methods.

4.4.2. The similarity law

In order to be able to have reliable results from the test done in the model, they have to be similar to the response which would have been given by the prototype. In this case, it can be said that exist a similarity between both, the prototype and the model, and results from the model can be extrapolated to the reality in the prototype.

Exists a law of Similarity which governs the similarity related to all the physical phenomena involved in the model: geometrical, kinematical and dynamical; it relates all the physical phenomena involved in the model.

- **Geometrical similarity** refers to all the dimensions which shape the model. It exists when the ratios of all the corresponding dimensions between prototype and model are equal. The scale ratio is Lr.

$$Lr = \frac{Lm}{Lp} \quad \text{(Eq. 8)}$$

- **Kinematic similarity** indicates similarity of motion between fluid particles. It is achieved when the ratio between corresponding components of all vectorial motions is the same in the model and the prototype.

$$Vr = \frac{Vm}{Vp} \quad \text{(Eq. 9)}$$

- **Dynamic similarity** refers to the forces and the masses that influence the flow situation. It is the most important prerequisite for physical modeling. It ensures that there is a constant prototype-to-model ratio of all masses and forces acting on the systems. It is achieved when the ratios of all vectorial forces in the two systems (geometric and kinematic) are the same.

$$Fr = \frac{Fm}{Fp} \quad \text{(Eq. 10)}$$

It arises from Newton's second law that equates the vector sum of the external forces acting on an element to the element's mass reaction to these forces.

$$\sum_n Fn = m \cdot \frac{dV}{dt} \qquad F = m \cdot a \quad \text{(Eq. 11)}$$

4.4.3. Froude's model law

The theory of similarity ensures the needed to accomplish the similarity of each force acting on the model, the contrary the results obtained at one scaled might not be transferable to different scales. Conversely, while the model is smaller than the prototype, there is not known fluid that will satisfy all force ratio requirements at the same time. Therefore, it is an important task in scale model design to find the most important force ratios to relate, while providing justification to neglect the others.

On the one hand, Reynolds similarity relates the inertial force with the viscous force. It is the main similitude criterion for flows where the viscous forces are important, and the fluid shear should be considered.

$$\frac{Inertial\ force}{Viscous\ force} = \frac{\rho L^2 V^2}{\mu VL} = \frac{\rho LV}{\mu} = Re \qquad \text{(Eq. 12)}$$

On the other hand, Froude similarity relates inertial to gravity forces. It is used when the flow is driven by gravity, as it happens in open channels flows and spillways. Almost all models of rivers and hydraulic structures are operated according to the Froude model law.

$$\frac{\sqrt{F_i}}{\sqrt{F_g}} = \frac{\sqrt{Inertial\ force}}{\sqrt{Gravity\ force}} = \frac{\sqrt{\rho L^2 V^2}}{\sqrt{\rho L^3 g}} = \frac{V}{\sqrt{gL}} = Fr \qquad \text{(Eq. 13)}$$

The last similarity criterion is the one used in the report due to the adequacy of the characteristics of the flow. In the next section the relation between all the parameters in the model and the prototype are shown.

4.4.4. The scale in the model

The model was scaled in the biggest possible scale to construct, 1:5. According to the theory applied, the following are the relations among the prototype and model magnitudes:

Length $L_m = \frac{L_p}{5}$	**Area** $A_m = \frac{L_p^2}{25}$	**Velocity** $V_m = \frac{V_p}{\sqrt{5}}$
Time $t_m = \frac{t_p}{\sqrt{5}}$	**Discharge** $Q_m = \frac{Q_p}{5^{2.5}}$	**Force** $F_m = \frac{F_p}{125}$

(Equations from 14 to 19 respectively)

In accordance with these formulas, all the numerical data have been adapted from the real intake facilities to the model. Thanks to this, results from the tests proposed in the model will be representative enough for the development of research.

5. Testing in the model

As it has been commented before, the hydraulics features of the project were assessed in previous researches in order to ensure a correct functioning of the installation; but it cannot be neglected the environmental aspects of the intake aiming to ensure the downstream fish migration. Consequently, it has been proposed in this report assessing the velocity distribution of the chamber located upstream the rack during the normal operation, to ensure the fish requisites in this part of the installation, observe its problems and propose new details

The chamber where the measurements will take place constitutes the union of the three different parts of the model, the water tank (before the intake gate), the inner chamber (downstream the rack, where the production pipe is located) and the flushing conduit (connecting with the flushing pipe). For this reason, in this chamber the flow pattern will be the most unexpected, and therefore a study to ensure that the fish requirements related to the flow are accomplished is necessary.

5.1. The description of the tests

Only two kinds of measurements were done: punctual flow velocity measurements and measurements of the height of the water level. But at the same time, they were organized in different tests according to its purpose.

Test 1: Velocity measurements in 9 determined points located above the horizontal rack, with and without the rack.

The purpose is the comparison of the velocities with and without the rack, in order to check if the rack is necessary to have accurate velocity values in the rest of the tests.

Test 2: The velocity measurements in the chamber upstream the rack during the normal operation in 33 concrete points with three different racks: horizontal, 39 degrees and 29 degrees inclined rack.

These measurements are used to complete a velocity field for this part of the model, as well as obtain the normal and parallel velocities nearby the rack in all these three different situations.

Test 3: Measurements of the water level surface before and after the rack for the two inclined racks.

The aim is to compute the head loss for each rack proposed and compare it with the information provided from previous reports.

5.2. Considerations during the tests

The geometrical flexibility of the model offers multiple possibilities of each of its parts. In this section, the specific considerations the tests have been carried out according to are explained.

5.2.1. The intake gate

The intake gate opening was 0.21 meters. This opening was maintained during all the tests in order to become a constant and ease the comparison of the velocity fields changing other parameters of the model.

5.2.2. The racks

Since in the previous research it was demonstrated a high head loss due to the horizontal rack, it was immediately planned to try with other geometrical shaped racks. For this reason tests have been assessed with two different racks: the horizontal and an inclined rack, (collocated with two different angles 38.9 and 28.7 degrees).

It has to be noticed that to be able to install the same inclined rack with the same dimensions in the model, but with a changed inclination (from 38.9 to 28.7 degrees) it was necessary to move the in intake gate 2.5 cm upstream. At the same time, no more changes in the model were induced from this variation.

5.2.3. The inflow discharge

The discharge going into the model (Q_{in}) was decided according to the velocity needed near the rack. Therefore with numbers from the prototype: from a velocity of 0.5 m/s, the area of the rack, and according to the continuity equation (Eq. 7), a discharge of 23.5 l/s was estimated.

5.2.4. The two outflow discharges

The discharge destined to the production is reduced depending on the amount of water needed for the environmental flow in the flushing pipe in the normal operational phase. During our tests, the environmental flow was established to be around 5%.

Everything considered, both outgoing discharges, through the production and flushing pipe were 22.3 and 1.2 l/s respectively; whereas, with the same velocity restrictions near the rack and other rack geometry, different discharges can be assessed.

5.2.5. Testing with fish species

Even though the report is focused on the behavior of the fishes in the flow prepared for them in the chamber before the rack, tests have been carried out without real fish species. This is due to the several certifications required for it. In fact, as a consequence of the importance of evaluating the fish behavior in the most real habitat that can be arranged, further research is planned to be developed in a higher scale model with real species.

5.3. The devices

The following are the gauges used to compile and organize the data extracted from the tests:

5.3.1. The data register

The data register, Agilent U2300, used in order to compute the signals from the laser and flow gauges. It is a USB Modular Multifunction Data Acquisition device useful for data logging, measuring and monitoring.

Figure 22. Agilent USB

5.3.2. The water surface device

Laser gauge from KBK, 10,/IU/TC 4-20mA + 0-10V, with an accuracy of 1%. As it can be seen in the figure 26, it was located in two points, the water tank and the inner chamber.

5.3.3. The velocity measuring

An Acoustic Doppler Velocimeter (ADV), or Vectrino. It is a high-resolution acoustic velocimeter used to measure 3D water velocity, adequate for applications in the laboratory. The basis measurement technology is coherent Doppler processing, which is characterized by accurate data with no appreciable zero offset.

The device emits an acoustic signal to a determinate point from the transmitter. The pulse propagates through the water column and it is reflected by the suspended particles moved by the flow. The received signal is computed and transform to the needed data at the measured point, thanks to Doppler and wave principles. These measured points are located 5 cm from the head of the device.

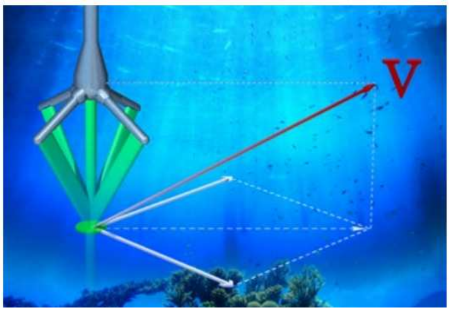

Figure 23. Measuring procedure.

As a consequence of the location in the model of the points necessary to measure, two different gauge models have been used:

i. Vectrino 3D Downlooking, fixed stem, for those points above the rack

Figure 24. Vectrino 3D downlooking fixed stem and detail of this head.

ii. Vectrino 2D-3D Sidelooking, Cable Probe, for the rest, below the rack.

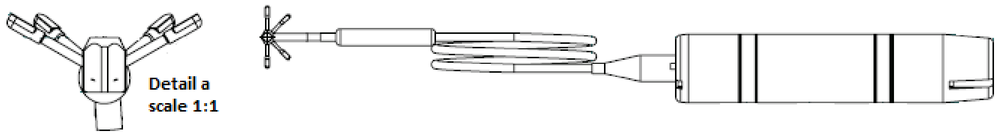

Figure 25. Vectrino 3D sidelooking cable probe and detail of this head.

To ensure the accuracy of the measurements it is necessary to achieve the thresholds for the values of the correlation and the SNR, which are 70 and 15 respectively.

5.3.4. The flow water meter

The flow water meter SITRANS F M MAG 5000 combined with the SITRANS F M MAG 5000W sensor from Siemens, has a measuring accuracy of ± 0.4% of the flow rate (incl. sensor). It was located in the main pipes governing the water income and outcome of the model: Q_{inflow}, $Q_{flushing}$, $Q_{production}$.

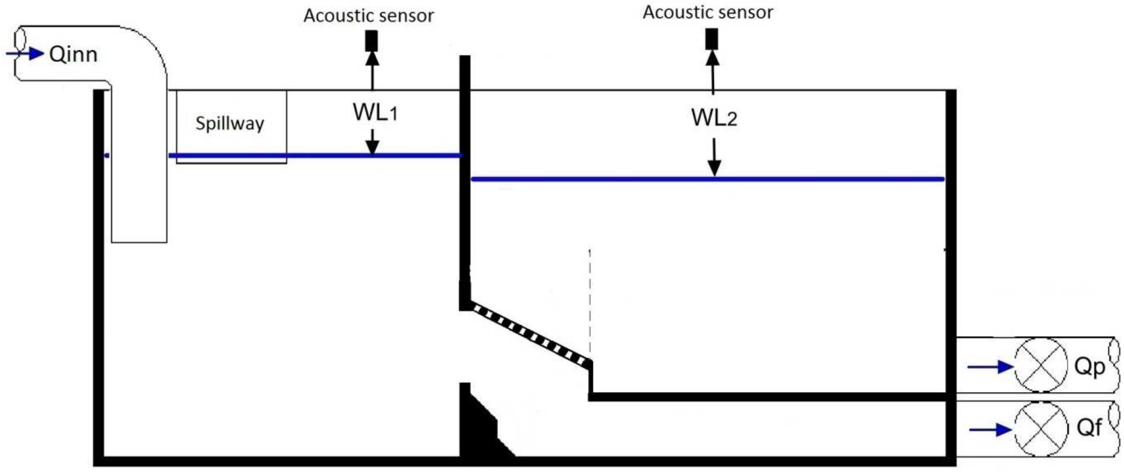

Figure 26. Acoustic sensors and flow water meter location.

5.4. Plan and schedule

Considering only the tests and not the work related to the construction of the model, the tasks in the laboratory had duration of an intensive week.

Day 1: Measurements of the nine points on the horizontal rack surface above the rack with and without it.

Day 2: Measurements of the nine points in the three elevations for the horizontal rack.

Day 3: Measurements of the nine points in the three elevations for the 39 degrees inclined rack.

Day 4: Measurements of the nine points in the three elevations for the 29 degrees inclined rack.

Day 5: Measurements of the two lowest points for all the racks. Measurement of the head loss for 39 and 29 degrees inclined rack.

Day 6: Photographic and video reportage with colored flow.

The days of the measurements were not consecutive. For instance it took some time, after day 1, due to the necessity of obtaining a new device for carrying out the rest of the tests. Tests from day 2 to 5, both included, took place during the same week due to the continuity aspect of the tests. Tasks from day 6 were done after the output data was analyzed and assumed to be right.

More tests were not realized because it was considered more interesting to analyze the results already obtained. If more data had been computed observations and comparisons would not have been done due to the limited time.

5.5. Description of the tests

***Test 1:* Velocity measurements in 9 determined points above the horizontal rack, with and without it.**

The election of the nine points measured is the same for all the tests of this report; they follow the distribution of the previous essays developed in the model.

They are equally shared out in the entire surface in a 3x3 pattern. As it can be seen from the picture, the distances have become dimensionless by comparing them with the horizontal rack dimensions H_r and B_r, which is equivalent to the available space. In addition, the same coordinate system from the model is used to identificate of the 9 points.

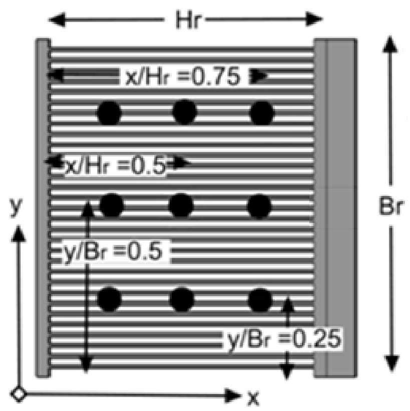

Figure 27. Distribution of the 9 points on the rack. Plant view.

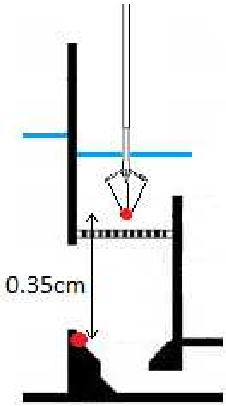

Figure 28. Measuring points above the horizontal rack with the ADV.

The nine points measured are located 5 cm above the rack, which means a total vertical distance of 0.35 meters from the reference point of the chamber.

They were measured with the Downlooking Vectrino, which was submerged vertically from the water surface. In accordance with the character of the device, its head was located 5 cm above the points to measure, with means 0,4 cm from the reference point of the chamber.

Test 2: **Velocity measurements of 33 points in the chamber upstream the rack during the normal operation with all the racks.**

This is the main test of the report. The 33 points are able to be measured thanks to correctly orientation of both Vectrino devices, for each point and each rack. The location of the points can be explained based on the 9 points from the last test exposed.

The 9 points measured in the case before, are the same points which will be measured all the time (same X and Y coordinates), but with different elevation from the reference point of the chamber: 3.6, 15.5 and 25.5 cm.

The last 6 points follow the same pattern, but they are located 10 cm below the reference point. They should have been 9 points, but the wall in the model is inclined in the lower part near the intake gate, preventing the three closest points to the intake gate from measuring. (Points corresponding to the X_1 coordinate).

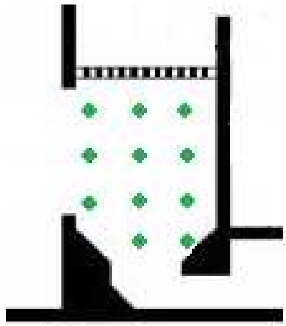

Figure 29.Elevation view of the distribution of the 11 points.

The correct location of the Vectrino was determinant for the measurements. The different racks and the lack of access with the Vectrino to the required point, are the reasons why two Vectrinos were needed. What is more, for the same rack both Vectrinos have been used, depending on if the point was above or below the rack.

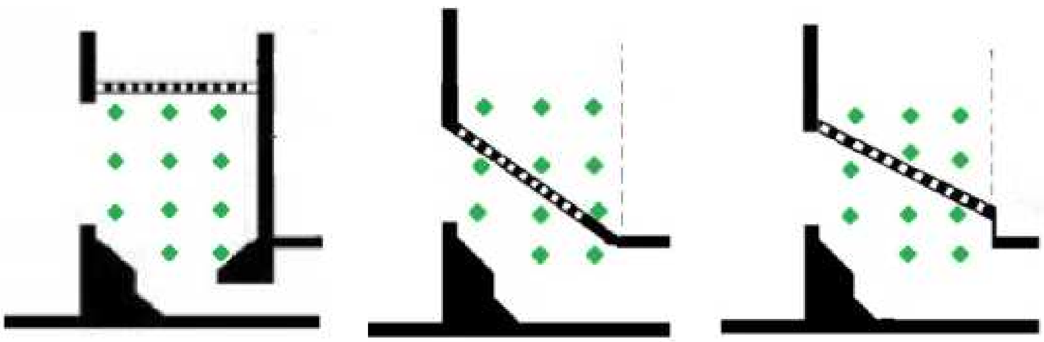

Figure 30. The 11 points distribution with the horizontal, 39º and 29º inclined rack respectively.

