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Finally, I want to thank my family and friends for giving life a taste of sweetness.

Only Love Can Reach The Shore…

"Chris De Burgh"

Table of contents

Nomenclature

Symbol	Meaning	Unit
ρ	Density	kg/m^3
ρ_L	Density of the liquid	kg/m^3
ρ_G	Density of the gas	kg/m^3
λ_L	No slip liquid fraction	-
λ_G	No slip gas fraction	-
ε_L	Real liquid fraction	-
ε_G	Real gas fraction	-
μ	Viscosity	$pa.s$
μ_L	Viscosity of the liquid	$pa.s$
μ_G	Viscosity of the gas	$pa.s$
μ_m	Viscosity of the mix	$pa.s$
β	Pipe inclination	Degree
A	Flow cross sectional area	m^2
A_L	Liquid cross-sectional area	m^2
A_G	Gas cross-sectional area	m^2
D	Diameter of the pipe	$meter$
f	Friction factor	-
G	Total mass flowrate	kg/s
G_L	Mass flowrate of the liquid	kg/s
G_G	Mass flowrate of the gas	kg/s
h	Height of the liquid center	$meter$
L	Length of the line	$meter$
L	Length of the gas line	$meter$
L	Length of the liquid line	$meter$
m	Mass flowrate	kg/s

Symbol	Meaning	Unit
P	Pressure	Pascal
Q	Flowrate	m^3/s
q_L	Liquid flowrate	m^3/s
q_G	Gas flowrate	m^3/s
Re	Reynolds number	-
S	Slip Ratio	-
u_L	Real Liquid Velocity	m/s
u_G	Real gas Velocity	m/s
u_s	Slip Velocity	m/s
U	Velocity of the flow	m/s
U_{LS}	Superficial liquid velocity	m/s
U_{GS}	Superficial Gas velocity	m/s
U_{mix}	Velocity of the mix	m/s
V	Volume of the pipe	m^3
V	Volume of the gas	m^3
V	Volume of the liquid	m^3
X	Dynamic gas fraction	-

List of figures

List of Tables

1. Introduction and aim of study

Its springtime, you are setting by the edge of a river, a nice breeze is hitting your face while you were looking through the clear water trying to spot some of the stones that are moving down the riverbed. This is a very simple beautiful scene by mother earth, but behind this simplicity lies the laws of physics, thermodynamics and fluid mechanics. Now the situation is not as simple as it was described before, but its beauty just got very intensify.

Fluid mechanics controls a big part of our life, we are able to fly with planes based on the lift principle by Bernoulli and while our drinking water flows in pipes to modern cities so we can drink, blood flows in our vessels so we can enjoy all of the previous.

In our field which is the petroleum industry, fluid flow is also very essential. From the early days of oil discovery, it became very clear that a big part the oil industry is and will be based on the science and the principles of fluid mechanics.

Nowadays and looking into the future, we still possess the need and the passion to gain more understanding of the behavior of fluids in motion. This will lead us to more stable and efficient operations along with drilling, separation of hydrocarbons and water, transportation of liquids and many more.

The main aim of this work is to build and assemble a two-phase fluid-loop. This loop will allow us and the future students at the university of Stavanger to access a facility which will provides direct opportunities to investigate flow of fluids at their different phases with their different flow regimes for educational and research purposes.

This work will also include practical experiments with water as a one phase flow and with air and water together as a two-phase flow.

This work will also include some observation and notes that we thought it was interesting enough to be written and shared with the readers.

2. Theory

This chapter includes a quick look to some of the principles that this work was based on.

Equations 2.3 to 2.35 are taken from “*R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017* ”

2.1. Single phase flow

The simplest case of a flowing liquid. While in reality the most common case of flow is multiphase flow, understanding single phase flow can be a good start for studying multiphase flow.

The velocity of the flow is one of the most important values that we look for in every flow.

Let’s assume we have a pipe with constant diameter, a single-phase fluid is flowing through it from point 1 to point 3 passing point 2 on its way (figure 2.1). let’s focus on the cross-section of point 2 and imagine that is moving with the flow, If we know the flowrate value at point 2 and the cross-sectional area of the flow, the velocity of the flow can be easily calculated using equation 2.1

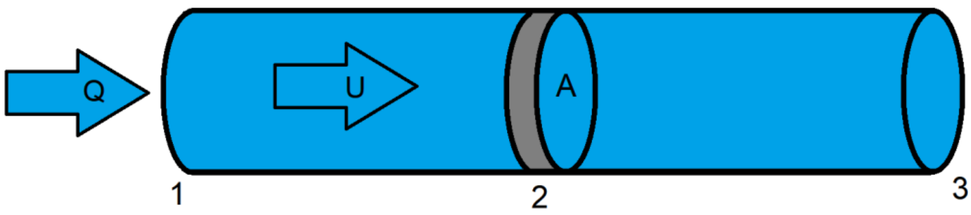

Figure 2.1. single phase flow in a pipe.

The volumetric flow rate of a liquid flowing through a pipe can be calculated by

$$Q = A * U \tag{2.1}$$

Sometimes it good to know how much mass is going through the system and that is called the mass flowrate which can be calculated by

$$m = Q * \rho \tag{2.2}$$

2.2. Multiphase flow

Now more than one phase is flowing in a pipe, let’s take gas-liquid flow for example. we will use the Letter L for liquid and the letter G for Gas, now the situation is more interesting, let’s look at Figure 2.2.

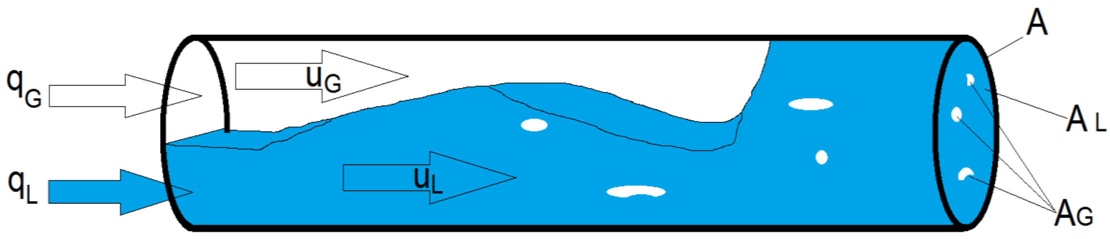

Figure 2.2. gas-liquid flow in a pipe.

Now we have a flowrate, a velocity and an area for each phase. If we divide the pipe to several cross-sections along the flow, we can see clearly that the area of the phases is changing along the pipe.

The mass flow rates can be calculated as the following

$$G_L = \rho_L \cdot q_L \tag{2.3}$$

$$G_G = \rho_G \cdot q_G \tag{2.4}$$

$$G = G_L + G_G \tag{2.5}$$

If we know the volumetric flowrate of each phase and the cross-sectional area of the pipe A the following velocities can be calculated,

$$U_{LS} = \frac{q_L}{A} \tag{2.6}$$

$$U_{GS} = \frac{q_G}{A} \tag{2.7}$$

These are not the real velocities in the flow. we refer to them as the superficial velocities or apparent velocities. However, the sum of these velocities is called the mixture velocity and it equals the real average velocity in the flow.

$$U_{mix} = U_{LS} + U_{GS} \tag{2.8}$$

The real velocities are called the phase velocities. Which are the local velocities at each cross section along the pipe, they can also be defined for an average cross-section of the pipe.

$$u_L = \frac{q_L}{A_L} \tag{2.9}$$

$$u_G = \frac{q_G}{A_G} \tag{2.10}$$

In order to determine the values of the real velocities, the areas A_L and A_G must be determined. These areas correspond to the fraction of each phase in the flow.

The slip velocity is defined by $u_S = |u_G - u_L|$ (2.11)

Where the slip ratio can be expressed as

$$S = \frac{u_G}{u_L} \tag{2.12}$$

When the slip ration equals to one, the situation referred to as "no slip situation". In this situation all the following velocities are equal.

$$u_G = u_L = U_{mix} \tag{2.13}$$

We have mentioned before that the areas of the phases correspond to the fraction of each phase in the flow. Many methods are available to measure these fractions.

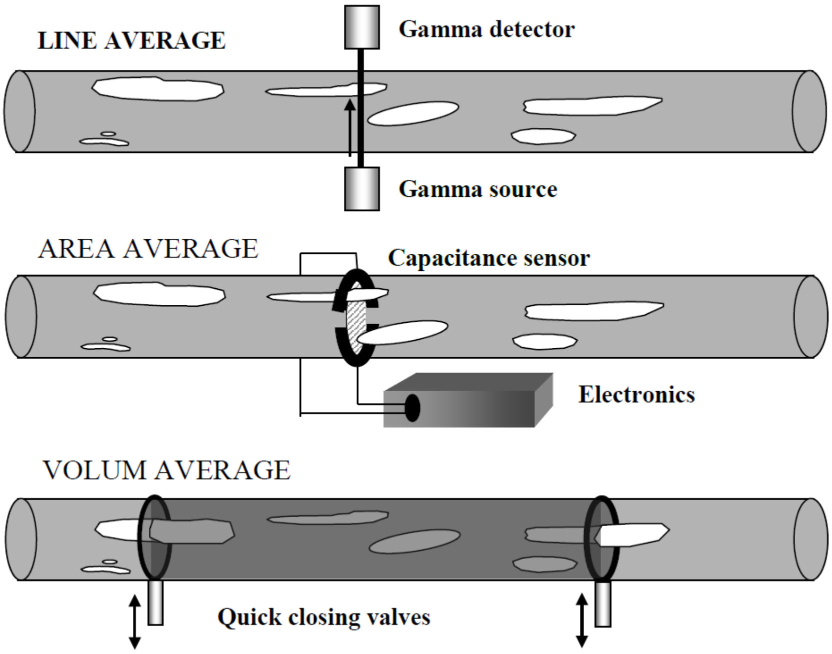

Figure 2.3. Techniques for fluid fraction measurements. R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017.