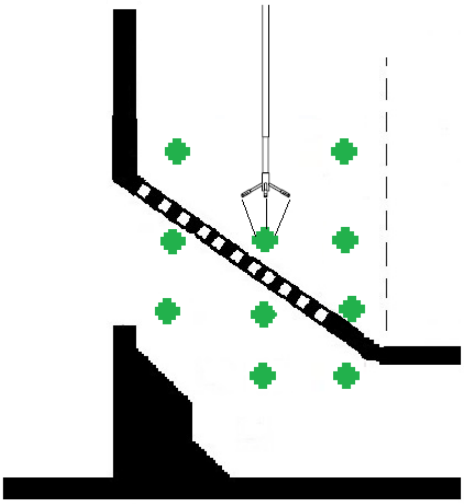

Figure 31. . Measurements above the rack with the Downlooking ADV.

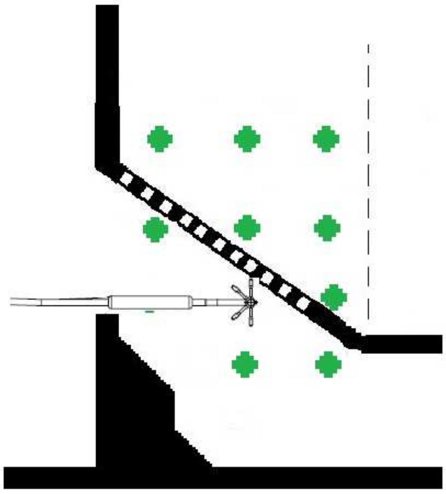

Figure 32. Measurements below the rack with the Sidelooking ADV.

Undoubtedly, the condition that thoses devices measure 5 cm from the head has been taken into account while doing the measurements. For this reason it can be ensured that the same points have been measured with the different racks, and consequently can be compared.

Test 3: **Measurements of the head loss for each of the situations proposed in the report.**

In previous research in the model, a high head loss was observed due to the horizontal rack and the additional vertical wall installed. In these tests, the height of the wall of the weir changes depending on each case in accordance with the rack.

The head loss was measured for different and increasing discharges. The in and outflow discharges were increased in the intake and the production pipe of the model from 5 l/s up to 30l/s. They were increased 5 l/s each time. Two laser gauges measured the water height up and downstream the rack, in the water tank and the inner chamber respectively.

6. Results and discussion

Results from the tests realized are organized and compared in this chapter. The first two sections are the basis to justify the rest of the results. They explain why it was necessary to do the measurements with the rack, and why it is correct to show the results in 2D.

The last three sections speak about the most important tests of the report, the velocity fields, the velocity analysis, and the head loss. They contribute to the main goal of the tests in this model: to obtain the geometry which finds the compromising point between the head loss and the fish requirements.

6.1. Tests need to be done with the rack

It appeared the doubt about the necessity of running the measurements with or without the rack, and its influence to the results. Obviously, tests were easier to run without any rack, and even more, a new device was required if the rack was indispensable.

Results from the test 1 revealed that velocities were quite similar for coordinates X_1 and X_3, but not for X_2. This could be easily explained because coordinate X_2 was located in the middle of the rack, without the influence of the not-sliding condition of the walls.

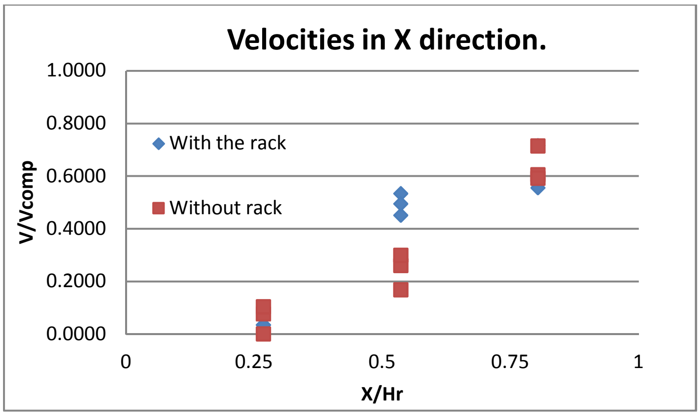

Figure 33. Vx for the horizontal rack and highest level.

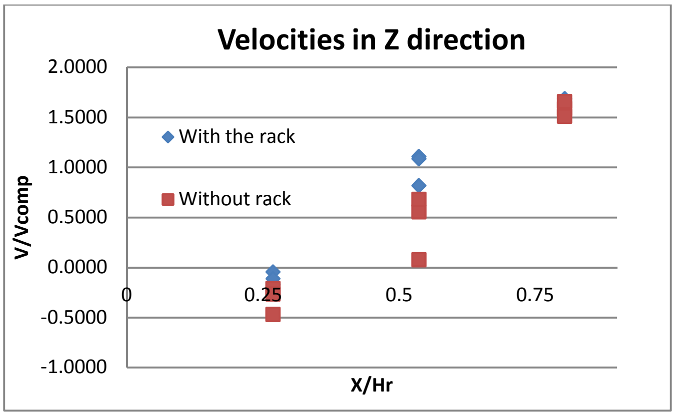

Figure 34. Vz for the horizontal rack and highest level.

The graphs showed are based on the data taken for the velocities for horizontal rack with a height of 25 cm from the reference point in the chamber. Tables showing results in the rest of the situations are attached at the Appendix C.

As the report studies how the flow in the model around the rack is, it was concluded that uncertainties in the velocities obtained in the tests were not desired. So to keep the sureness of our results, tests would be run always with the respective rack.

6.2. Results can be presented in 2D

Obtained from test 2, two different criteria have been found to support the correction of showing the results in 2D.

6.2.1. The comparison of the mean velocity and the velocity fluctuation

The velocity and the velocity fluctuation correspond to the parameters of the Reynolds decomposition, and they have been given by the Vectrino device.

It has been observed that, while the magnitude of the fluctuations in the three directions of the model X, Y and Z, is similar, the mean velocity in the Y direction (V_y), is much lower than the rest V_x and V_z, and what is more, its value is quite close to the velocity fluctuation in the same direction, $[V_y']$~V_y. These three criteria can be summarized as it follows:

- ✓ $V_y << V_x$ and $V_y << V_z$
- ✓ V_y~~~$[V_y']$
- ✓ $[V_x']$~~~$[V_y']$ ~~~$[V_z']$

The following figures show values for the mean velocities V, and its fluctuations [V']:

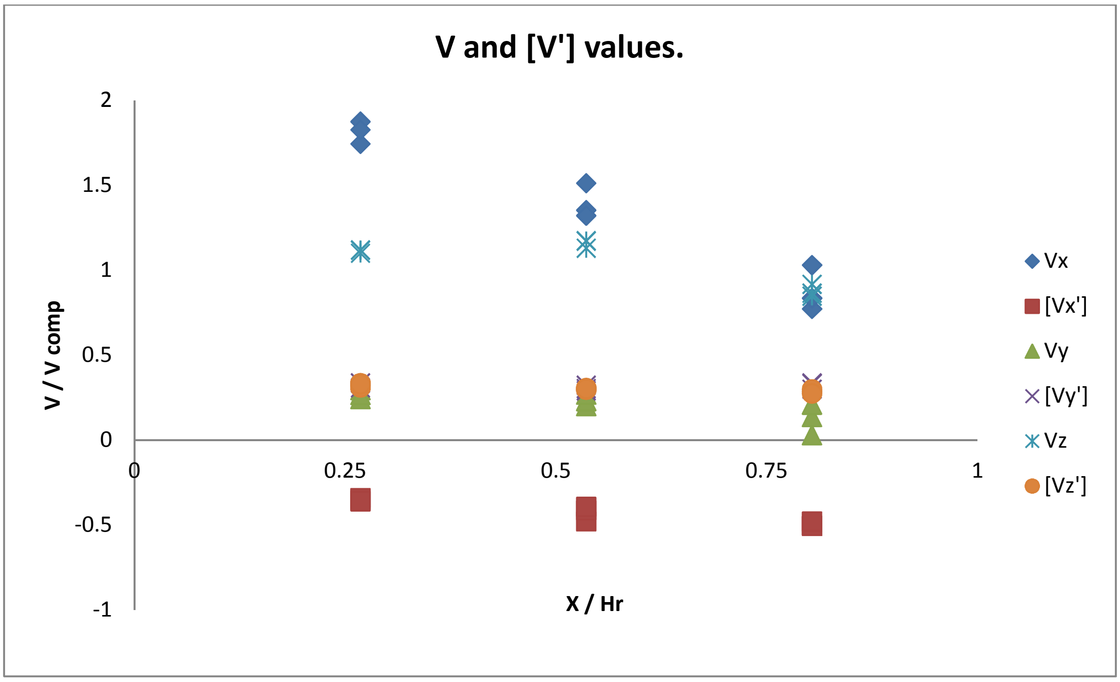

Figure 35. Mean velocities and velocities fluctuations for all the directions.

The graphs showed are based on the data taken for the velocities for horizontal rack with a height of 25 cm from the reference point in the chamber. Tables showing results in the rest of the situations are attached at the Appendix C.

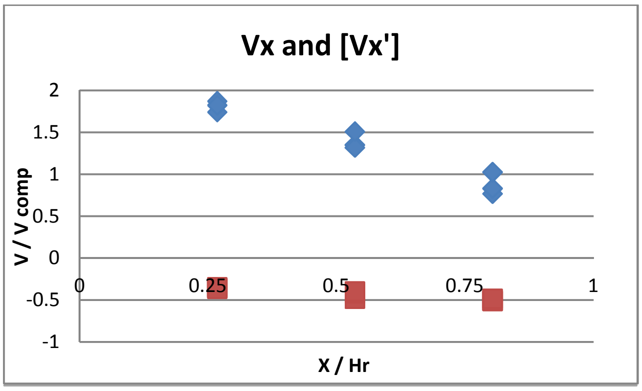

Figure 36. Mean and fluctuating velocity for X direction.

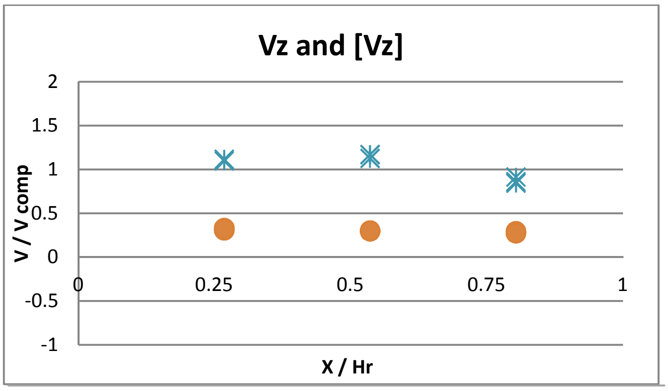

Figure 37. Mean and fluctuating velocity for Z direction.

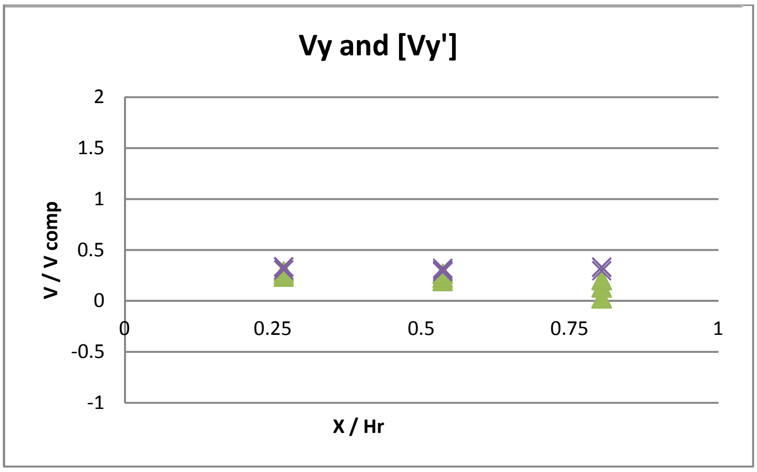

Figure 38. Mean and fluctuating velocity for Y direction.

In this way, according to its magnitude the main directions of the flow are X and Z, and they are not much influenced by the turbulence fluctuation velocity. On the contrary, for Y direction the main velocity is affected basically by its fluctuating velocity; which is further demonstrable with the similarity of its values. At the end, V_x and V_z become the most interesting velocities for our study.

6.2.2. The comparison of the velocities along the width of the model

This part is based on observations of the relative magnitude of the obtained values for the velocities in the X and Y direction. These relations will be supported by graphs in order to make easier its understanding.

On the one hand, the velocities in the same X coordinate for Y_1, Y_2 and Y_3, are similar; this means that velocities are uniform for same X values and variations in Y axis. Observe that lines should be as horizontal as possible.

On the other hand, there is no importance of having a different range of values for different X positions. This is represented by the vertical spacing among the different colored lines.

Another factor to take into account is the convenience of having the same pattern of the lines among them, (the same shape); if this occurs, it can be stated that changes in Y direction affect the same manner all values of X.

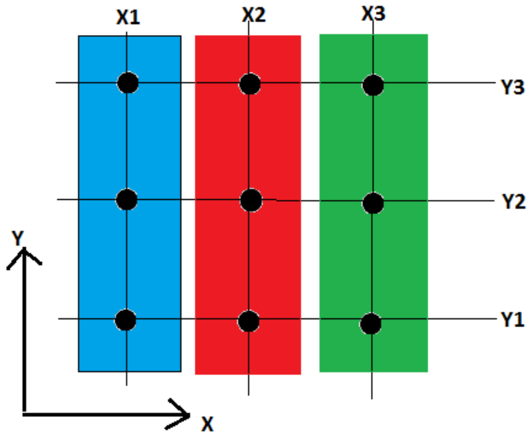

Figure 39. Situation of the points. Plant view.

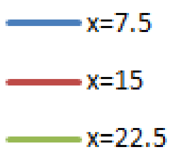

Figure 40. Legend for the graphs.

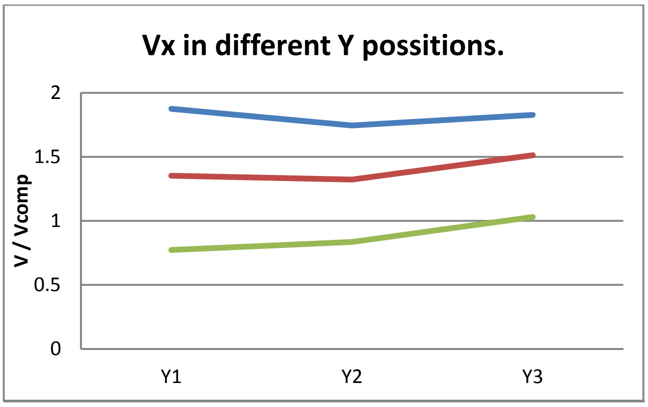

Figure 41. Vx along the with for the horizontal rack and z=25cm.

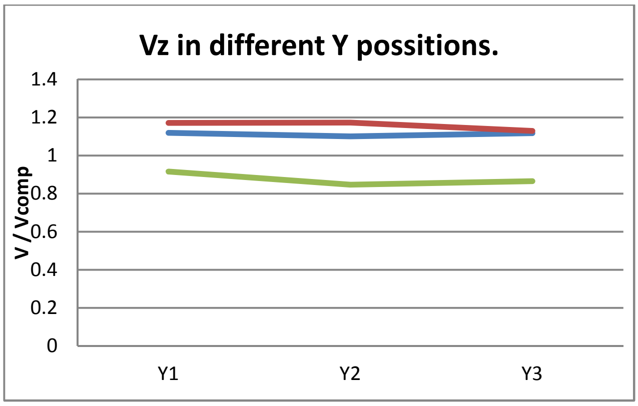

Figure 42. Vz along the with for the horizontal rack and z=25cm.

The graphs showed are based on the data taken for the velocities for horizontal rack with a height of 25 cm from the reference point in the chamber. Tables showing results in the rest of the situations are attached at the Appendix D.

In short, it is proved that, for a specific X value, the Y coordinate in which velocity is measured doesn't affect strongly the obtain velocity value. This means that velocities V_x and V_z can be measured for Y_1, Y_2, Y_3 or even a new Y coordinate, for the same X value resulting in similar values.

From this point, further results in the report would be shown in a 2D way, paying no heed to Y direction while the results remain logical.

6.3. Velocity Fields

In this part not only the final velocity field in all the rack situation will be shown, but the treatment of the data to acquire the plots as well. This is due to the several assumptions done, in order to allow the reader to follow the procedure, and observe the data in all its situations. Moreover, data collections will be added to the final Appendixes to ease the task for future reports.

As it was demonstrated the convenience of working in 2D, the velocities in the same X coordinate have been averaged in order to show velocities in the chamber in an elevation view. After that, plots of the 11 points were done in each situation, but they were far from being interesting due to the punctuality aspect of the graphs.

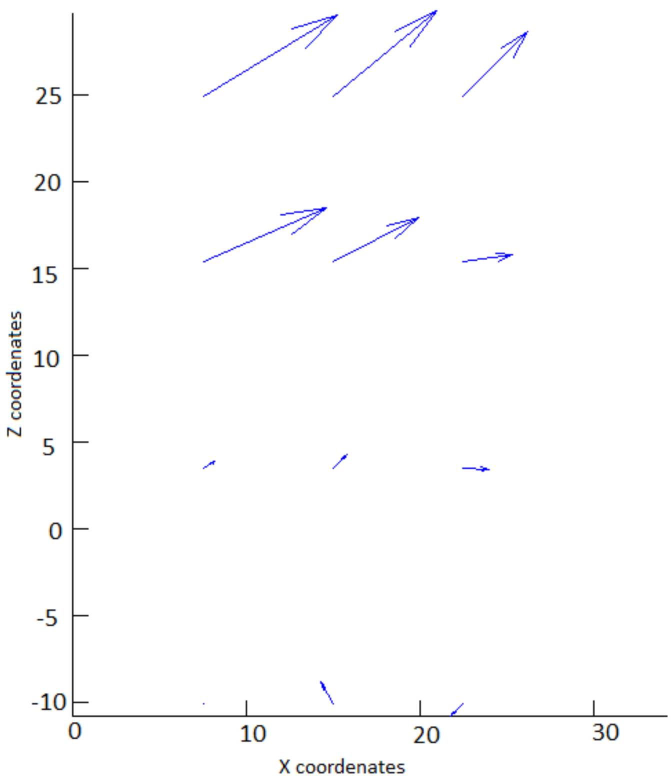

Figure 43. Punctual velocity field with the horizontal rack.

After that, it was decided to interpolate values among the punctual measurements. Thanks to Matlab software, 7 points were linearly interpolated in between each two given values. It can be observed in the figures below, that new values outside of the boundary composed by the measured points were not obtained. This can be easily explained due to the uncertainty of the extrapolations functions added to the phenomenon of non-sliding condition near the walls, that will surely influence these values. For the same reason, details from the lower left part of the model were not computed.

The arrows from all the following graphs are showed with a scale factor of 0,5, in order to avoid overlapping:

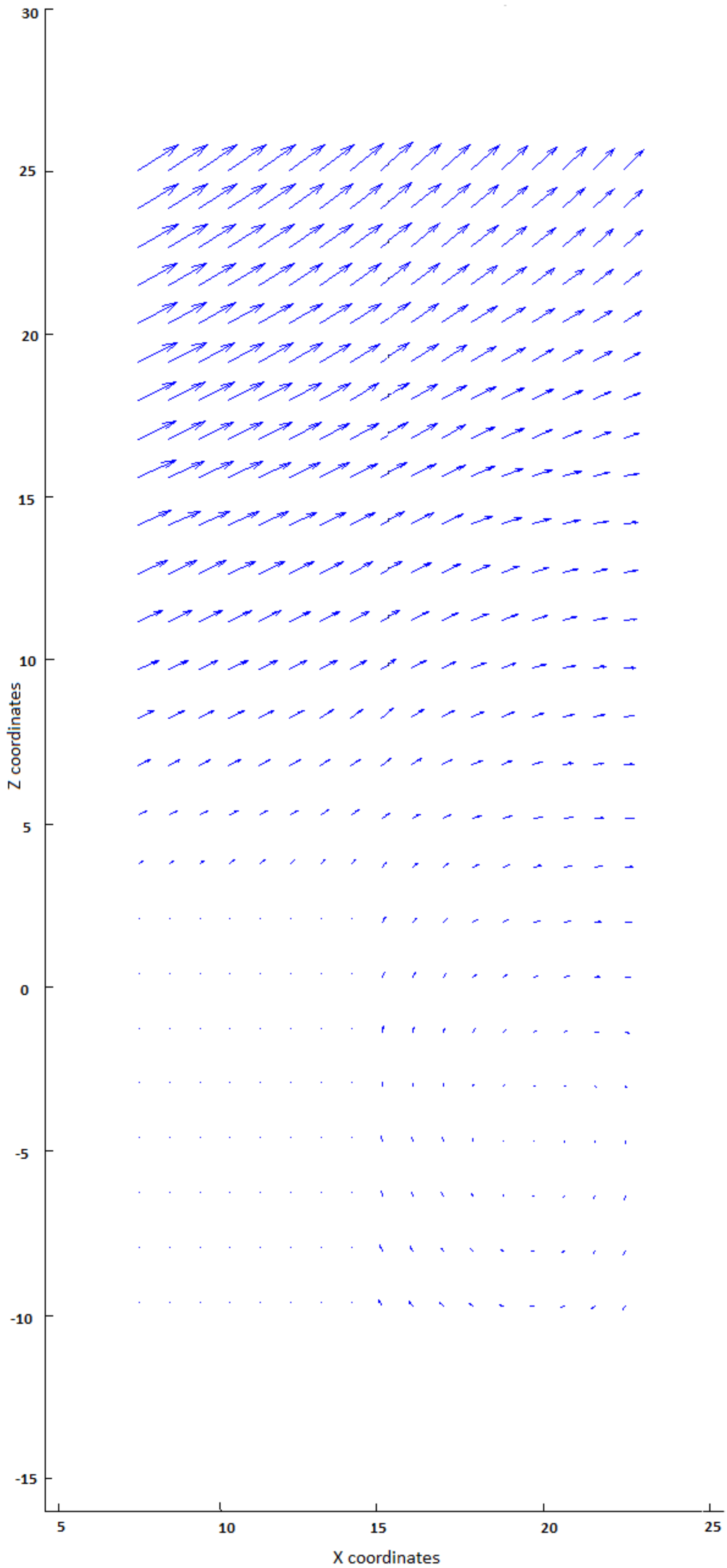

Figure 44. Velocity field with the Horizontal Rack.

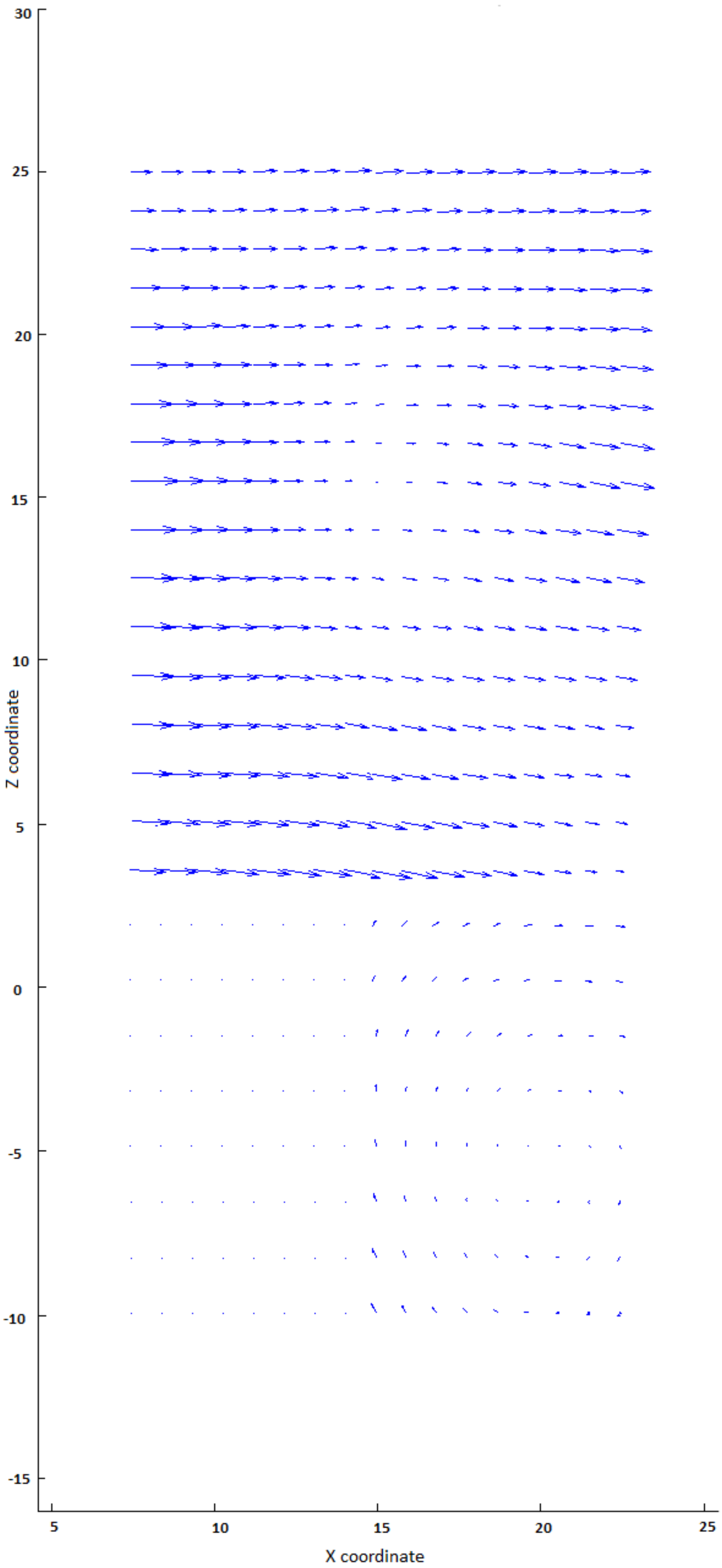

Figure 45. Velocity field with 39º Rack without correction.

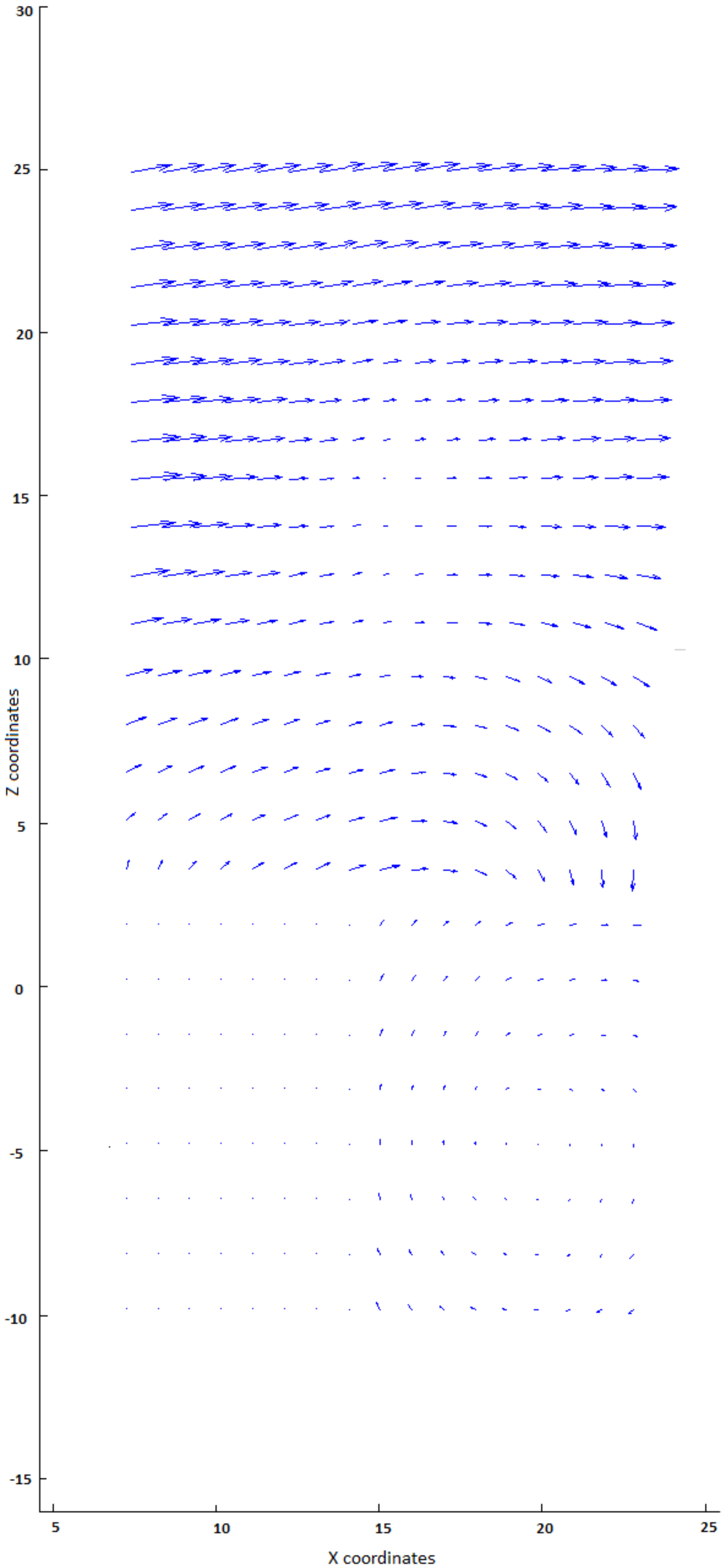

Figure 46. Velocity field with 29º Rack without correction.

Having achieved values in the entire area which can show the pattern of the flow, it was evident that some unusual values were affecting the central part of the plots of the 39 and 29 degrees inclined rack. Interpolated values were checked and the middle point from the 11 original values was detected to be the unsuitable one.

Searching for the source of error, it was remembered that during all the measurements the correlations limits were respected, but as the same time this point was the nearest to the rack. This was supposed to be the cause the alteration, and for this reason, it was decided to repeat the interpolation of the data from the 39 and 29 degrees inclined rack, but in two phases:

Phase 1: Interpolate the central value from those situated in the corners in the 11 pointed patterns.

Phase 2: Once the 11 initial points are logic, continue with the main interpolation which creates a grid of 17x25 values.

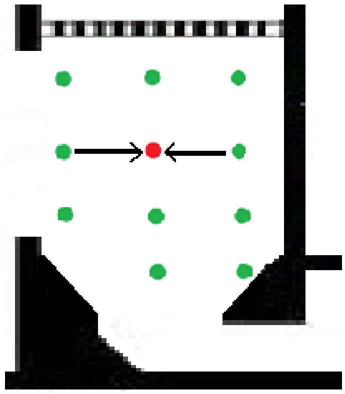

Figure 47. Representation of the phase 1 of the interpolation.

Finally, once the plots are correct enough, they can explain the flow in each situation. The magnitude of the velocities decreases with the depth in all the situations, because it loses influence of the flow going to the production pipe, which represents the maximum water outflow during the normal operation.

The upper part of the flow with the horizontal rack is strongly affected by the height of the weir. This explains the arrows having an inclination angle of 40º with the horizontal. An extra head loss is caused by the needed elevation of the flow to surpass the weir. Contrarily, with the inclined racks, the arrows are almost horizontal; there is not extra head loss to go over these racks.

In the middle part of the plots, the arrows are quasi horizontal and its values really small. It can be stated that, as well as the velocity magnitude decrease with the depth, it happens the same with as the points are closer to the flushing conduit.

What is more, at the square in the lower and right part of the plots, there is a small recirculation flow. In it, the water discharge coming from the intake finds the flushing conduit, where the velocities are much lower. This phenomenon can be also explained due to the fact that water cannot be completely in repose while it is there is a current nearby, even velocities are really low. At the same time, as it can be seen from the photo, with the 29º inclined rack, the 2.5 cm wall on the right helps the recirculation scheme to form easily.

Figure 48. Recirculation phenomenon.

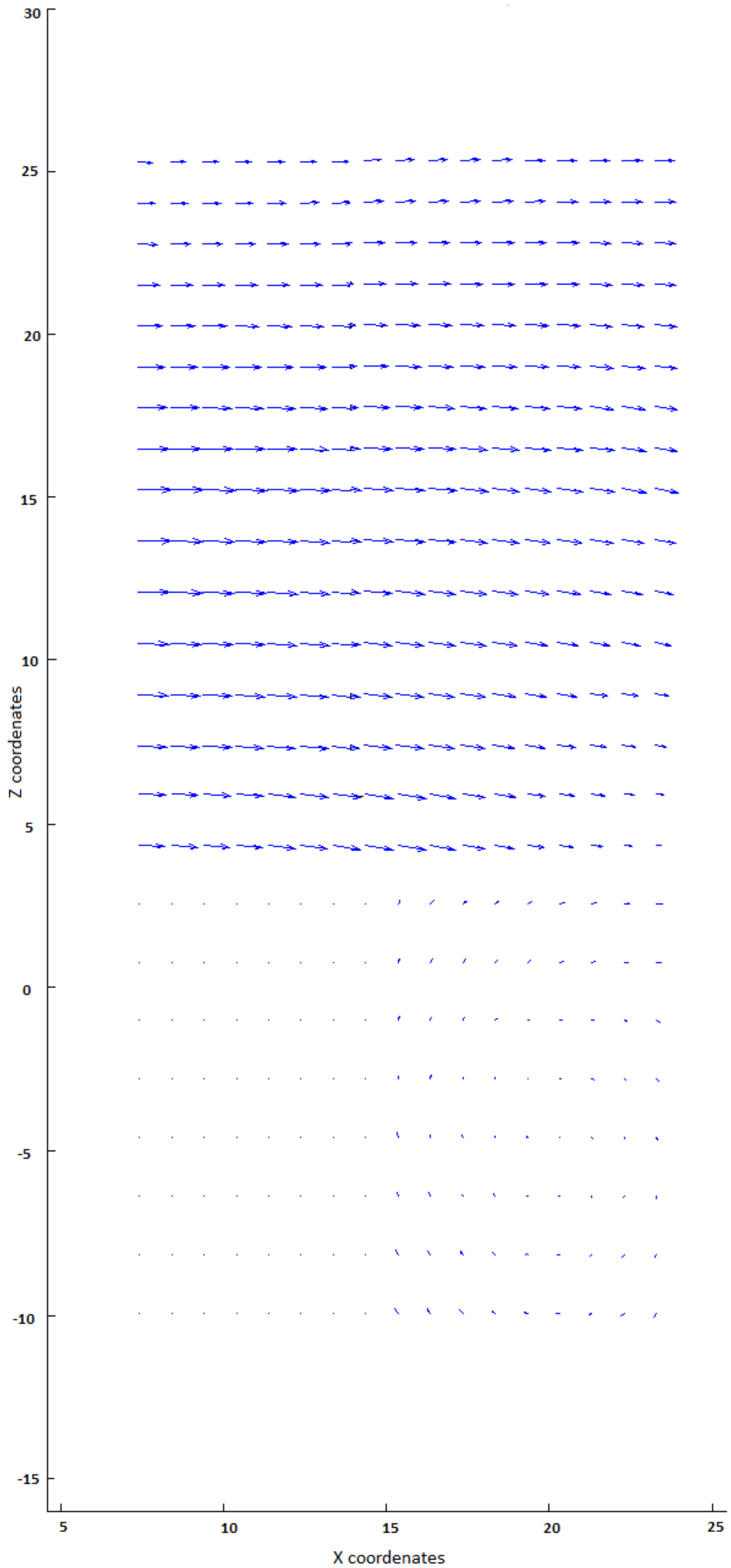

Figure 49. Velocity field with 39º Rack corrected.