"Line averages are measured e.g. with a narrow beam gamma(γ)-densitometer. Area averages we obtain with a wide beam gamma-densitometer, or with (electric field) impedance sensors having electrodes made into the pipe wall. Volume averages (pipeline average) may be obtained by using quick closing valves." R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017

Based on the techniques in Figure 2.3, Gas and fluid fraction can be defined as:

$$\varepsilon_G = \frac{V_G}{V} \quad \text{or} = \frac{A_G}{A}, \quad \text{or} \quad = \frac{L_G}{L} \tag{2.14}$$

$$\varepsilon_L = \frac{V_L}{V} \quad \text{or} = \frac{A_L}{A}, \quad \text{or} \quad = \frac{L_L}{L} \tag{2.15}$$

Where V is the volume, A is the Area, and L is length.

Sometimes very few information is available about the dynamics in the flow and an accurate value of the phase fractions are impossible to calculate. However, it important to obtain an estimate value of the fractions which is called the no slip fractions.

$$\lambda_L = \frac{q_L}{q_L + q_G} \tag{2.16}$$

$$\lambda_G = \frac{q_G}{q_L + q_G} \tag{2.17}$$

If we know the value of the slip ratio, we can determine the true fraction of the phases.

$$\varepsilon_L = \frac{q_L}{q_L + \frac{1}{S} \cdot q_G} = \frac{U_{LS}}{U_{LS} + \frac{1}{S} \cdot U_{GS}} \tag{2.18}$$

$$\varepsilon_G = \frac{q_G}{S \cdot q_L + q_G} = \frac{U_{GS}}{S \cdot U_{LS} + U_{GS}} \tag{2.19}$$

2.3. Fluid properties in two phase flow

Knowing the density and the viscosity at the single phases and the fluid fraction will allow us to calculate the mix density and viscosity.

The mix density can be calculated simply by:

$$\rho_m = \rho_L \varepsilon_L + \rho_G \varepsilon_G \tag{2.20}$$

The mix viscosity unlike the mix density depends on many dynamic factors, thus many models are existed to calculate it.

Some of the models are:

Cichitti model for small gas fraction:

$$\mu_m = x\mu_G + (1-x)\mu_L \tag{2.21}$$

McAdams model for low liquid fraction:

$$\frac{1}{\mu_m} = \frac{x}{\mu_G} + \frac{(1-x)}{\mu_L} \tag{2.22}$$

Where X is the dynamical gas fraction X = GG/G.

Dukler model:

$$\mu_m = \varepsilon_G \mu_G + (1-\varepsilon_G)\mu_L \tag{2.23}$$

Viscosity models

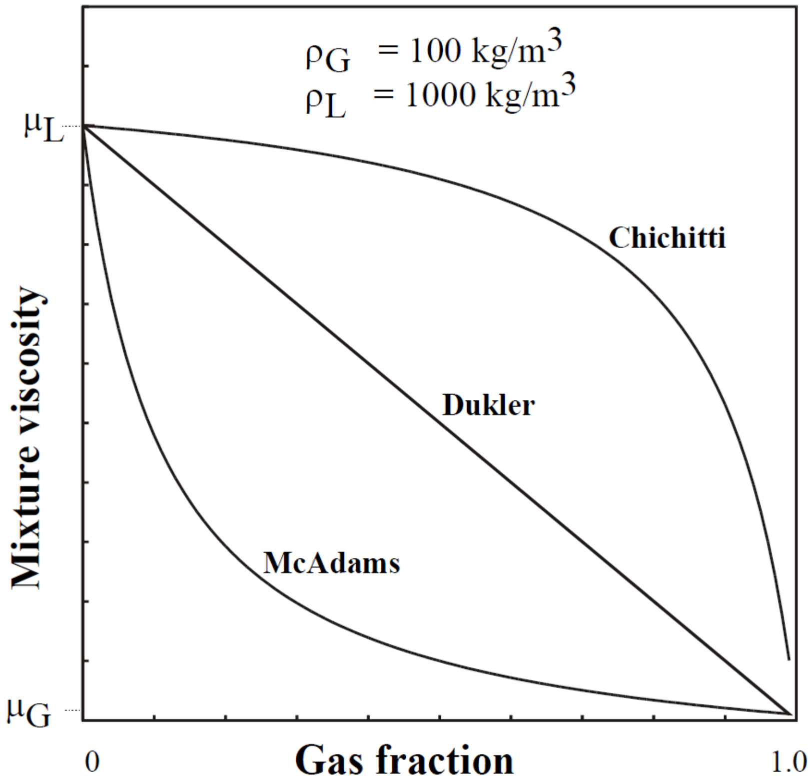

Figure 2.4. Viscosity models versus gas fraction. R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017.