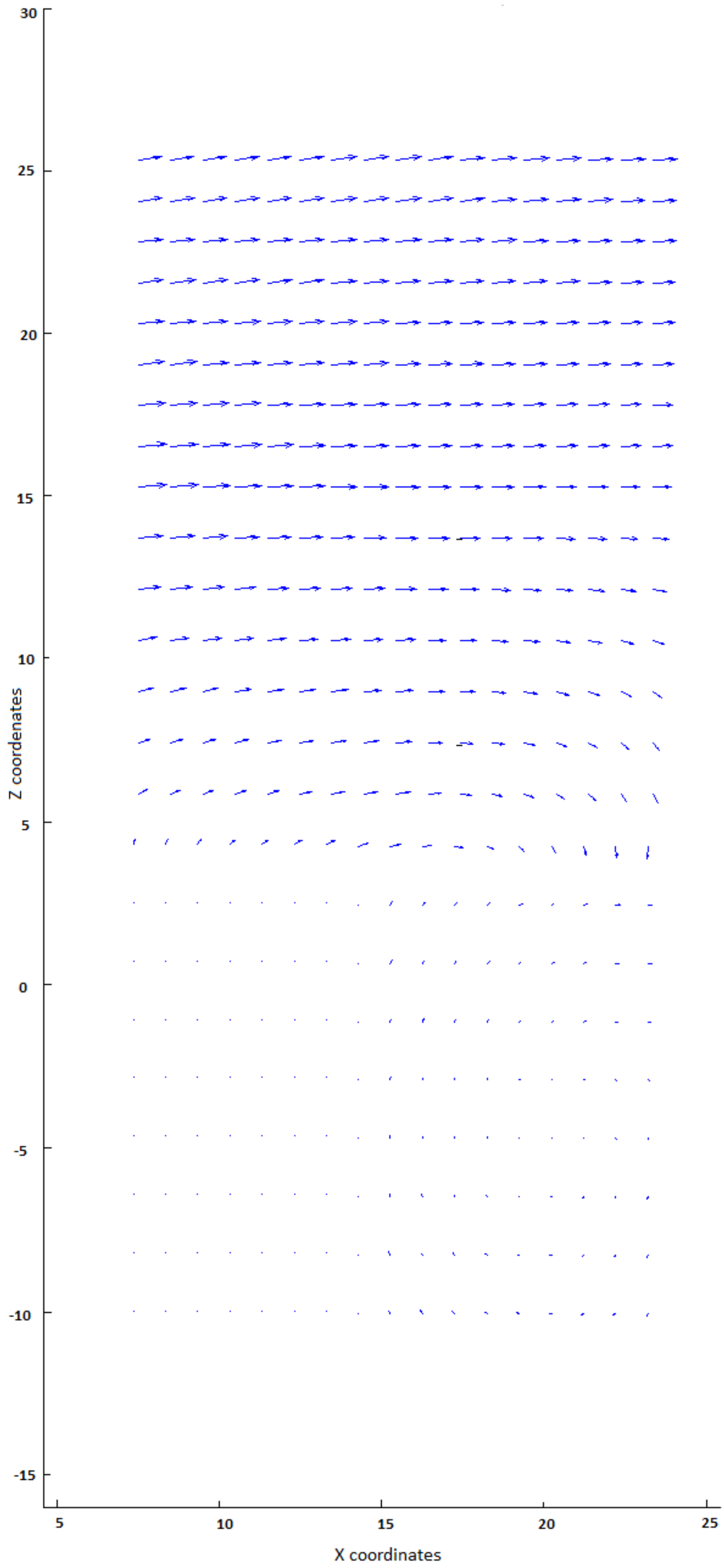

Figure 50. Velocity field with 29º Rack corrected

6.4. Velocity analysis

Velocities below the rack have been studied further in depth to relate their values to those of the fish requirements. The surrounding area of the rack varies from rack to rack, accordingly, the points, which velocities are used, have been carefully chosen for each case:

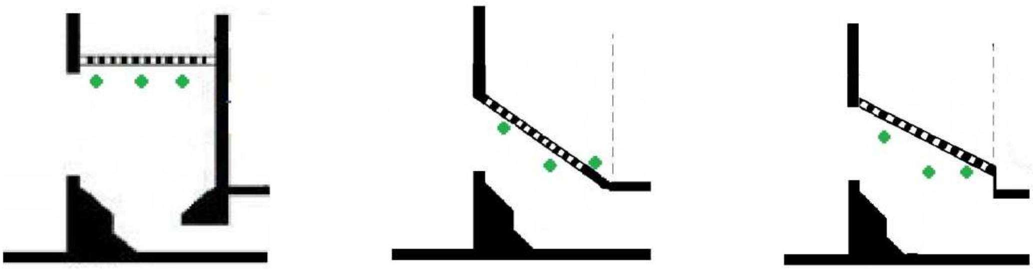

Figure 51. Situation of the points used in the analysis depending on the rack.

Two comparisons have been developed depending on the physical phenomena to study:

6.4.1. Normal velocities over the limit velocity for fishes

Firstly, it is analyzed in which areas the velocity in a normal direction to the rack exceeds the limit velocity for the fishes, (as well know as comparison velocity). It is an evaluation of the areas of the rack where fishes can be threaten of the impingement with the respective rack.

It can be observed high perpendicular velocities to the horizontal rack extended in its entire area. The dimensionless values are above the unity mainly, which will induce problems to fishes. On the other hand, with the inclined racks, values decrease as they are nearer the inner chamber, because the flow becomes more horizontal. In addition, values remain below the velocity limitation, providing a right functioning.

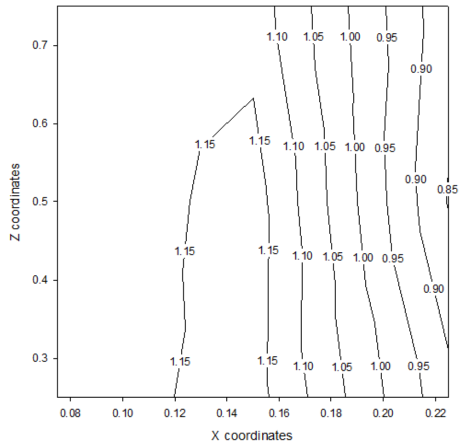

Figure 52. V/Vcomp with the horizontal rack.

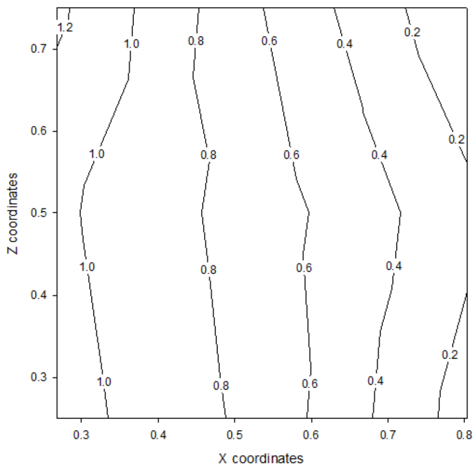

Figure 53. V/Vcomp with the 39º inclined rack.

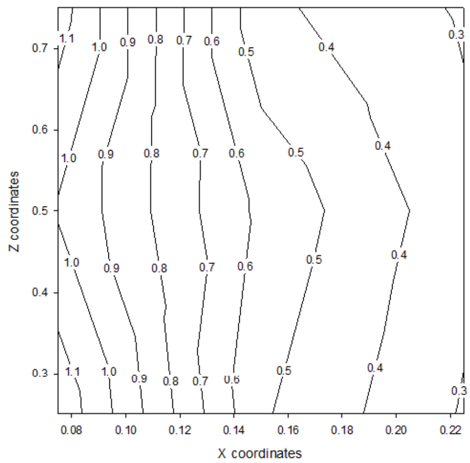

Figure 54. V/Vcomp with the 29º inclined rack.

6.4.2. Parallel velocity over the normal velocity

Secondly, it is computed how big the parallel velocity to the rack is over the normal one. As it has been explained before, a higher proportion of parallel velocity, constituting the main component of the flow, will induce the fish direction along the rack to find other way to follow;

As it is logic due to the position of the weir with the horizontal rack, parallel velocities are higher in the left part of the plot. On the contrary, with the inclined racks the parallel velocities develop as near the inner chamber is.

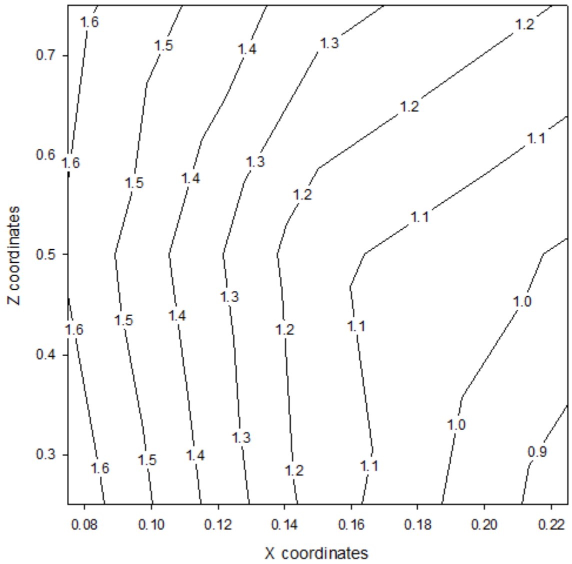

Figure 55. Vp/Vn for the horizontal rack.

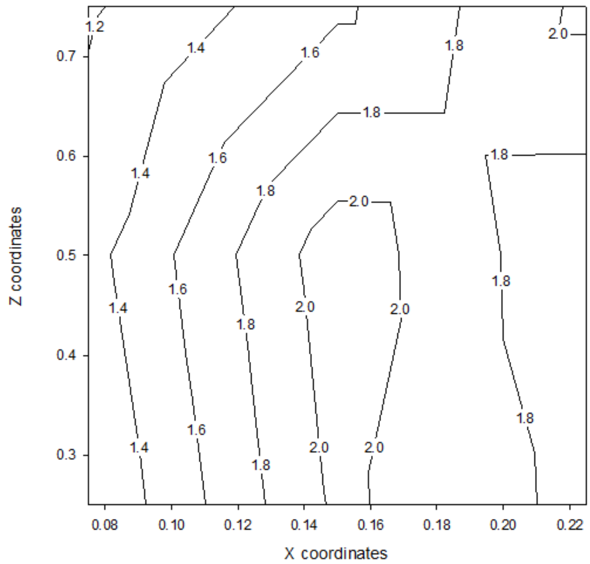

Figure 56. Vp/Vn for the 39º inclined rack.

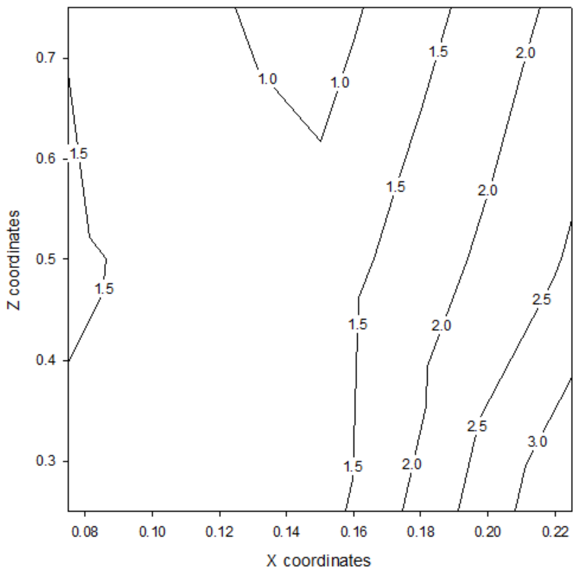

Figure 57. Vp/Vn for the 29º inclined rack.

Thanks to comparison of these plots, it can be concluded that the better results are obtained as the rack is more inclined; and as a result, the statement of the background that ensure that the inclination of the rack to obtain tangential velocities is able to guide fishes at the bottom point, is checked.

This phenomenon is especially useful for the case of study due to the location of the flushing conduit. In this way, with the inclined rack, which has shown the best behavior, fishes will swim along the inferior part of the rack and will find themselves already in the beginning of the flushing conduit.

6.5. The Head loss

In Test number 3, measurements of the head loss for the 39º and 29º inclined rack were done in order to compare them with those of the conventional vertical rack in intakes, and with other data obtained previously by the same test with the horizontal rack.

Following the relations of the water surface height in two points of the system and its relation to the energy loss, the head loss has been calculated. After that, a function showing the tendency of the data of the head loss with respect to the discharge was obtained for each situation. The comparison is shown in the next graph:

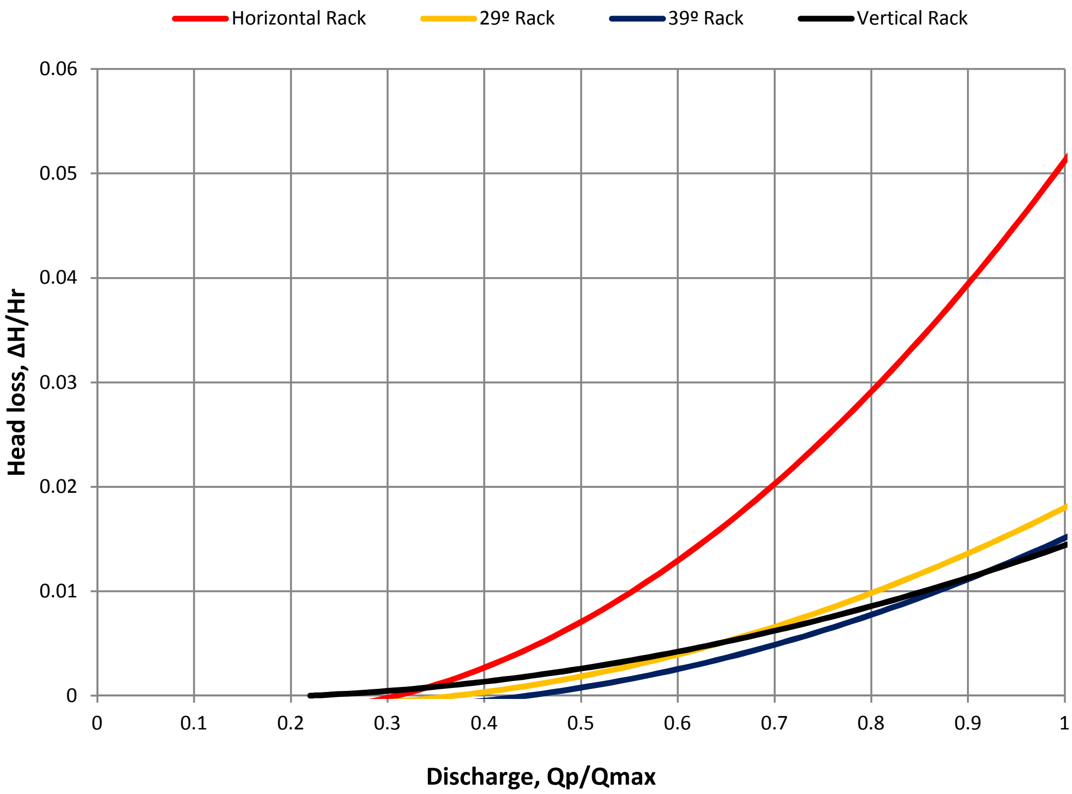

Figure 58. Head loss with respect to the discharge for different racks.

Obviously the head loss occasioned in the model with the horizontal rack is much higher than the rest. It is caused by the wall which, constituting a weir, makes the water increase their level in the water column and loose energy. As the control of the head loss is one of the determinant factors for the viability of this kind of installations, it would not be productive enough to install a rack causing these losses; even if its functioning met the rest of the requirements.

On the other hand, it is observed that the new two racks proposed for this assessment provide values near the common ones, with the vertical rack; constituting those from the 39º inclined rack the lowest.

7. Conclusion and recommendations.

The design and dimensioning rules of fish friendly intakes needs to take into account the operating constrains, the head loss, the rack cleaning and the downstream migration. At the same time, it needs to ensure to protect fishes and divert them from the main flow to the turbines, to guide them towards a bypass entrance and to transfer them safely.

This report is participating in a wider investigation of a new intake concept “H-rista fish friendly intake for small hydro”. This is a promising reformulation of the intake facility which bases in the back flushing concept. Running a back flushing operational phase, it aims to flush not only the trash accumulated in the installed rack, but device the fishes swimming in the same chamber out from the generation part of the intake.

This intake conception tries to deal with the common impacts of this kind of installation regarding the native fauna, which have become a prominent concern after realizing the strong decrease of those fish population which needs to migrate to develop their life cycle.
In this report some features of its functioning have been studied. At first, all the required information about the previous studies in the model, intakes in small hydro and the downstream migration of the salmon and the eel were collected; and the limited parameters for our tests were established.