2.4. Flow patterns, flow regimes and the Reynolds number

In single phase flow, the flow pattern will either be laminar or turbulent, a transition between laminar and turbulent can also exist.

The dimensionless quantity "Reynold number" can allow us to detect the flow pattern in both single and multi-phase flow.

For single phase flow:

$$\mathrm{Re} = \frac{\rho U D}{\mu} \tag{2.24}$$

For multiphase flow:

$$\mathrm{Re}_m = \frac{\rho_m U_{mix} D}{\mu_m} \tag{2.25}$$

If

- Re ≤ 2000 The fluid will be laminar.
- 2000 < Re ≤ 4000 Transition flow between laminar and turbulent.
- Re > 4000 The fluid will be turbulent flow.

In multiphase flow, we differentiate the flow by its pattern just like in single phase flow but in addition flow regimes now exist and we also differentiate the flow according to its regime.

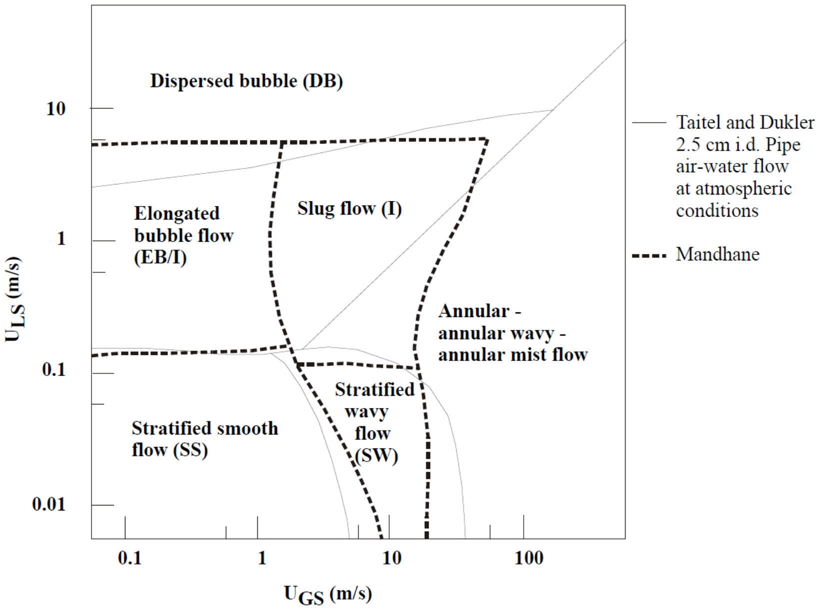

Figure 2.5. Flow regimes map in horizontal two-phase flow.

R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017.