Once the tests were carried out, it has been observed from the results a better functioning of the inclined racks for all the requirements established. Among the observations, the inclined racks cause a head loss which is in the same range of the conventional racks, lower normal velocities to the rack, as well as a more developed parallel flow along the inferior part of the rack, that due to the location of the flushing conduit devices easily the fishing into it. Given these results it is quite predictable that the next studies will focus on the inclined rack.

Certainly, there are still many factors to consider for achieving the correct running of the intake and all its goals. After the development of the present report, it is recommended to study the hydraulic conditions in the different chambers regarding the fish requirements for the flushing operation; for example, along the flushing conduit, to ensure the safety of the fishes transported downstream.

Finally, it should be remembered the importance of the right functioning of these parts of the hydrogenation facilities. A properly intake installation able to handle the debris, and be fish friendly at the same time, while having a correct operation and maintenance tasks, will increase not only the productivity and the economical benefits, but the environmental integration of this source of energy; and in the end the quality of the energy provided by small hydropower plants.

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Appendix A. Scale proportions.

Variable	Relation	Parameter	Prototype	Model
Distances (m)	$L_m = \frac{L_p}{5}$	Total length.	12.5	2.5
		Total height.	5	1
		Total width.	1.75	0.35
		Flushig chamber lenght. (L)	2.5	0.5
		Intake gate height. (Hi)	1.05	0.21
		Pipes diameter.	0.75	0.15
		Horizontal rack length.	1.4	0.28
		Inclined rack length.	2.05	0.41
Velocities (m/s)	$V_m = \frac{V_p}{\sqrt{5}}$	Velocity comparison. (V comp)	0.508	0.224
Discharges (m3/s)	$Q_m = \frac{Q_p}{5^{2.5}}$	Inflow discharge. (Qi)	1.313	0.0235
		Production discharge. (Qp)	1.246	0.0223
		Flushig discharge. (Qf)	0.671	0.0012

Appendix B. Dimensionless numbers.

Data of the graphs has been presented in a dimensionless way. Here there is a clarification of the magnitudes they have been compared to.

- Distances in the X direction have been compared with the length of the horizontal rack in all the cases. Although two racks are used, this is still the distance from the intake gate to the beginning of the inner chamber or the flushing conduit. — Hr= 0.28 m
- Distances in Y direction have been compared with the width of the model. — Hu=0.3 m
- Distances in the Z direction have been compared with the distance from the reference point to the location of the horizontal rack. — Width=0.35 m
- All the velocities have been compared with the maximum normal velocity. — V comp=0.5m/s

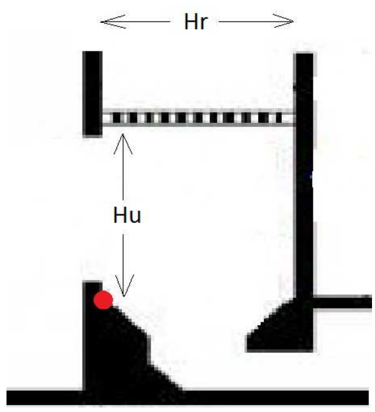
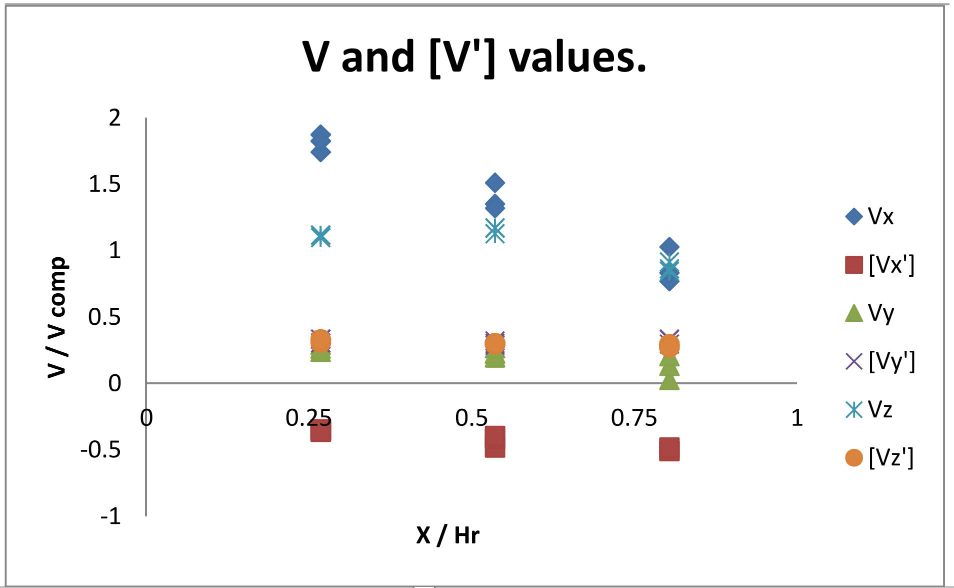
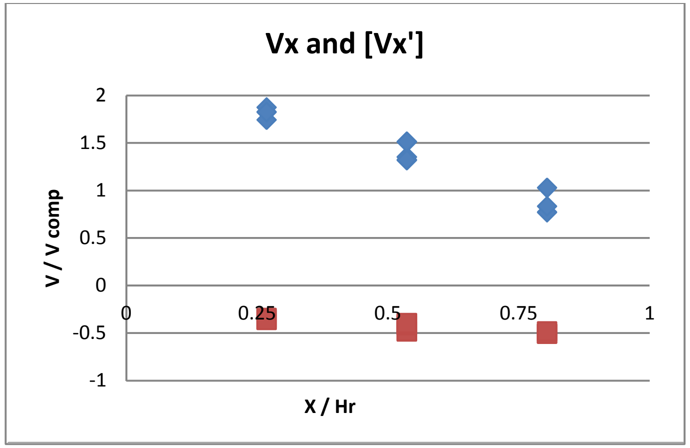


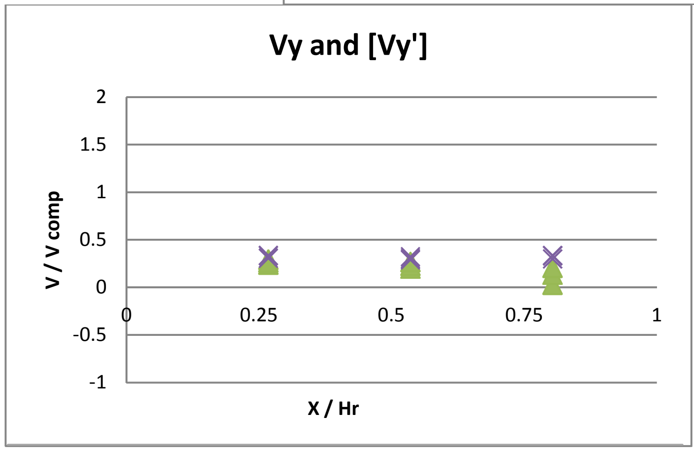
Figure 59. Measurements.

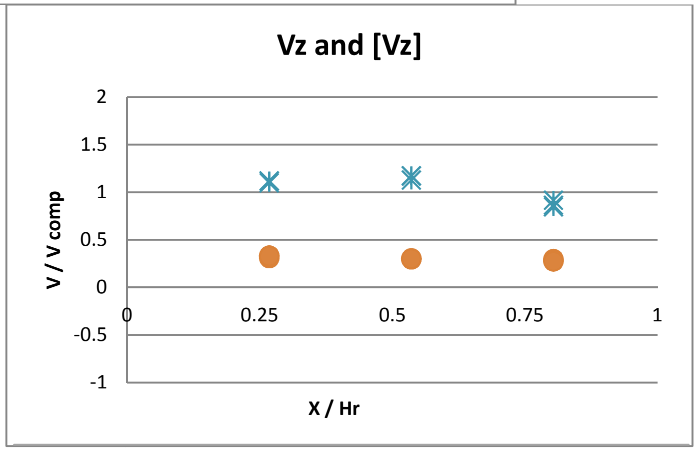
Appendix C: Mean velocities and velocities fluctuations

Mean velocities and velocities fluctuations for the Horizontal Rack at the z=25cm elevation from the reference point.

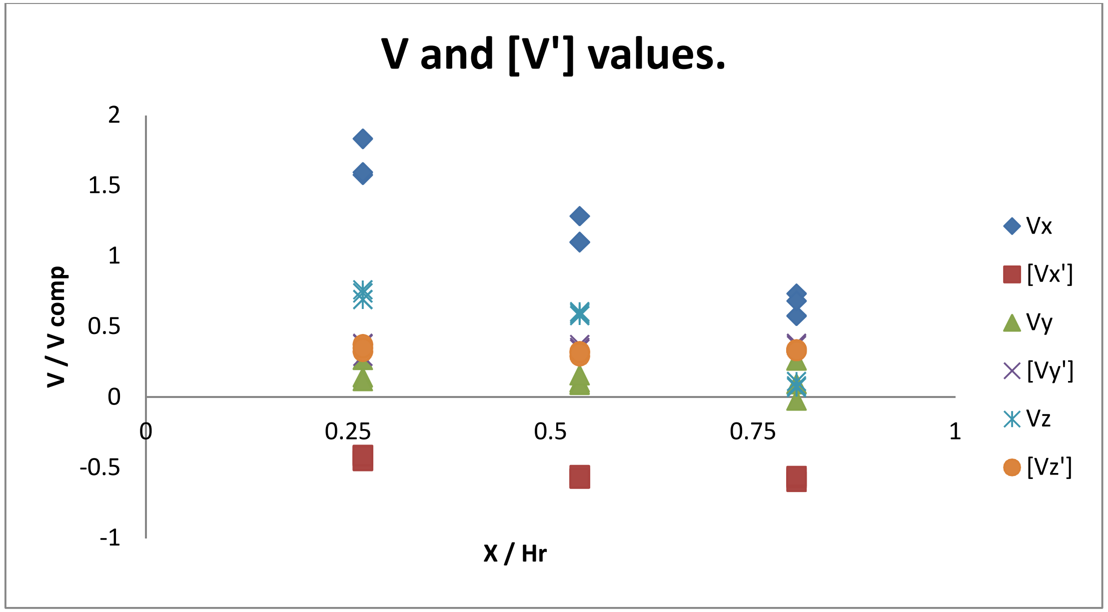


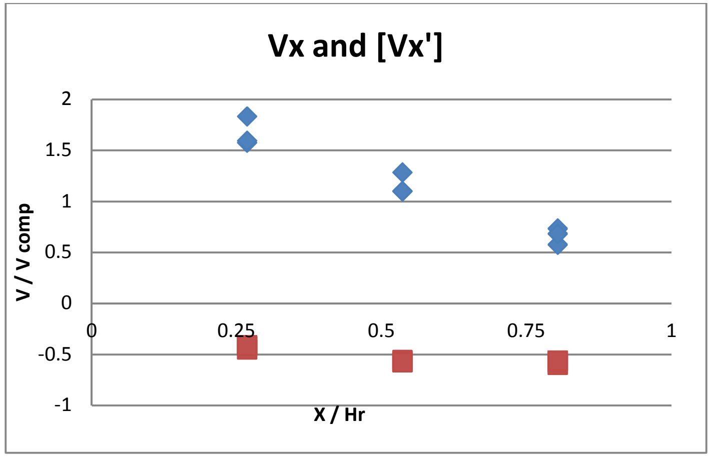


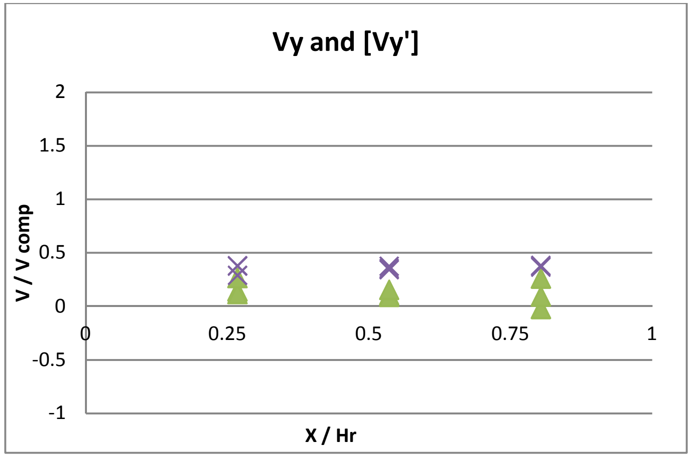


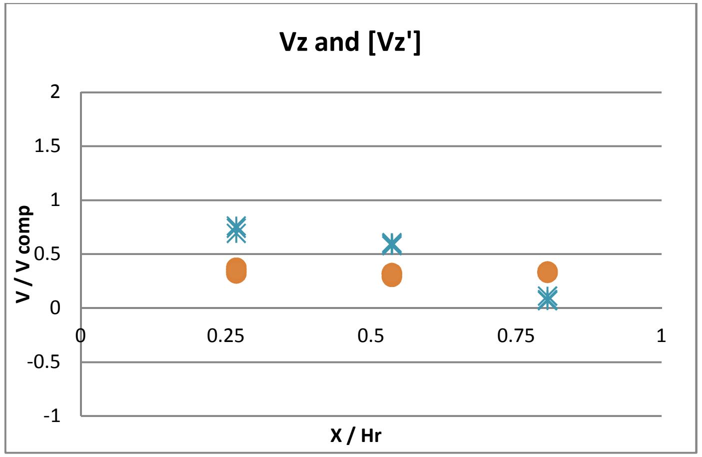


Mean velocities and velocities fluctuations for the Horizontal rack at the z=15,5 cm elevation from the reference point.

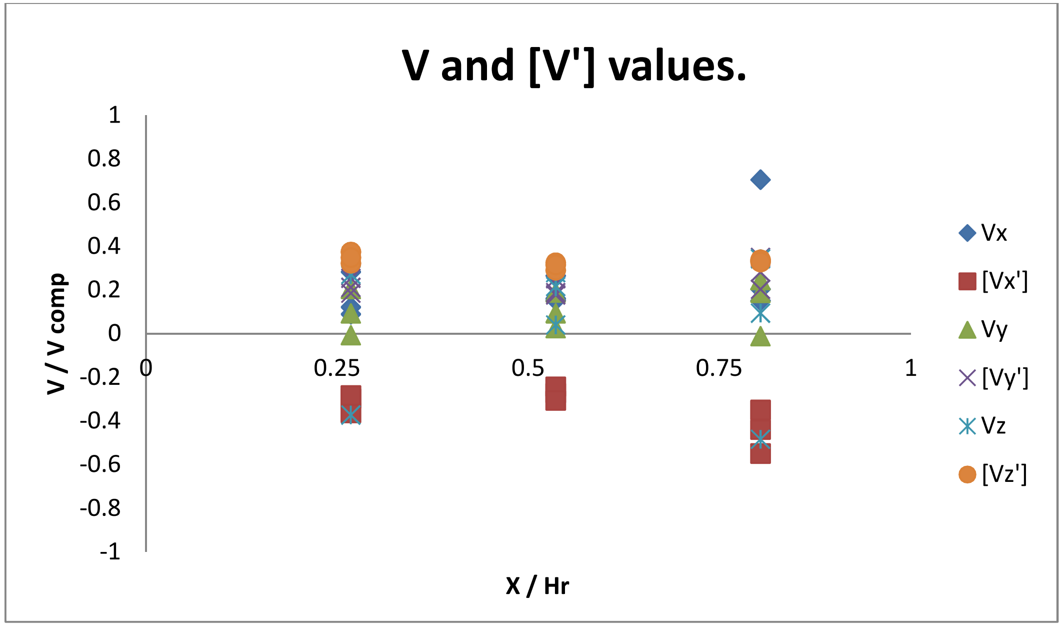


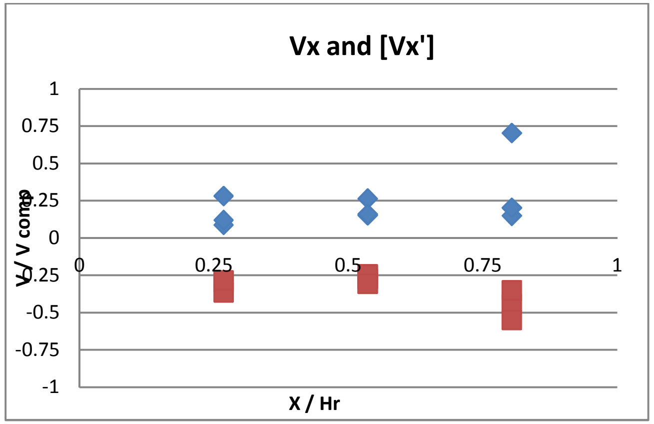


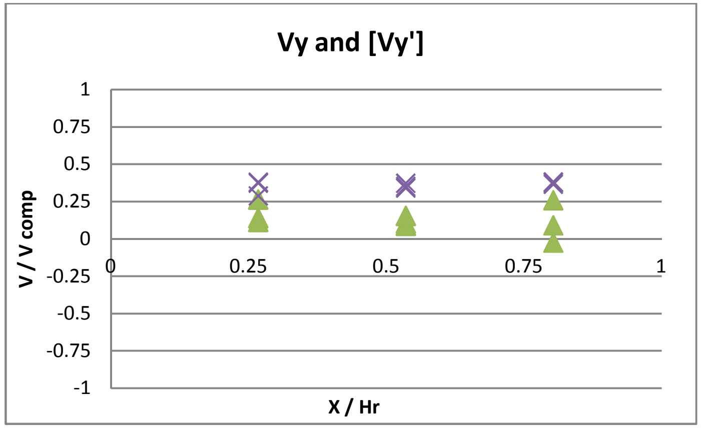


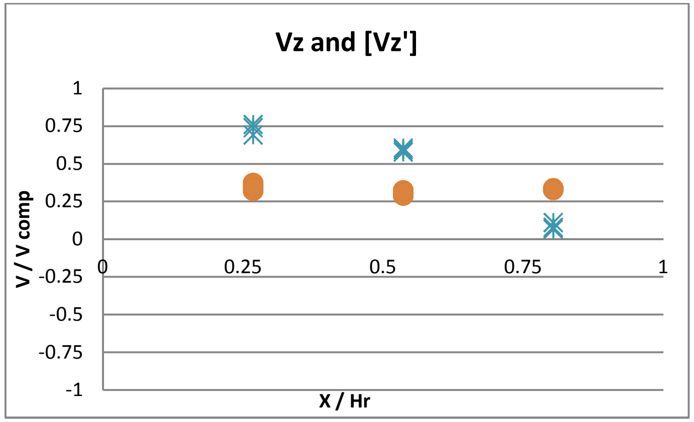


Mean velocities and velocities fluctuations for the Horizontal Rack at the z=3,6 cm elevation from the reference point.

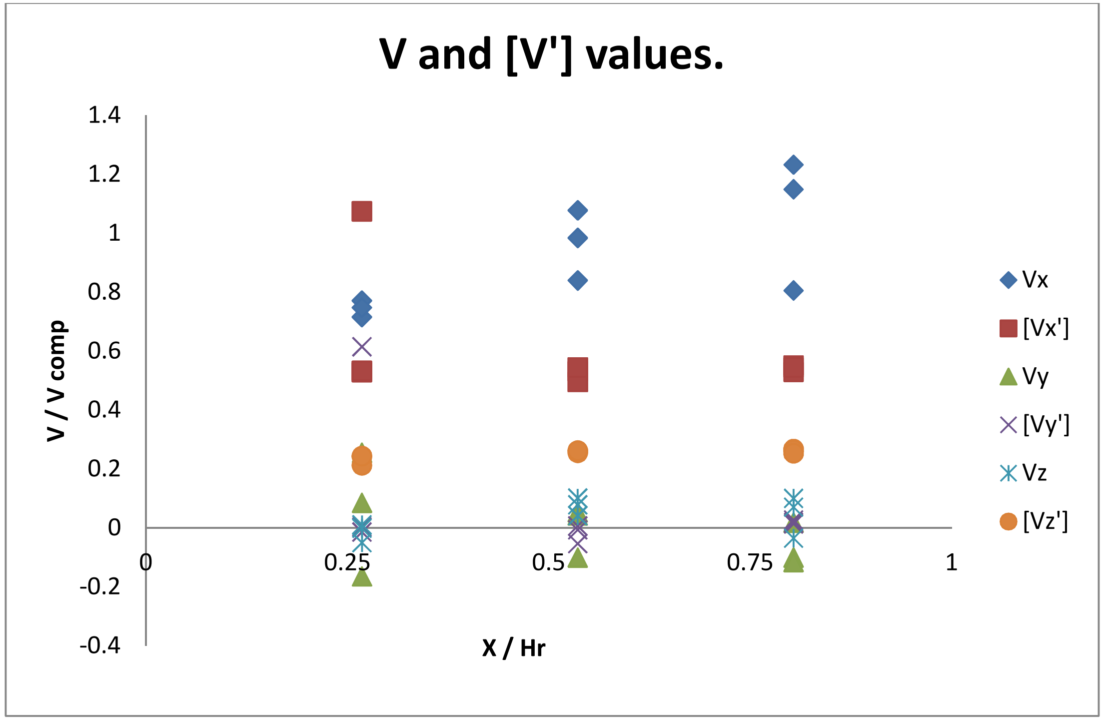


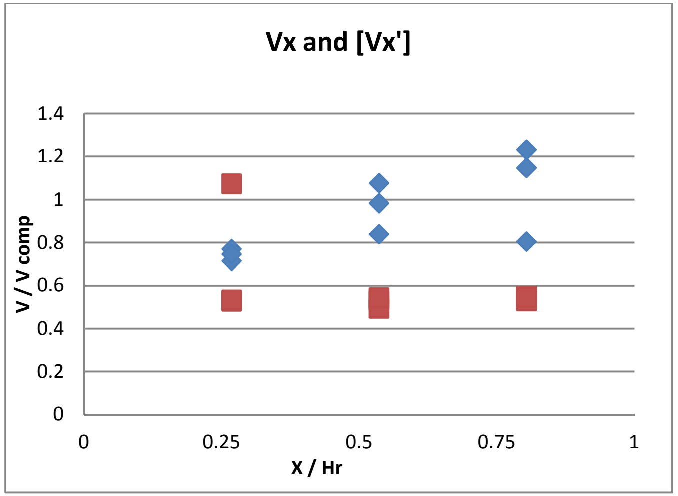


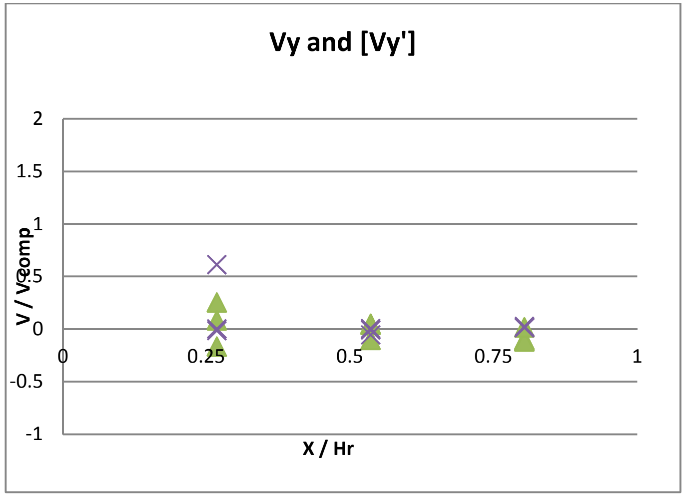


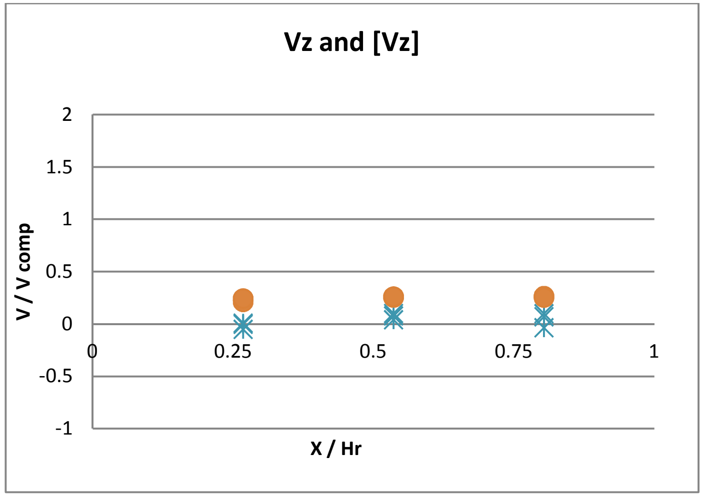


Mean velocities and velocities fluctuations for the 39º Inclined rack at the z=25cm elevation from the reference point.

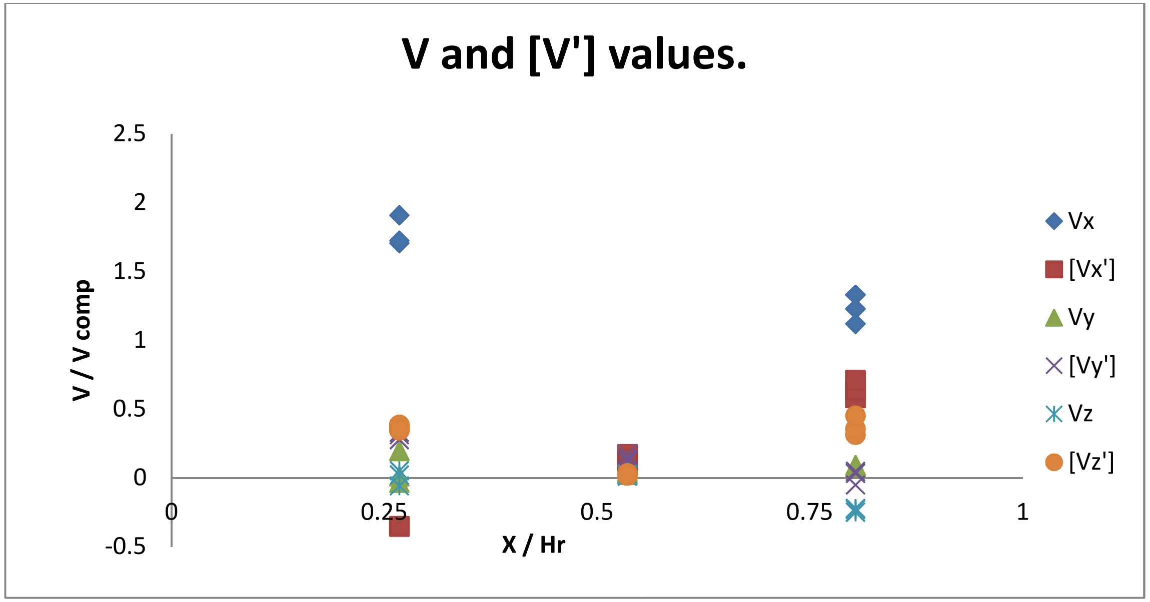


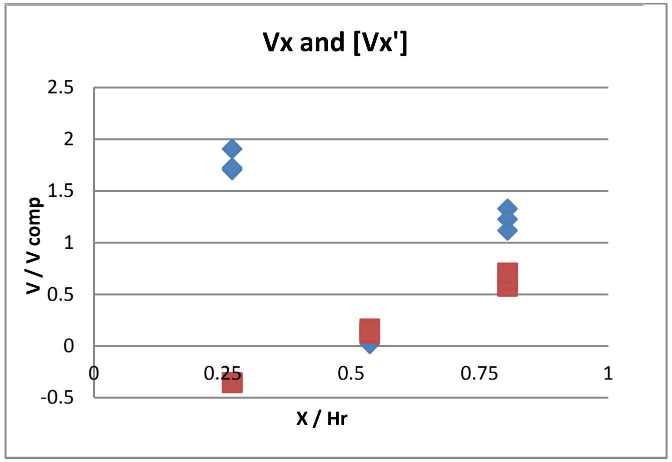


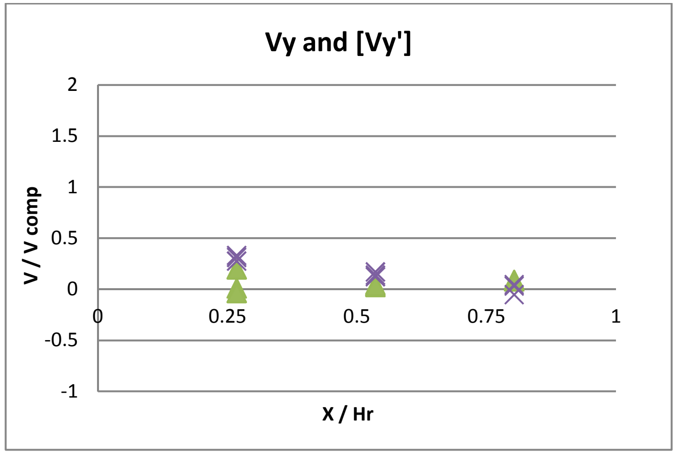


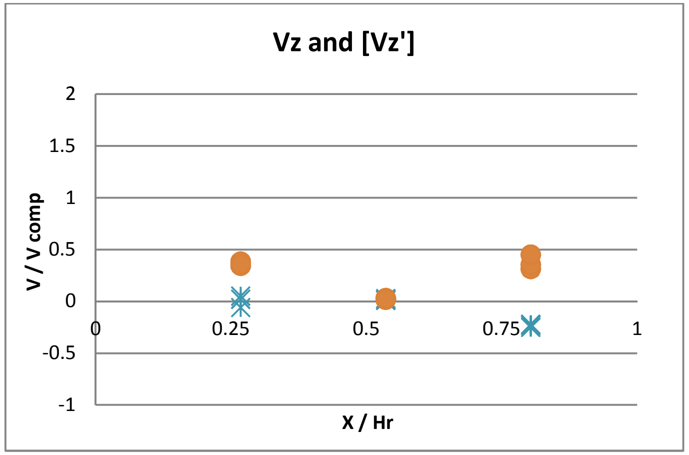


Mean velocities and velocities fluctuations for the 39º Inclined Rack at the z=15,5 cm elevation from the reference point.

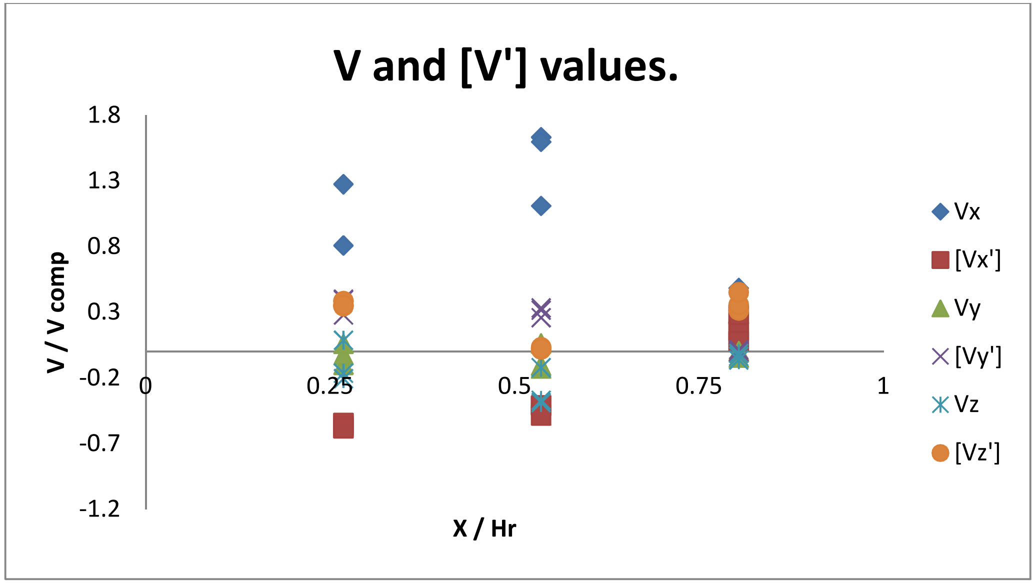


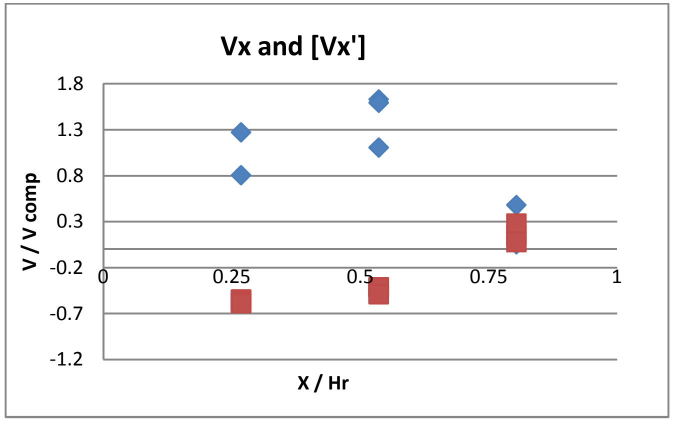


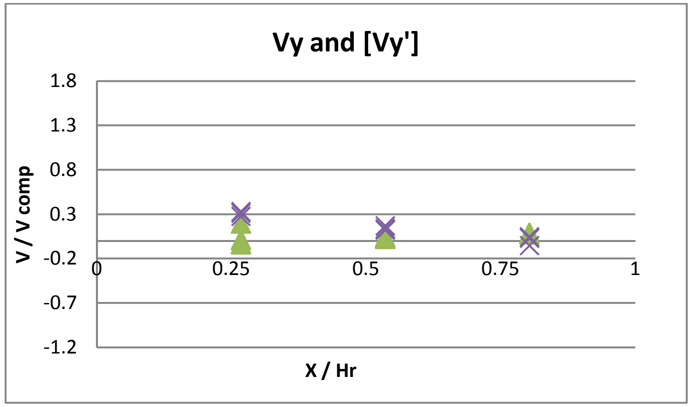


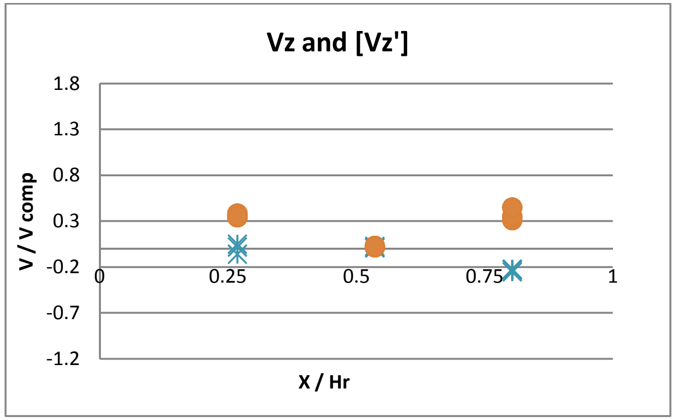


Mean velocities and velocities fluctuations for the 39º Inclined Rack at the z=3,6 cm elevation from the reference point.