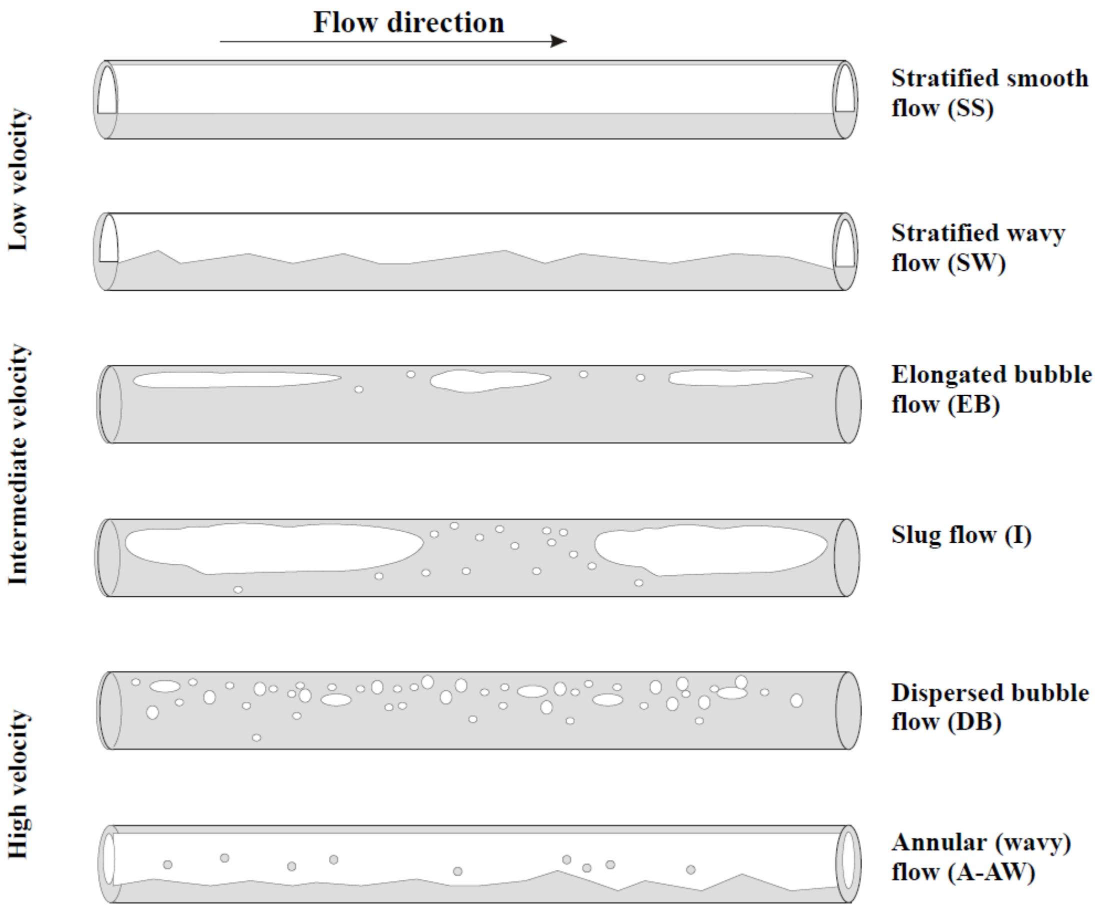

Figure 2.6. Flow regimes in horizontal two-phase flow. R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017.

2.5. Friction factors and Pressure gradient

In addition to all the quantities that contribute to the Reynolds number, pressure gradient (dP/dx) in pipe flows is also dependent on wall roughness and pipe inclination.

The pressure gradient in pipes can be composed of three terms:

$$\frac{dp}{dx} = \left(\frac{dp}{dx}\right)_f + \left(\frac{dp}{dx}\right)_h + \left(\frac{dp}{dx}\right)_a \tag{2.26}$$

Where:

f stands for Frictional pressure gradient

h stands for Hydrostatic pressure gradient

a stands for acceleration pressure gradient.

2.5.1 Pressure gradient in single phase flow

2.5.1.1. Frictional pressure gradient:

$$\left(\frac{dp}{dx}\right) = \frac{1}{D} \cdot \ f \ \cdot \frac{1}{2} \rho \, \mathrm{U}^2 \tag{2.27}$$

The flow pattern is the crucial elements of the frictional pressure gradient and that is clearly seen in the equations that calculate the friction factor f.

For laminar flow according to Moody the friction factor equals:

$$f = \frac{64}{\mathrm{Re}} \tag{2.28}$$

For turbulent flow according to Drew, Koo and McAdams (1932) Smooth Pipe:

$$f = 0.0056 + 0.5\,\mathrm{Re}^{-0.32} \tag{2.29}$$

For turbulent flow according to Haaland (1983) formula:

$$\frac{1}{\sqrt{f}} \approx -1.8 \cdot \log_{10}\left((\frac{\varepsilon / D}{3.7})^{1.11} + \frac{6.9}{\mathrm{Re}} \right) \tag{2.30}$$

Where ε is the roughness of the pipe.

* Glass roughness equals 10^-6 R.W.Time, Two-phase flow in pipelines, Course compendium, UiS, 2017.

2.5.1.2. Hydrostatic pressure gradient:

$$\left(\frac{dp}{dx}\right)_h = \rho \, \mathrm{g} \cos\beta \tag{2.31}$$

Where β is the pipe inclination relative to the vertical direction.

2.5.1.3. Acceleration pressure gradient:

$$\left(\frac{dp}{dx}\right)_a = -\rho \, \mathrm{U} \cdot \frac{\mathrm{dU}}{\mathrm{dx}} \tag{2.32}$$

2.5.2 Pressure gradient in two phase flow

2.5.2.1. Frictional pressure gradient:

$$\left(\frac{dp}{dx}\right)_f = \frac{4}{D} \cdot C(\mathrm{Re}_m)^{-n} \cdot \frac{1}{2} \rho_{\mathrm{m}} \mathrm{U}_{\mathrm{mix}}{}^2 \tag{2.33}$$

Where C = 0.046 and n = 0.2

2.5.2.2. Hydrostatic pressure gradient:

$$\left(\frac{dp}{dx}\right)_h = \rho_m \, \mathrm{g} \cos\beta \tag{2.34}$$

2.5.2.3. Acceleration pressure gradient:

$$\left(\frac{dp}{dx}\right)_a = -\rho_m \, \mathrm{U}_{\mathrm{mix}} \cdot \frac{\mathrm{dU}_{\mathrm{mix}}}{\mathrm{dx}} \tag{2.35}$$

2.6. Bernoulli's Equation

Bernoulli's equation is simply the conservation of energy inside a fluid

First let us take a look at the continuity equation for incompressible fluid.

$$A1 * U1 = A2 * U2 \tag{2.36}$$

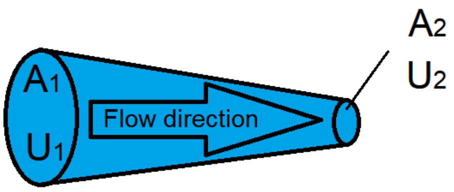

Figure 2.7. The continuity equation.

The same concept applies to Bernoulli's equation that can be expressed as:

$$\underbrace{P1}_{A} + \underbrace{\rho g h1}_{B} + \underbrace{\frac{1}{2}\rho U1}_{C} = P2 + \rho g h2 + \frac{1}{2}\rho U2 \tag{2.37}$$

Where A represent the pressure energy, B represent the potential energy and C represent the kinetic energy.

2.7. Principle of the electromagnetic flowmeter

The device creates a magnetic field in the inner pipe of the device (figure2.8. purple color). Two electrodes which are perpendicular to the flow direction is fixed on the inner pipe of the device as well (figure 2.8. red color). According to Faraday's law of electromagnetic induction, when a conductive fluid pass through a magnetic field, an electrical potential is induced which is perpendicular to the axis of the fluid velocity. The potential difference between the two electrodes reflects the velocity of the flowing fluid. (Appendix C, P11)

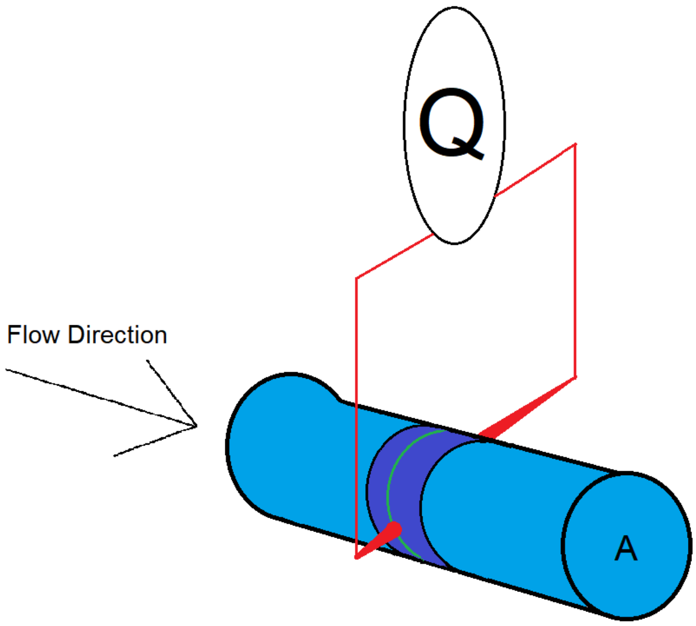

Figure 2.8. Electromagnetic flowmeter principle.

2.8. Hydrostatic pressure of liquid column

The hydrostatic pressure of a liquid column can in Pascal unit be calculated by

$$P = \rho * g * h \qquad (2.38)$$

Where:

g is the gravitational acceleration = [9.81 m/s2]

h is the height of the liquid [m]

ρ is the density of the liquid [kg/m3]

3. Rig building and instrumentation

This chapter will include a detailed description with pictures of the components and the work that has been done regarding building of the rig and the subsequent works that followed along with instrumentation set up, and calibration processes.