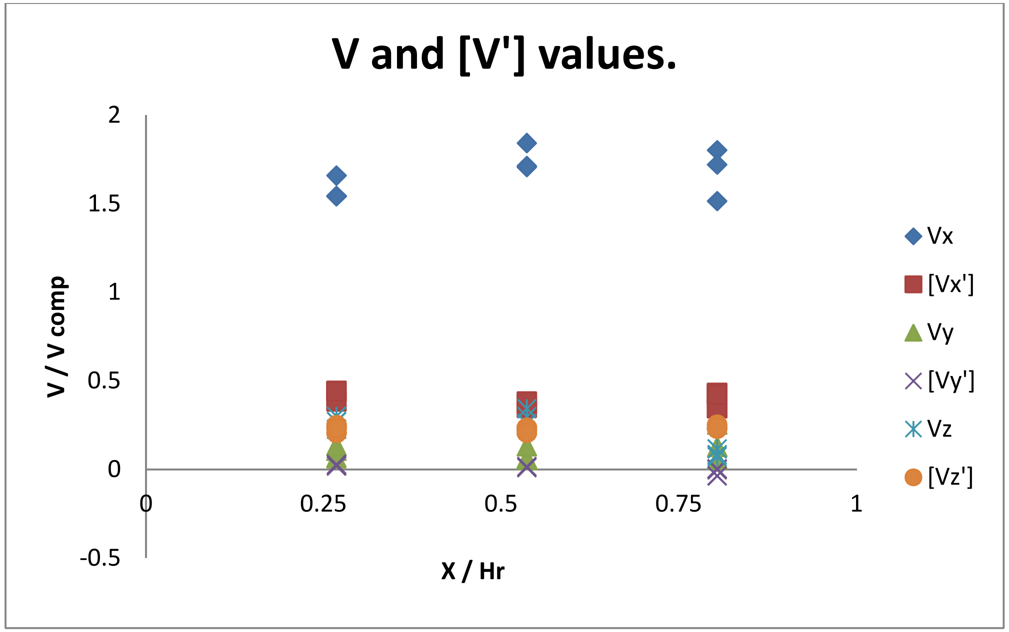


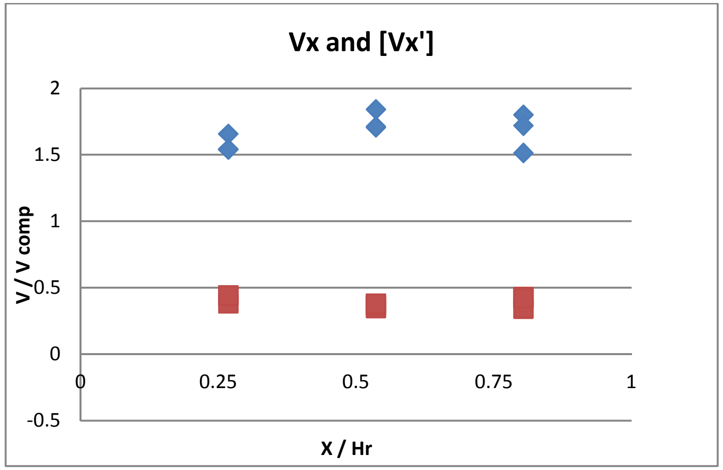


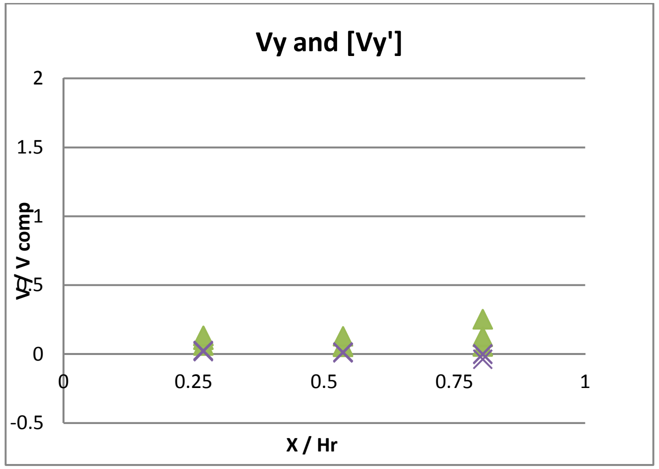


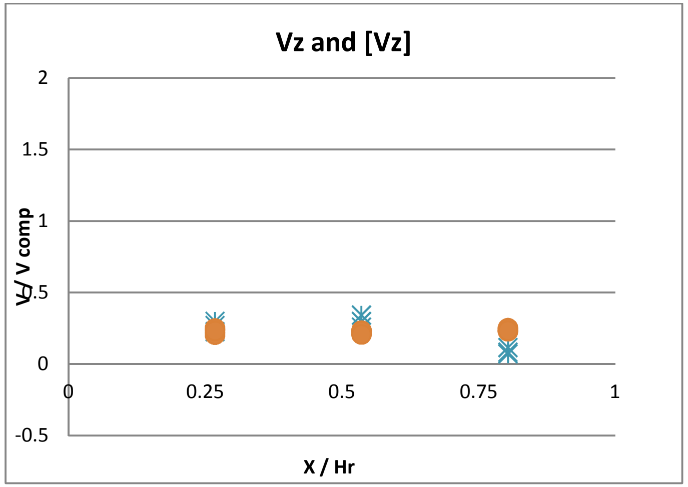


Mean velocities and velocities fluctuations for the 29º Inclined Rack at the z=25 cm elevation from the reference point.

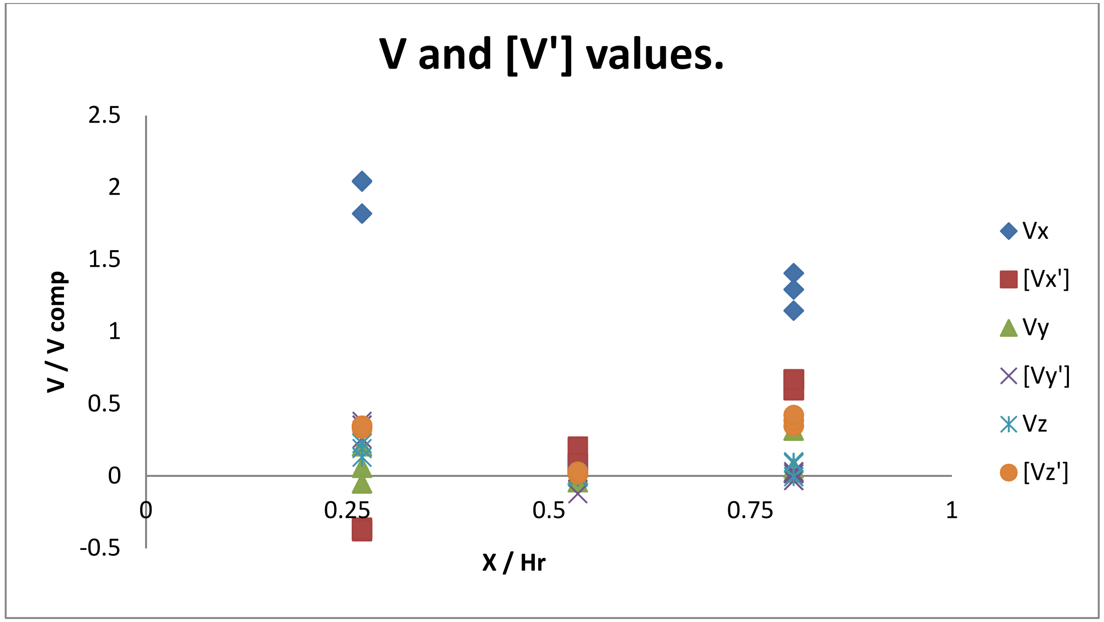


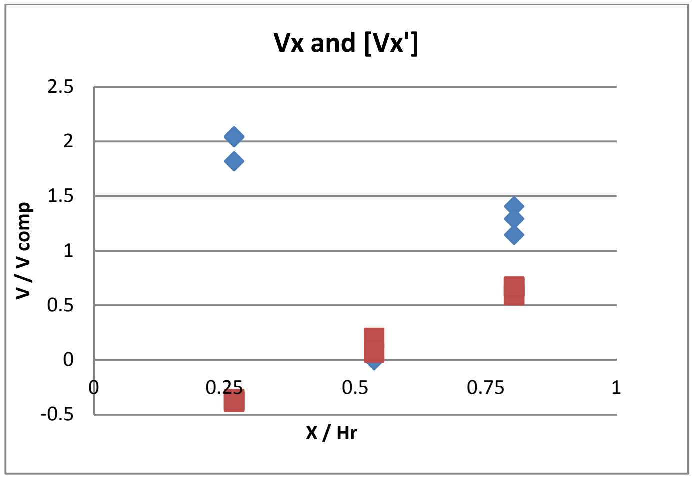


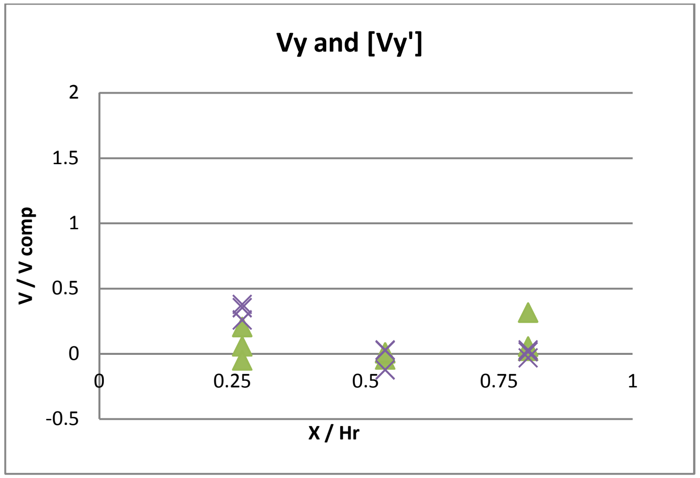


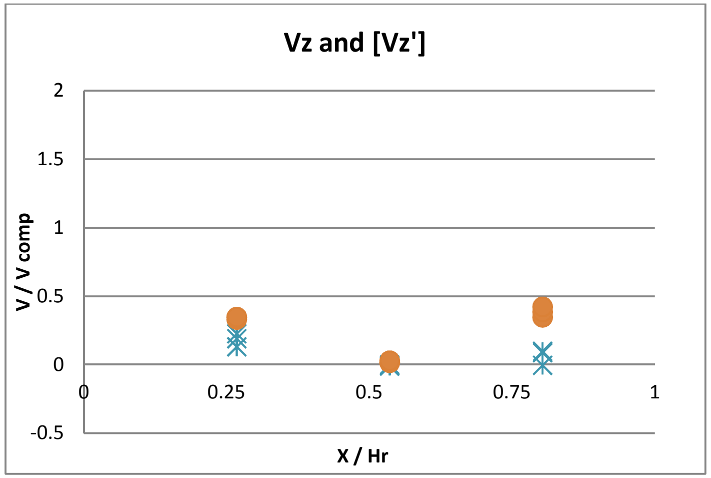


Mean velocities and velocities fluctuations for the 29º Inclined Rack at the z=15.5 cm elevation from the reference point.

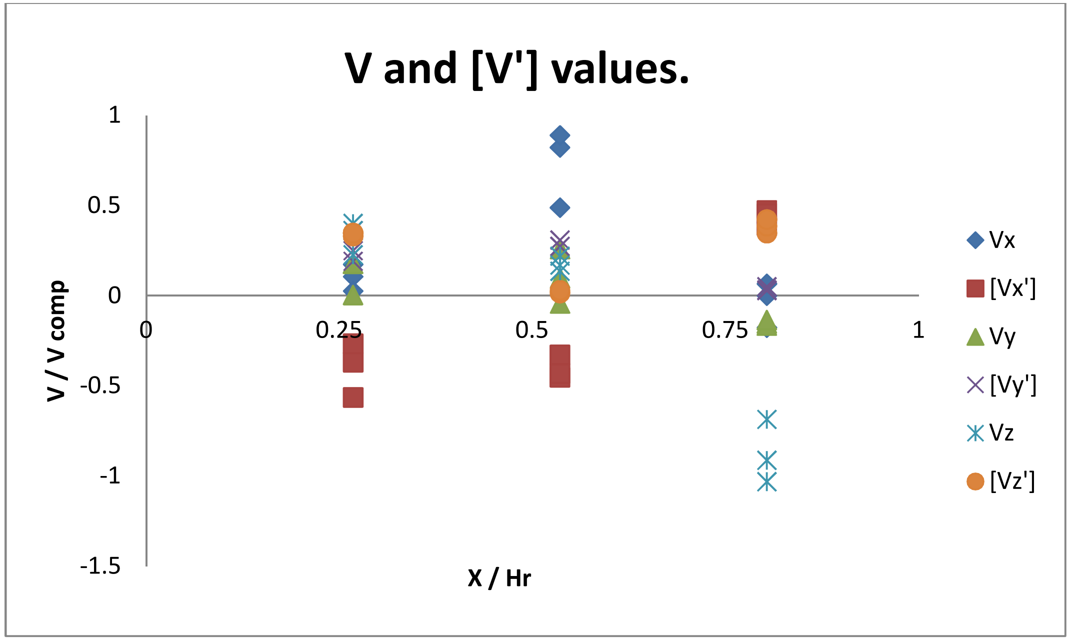


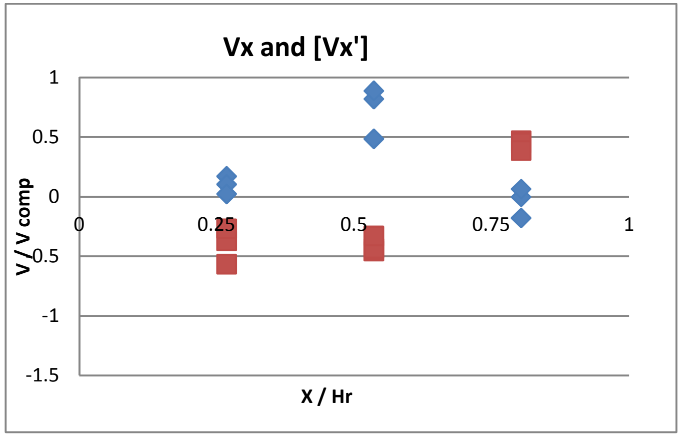


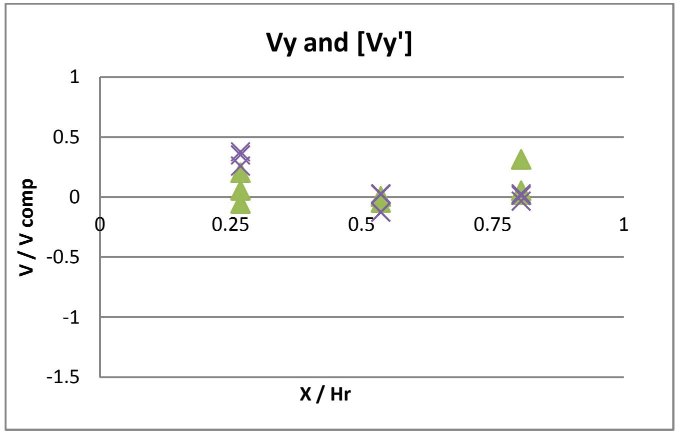


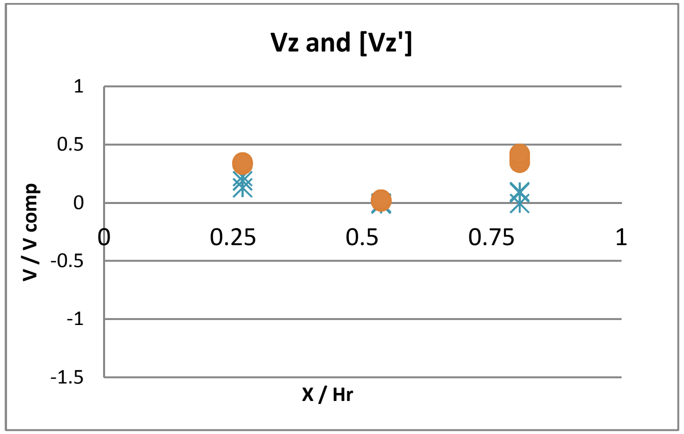


Mean velocities and velocities fluctuations for the 29º Inclined Rack at the z=3.6 cm elevation from the reference point.





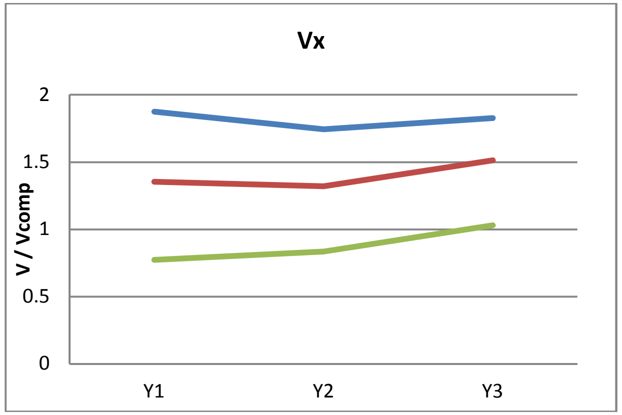


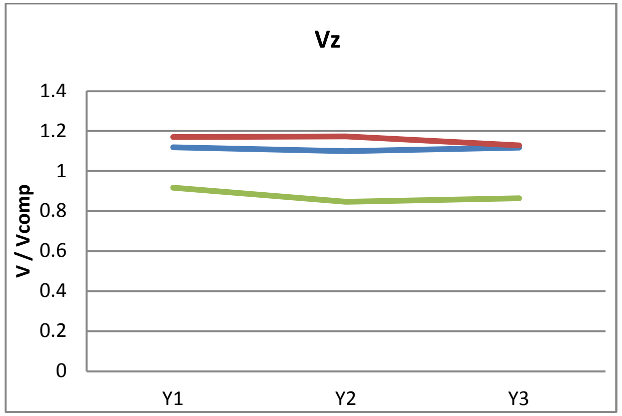


Appendix D: Velocities in X and Z direction along the width.

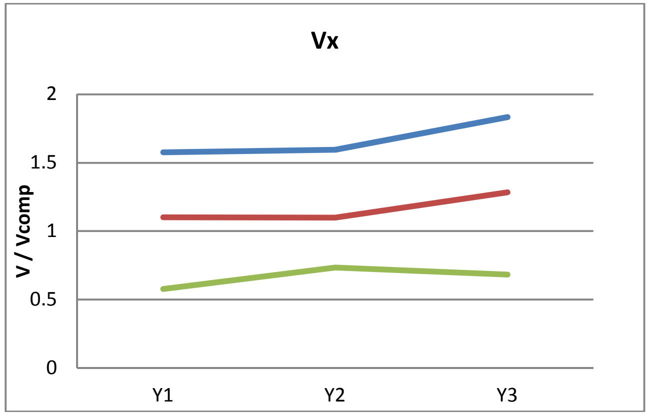
Horizontal Rack.

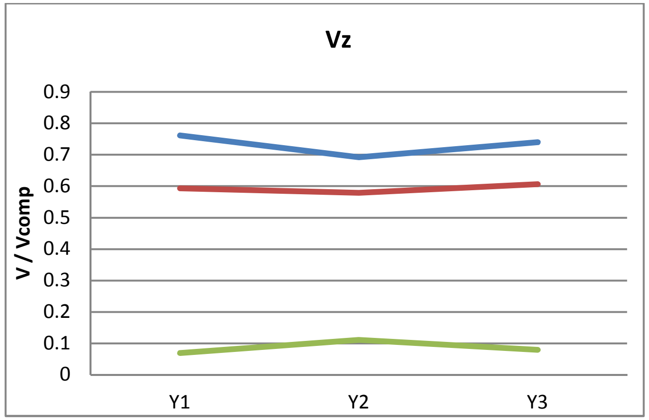
Values for Z = 25 cm



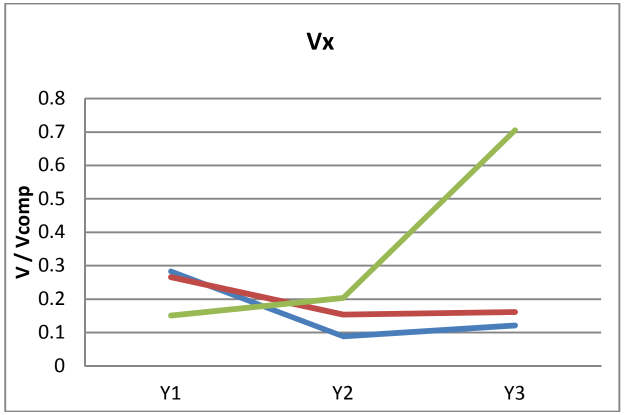


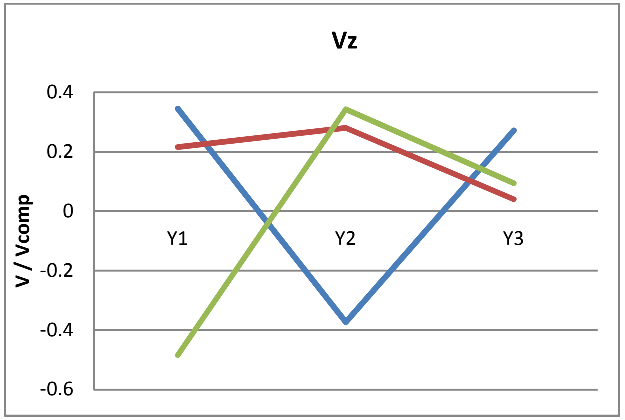
Values for Z = 15.5 cm





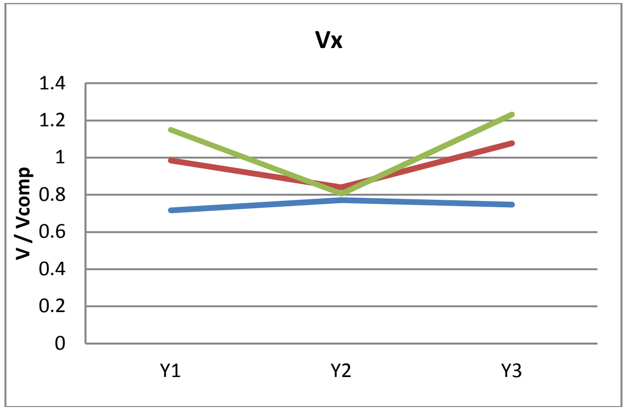
Values for Z = 3.6 cm



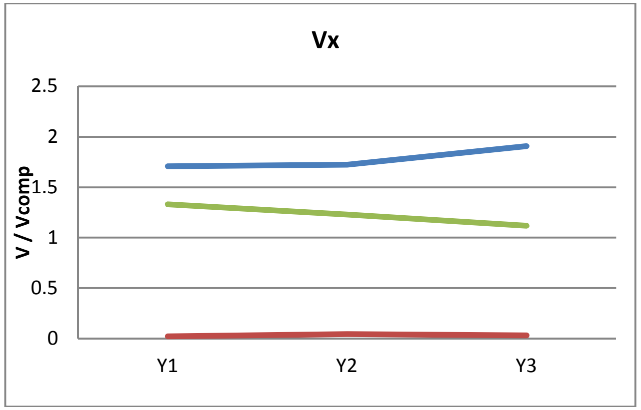


39º Inclined Rack.

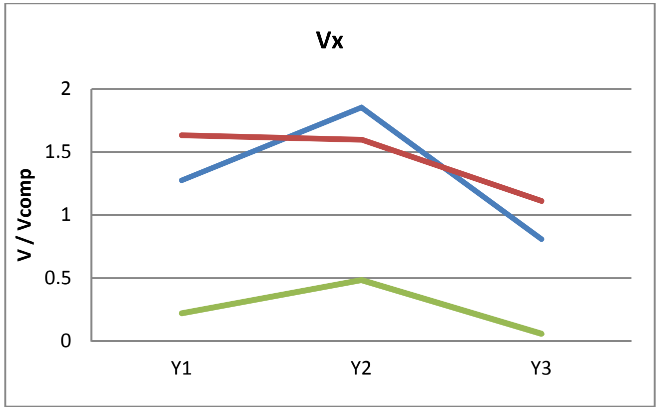
Values for Z = 25 cm

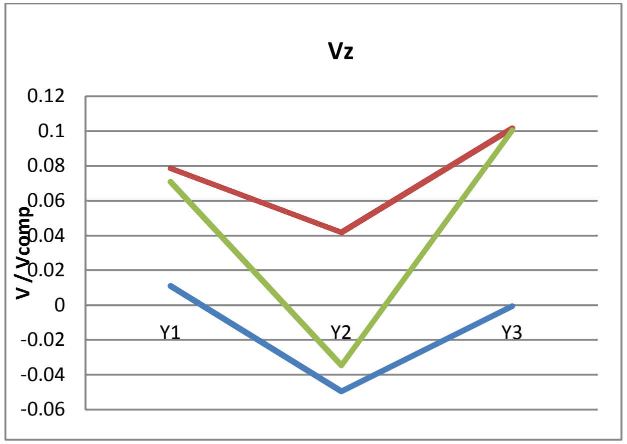


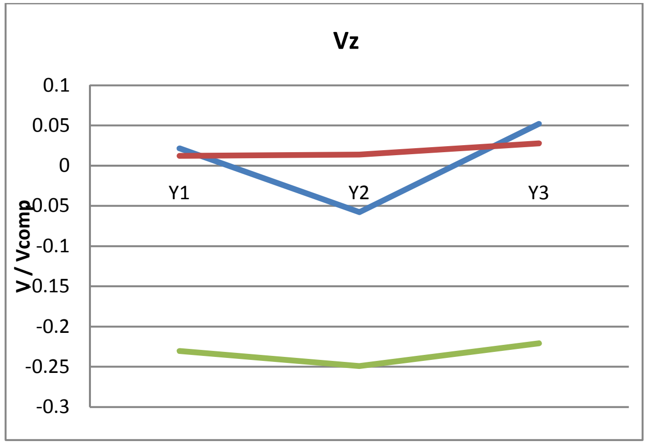
Values for Z = 15.5 cm

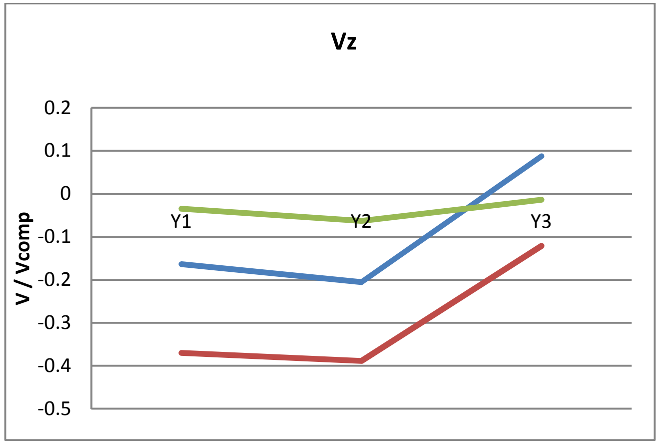


Values for Z = 3.6 cm



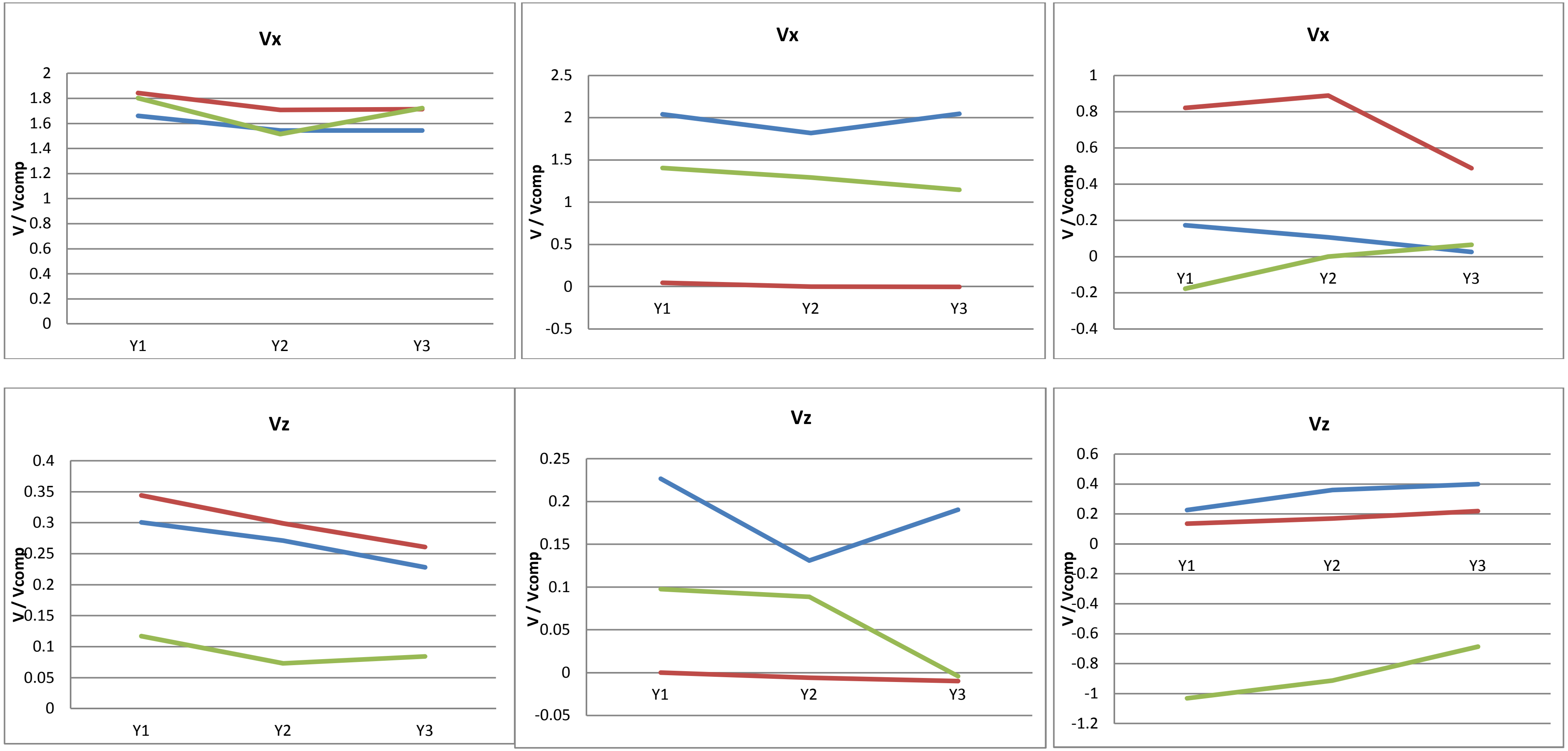






29º Inclined Rack.

Values for Z = 25 cm | Values for Z = 15.5 cm | Values for Z = 3.6 cm



Appendix E: Velocity measurements.

Racks	X (cm)	Y (coor)	Z = 25 cm			Z = 15.5 cm			Z = 3.6 cm		
			Vx	Vy	Vz	Vx	Vy	Vz	Vx	Vy	Vz
Horizontal	0.075	0.0875	41.9951	5.4074	25.0739	35.3283	3.1592	17.0668	6.3350	-0.1499	7.7260
	0.075	0.175	39.0663	6.5739	24.6367	35.7313	2.5702	15.5153	1.9945	2.0814	-8.3457
	0.075	0.2625	40.9213	5.9445	25.0361	41.0664	5.9324	16.5795	2.7218	4.6047	6.0782
	0.15	0.0875	30.3112	4.4690	26.2248	24.6630	2.3616	13.2905	5.9446	0.5686	4.8284
	0.15	0.175	29.5991	5.1170	26.2899	24.6305	1.9944	12.9746	3.4349	4.2384	6.2704
	0.15	0.2625	33.8780	5.9997	25.2926	28.7760	3.4919	13.5799	3.6077	2.1049	0.9029
	0.225	0.0875	17.2966	0.6424	20.5309	12.9168	-0.5278	1.5400	3.3746	-0.2476	-10.8357
	0.225	0.175	18.7067	3.0323	18.9769	16.4461	2.0790	2.4933	4.5664	4.2048	7.6868
	0.225	0.2625	23.0641	4.6546	19.3705	15.2986	5.8407	1.7848	15.7952	5.4954	2.1074
39	0.075	0.0875	41.9951	-3.6750	0.2481	38.2231	0.2558	0.4772	28.5622	-2.2304	-3.6685
	0.075	0.175	39.0663	5.7249	-1.1119	38.6186	-0.7777	-1.2967	41.5096	-0.5663	-4.5934
	0.075	0.2625	40.9213	1.9144	-0.0130	42.7497	4.4083	1.1662	18.1032	1.3410	1.9581
	0.15	0.0875	30.3112	-2.2399	1.7615	0.5409	0.5409	0.2777	36.5720	-2.8666	-8.2928
	0.15	0.175	29.5991	0.9503	0.9364	1.0054	1.0054	0.3067	35.7813	-2.3674	-8.7010
	0.15	0.2625	33.8780	1.1990	2.2756	0.7409	0.7409	0.6254	24.8666	1.4075	-2.7202
	0.225	0.0875	17.2966	-2.2470	1.5872	29.7974	2.0937	-5.1563	4.9428	-0.0751	-0.7844
	0.225	0.175	18.7067	-2.5896	-0.7766	27.5122	1.8183	-5.5769	10.8472	-1.0088	-1.4063
	0.225	0.2625	23.0641	0.4113	2.2537	25.0775	1.8049	-4.9496	1.3185	0.1149	-0.3009
29	0.075	0.0875	37.1795	2.3834	6.7357	45.6947	1.3007	5.0783	3.8680	0.0783	5.0757
	0.075	0.175	34.5705	1.4699	6.0745	40.7536	-1.1226	2.9321	2.3675	3.9509	8.0820
	0.075	0.2625	34.5768	3.0049	5.1097	45.8366	4.6242	4.2610	0.5661	3.9750	8.9651
	0.15	0.0875	41.2846	1.2346	7.7071	1.0815	-0.9648	0.0023	18.3945	-0.9814	3.0273
	0.15	0.175	38.2547	1.3905	6.6994	0.0610	0.1143	-0.1353	19.9174	2.1700	3.7898
	0.15	0.2625	38.3779	2.9440	5.8425	-0.0491	0.2452	-0.2200	10.9209	5.7804	4.9012
	0.225	0.0875	40.3885	1.2966	2.6218	31.4880	0.5115	2.1855	-3.9681	-3.4372	-23.0991
	0.225	0.175	33.9512	5.7042	1.6339	28.9626	1.2603	1.9837	-0.0127	-3.7222	-20.4436
	0.225	0.2625	38.5625	2.8665	1.8916	25.6695	7.0807	-0.0947	1.4721	-3.0174	-15.3642