3.1. Rig Elements:

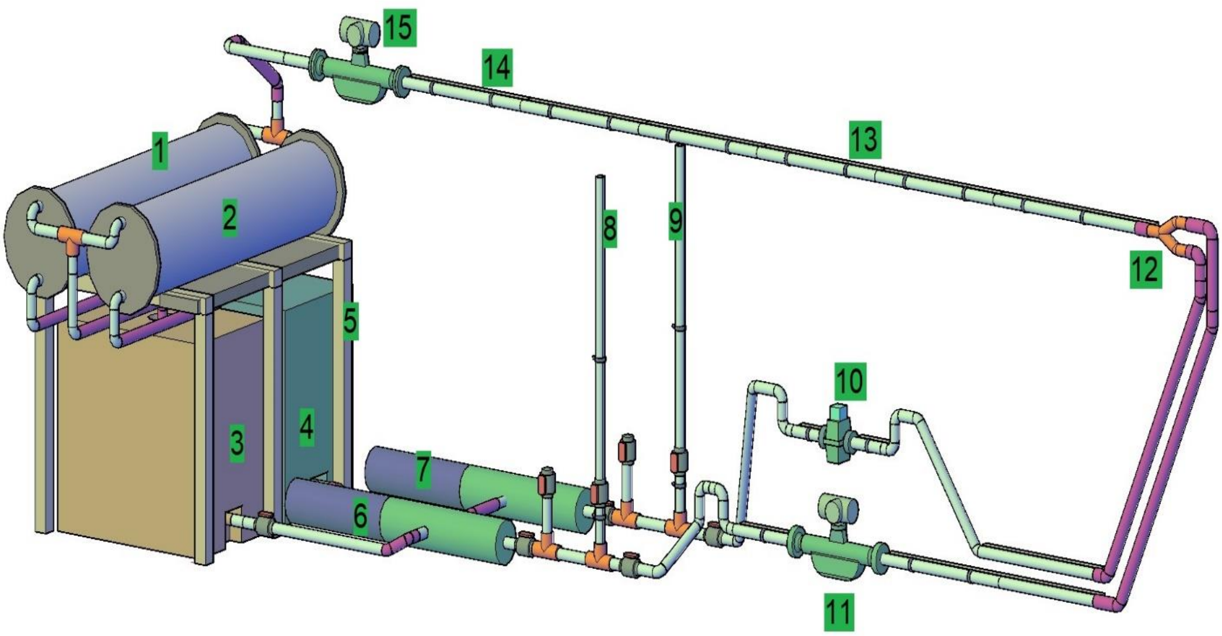

Figure 3.1. Original rig design. UiS

1.2. Separators.
3.4. Storage tanks
5. Separator's table
6.7. Pumps
8.9. Safety back lines
10. Electromagnetic flow meter
11. Coriolis flow meter.
12. Mixing unit.
13. Mixed section pipe
14. Test section pipe
15. Coriolis flow meter.

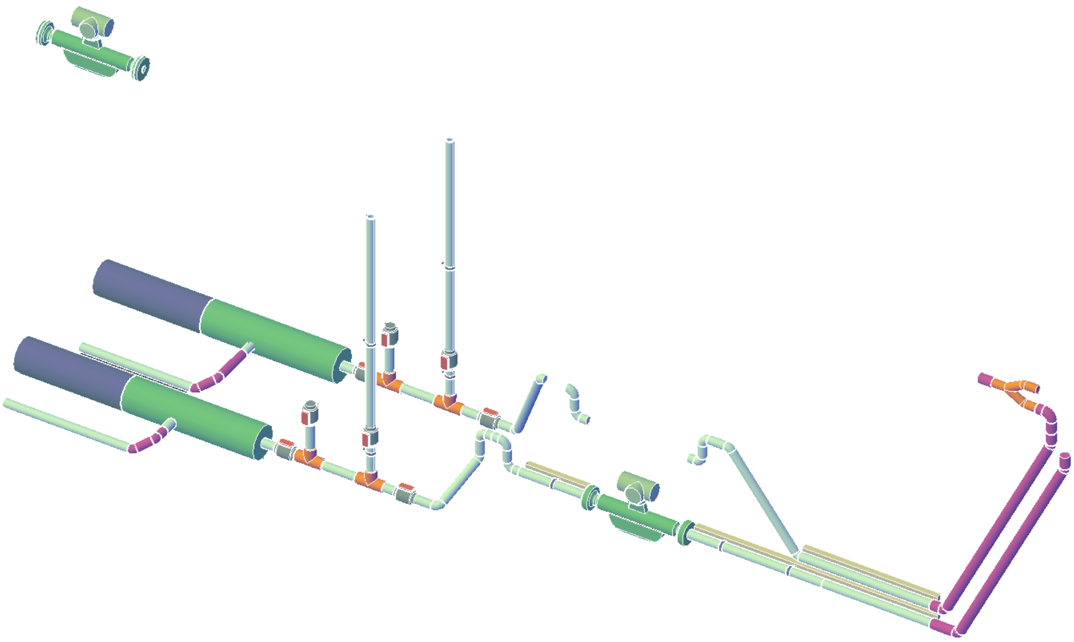

Figure 3.2. Elements which were functioning without any modifications. (UiS with modification)

3.1.1. Loop body:

In addition to acrylic transparent pipes with 52 mm inner diameter, semi-transparent hoses with inner diameter of 50 mm were already used to build the loop body. While the hoses were mainly used for flexibility reasons, many hose clamps were used to connect the pipes and the hoses together.

A set of ten valves were already used to connect between the tanks, the pipes and the hoses to allow flow stoppage in case maintenance were needed and for more control of the flow and damping purposes. An extra valve was added later to the outlet of the separator.

The loop body and all the instruments were already fixed to several aluminum profiles. These profiles were already connected and firmly fixed on four steel columns. All of these together play the rule as the rig's backbone.

The loop body consisted of many leakage spots that had to be fixed before proceeding.

(Appendix C P1 - P2)

Figure 3.3. Loop early stages.

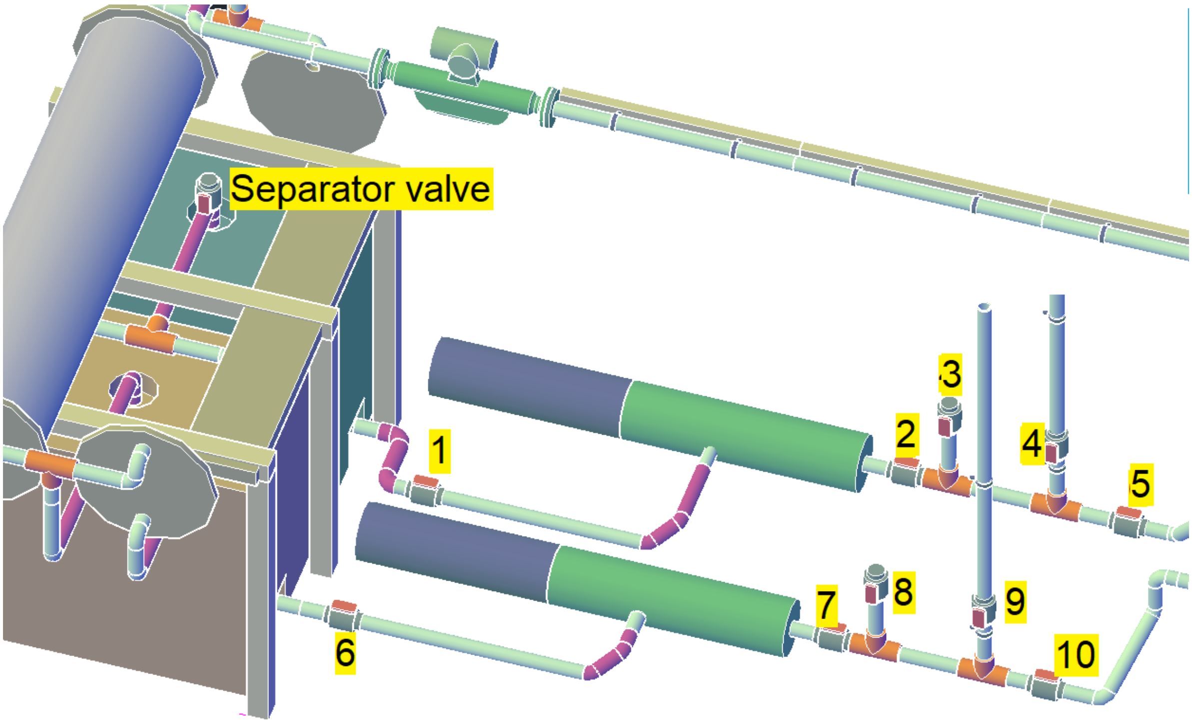

Figure 3.4. Valves of the loop after Final design. (UiS with modification)

3.1.2. Storage tanks:

Two identical (Werit) plastic tanks each with 800-liter storage capacity were used for storage purposes, one was used for oil storage and the other one for water storage purposes.

The tanks had marks on its walls that marks every 100 liters from the bottom of the tank until 800 liters at the top.

The two outlets of the storage tanks were too weak, and they needed to be replaced with stronger material.

One of the tanks was dirty with remains of black grease and had to be washed and scrubbed many times with hot water and grease removal solution.

(Appendix C P3 - P6)

3.1.3. Pumps:

Two identical SEW Eurodrive "RF 67 DRE132M4 TF V" helical progressing cavity pump (positive displacement pumps) that run with electrical power were already fixed on the floor, one to be connected to the oil tank while the other one to be connected with the water tank.

The pumps had to be connected to frequency regulators with the help of the electrical department at the university of Stavanger.

(Appendix C P7 - P9)

Figure 3.5. The pumps.

3.1.4. Flow meters:

Three flow meters were already been fixed in the loop, two Proline Promass 80F Coriolis flowmeters were used to measure the flow of the oil in the oil pipe and the flow of the mixture at the end of the test section pipe, while one Tecfluid FLOMID 2FX electromagnetic flowmeter was used to measure the water flow rate in the water line pipe.

While the Coriolis flow meter in the oil line was not in our interest, the other Coriolis flow meter in the mixed section pipe wasn’t technically working. therefore, we were mainly concerned of the installation of the electromagnetic flow meter.

Figure 3.6. FLOMID 2FX flowmeter.

Figure 3.7. Promass 80F Flowmeter.

The electromagnetic flow meter has an XT5 converter which has three buttons for configuration reasons and a screen where the values can be read.

The screen usually shows two values, one is the current flowrate of the liquid while the other one is the cumulative volume that went through the sensor from the beginning of working until the time of the measurements.

In case there was any need for the cumulative volume value to be set back to zero, this can be done very easily.

The devise also gave us the possibility to choose between 9 combinations of units to appear on the sensor screen, three units for volume and three units to measure time.

Volume	Time
L (Liters)	S (Second)
M3 (cubic meters)	M (Minute)
Ga (US gallons)	H (Hour)

Table 3.1. available flowmeter units.

Despite our unit choice, the flow meter always showed a flowrate value of zero while the accumulating volume by time showed a cumulative value. this problem caused us a lot of delay until we finally found out the reason and the solution.

The solution for this problem had two steps and these steps should have been made in order.

Step 1 the sensor cutoff: according to the sensor manual, the sensor *"has its maximum deviation in the low end of its working range. Due to this, a cut off flow rate can be configured, that means, the flow rate below which the flow rate indication will be zero."* *Tecfluid XT5 / XT5H Converter for Flomid/Flomat Sensors Instructions Manual.*

As a result, the cutoff value of the sensor was set to zero, which was half of the solution.

Step 2 the number of the decimals: while the device has four digits to represent the flowrate measurements, the device allows us to have maximum of two decimals in these four digits.

Obviously, our unit choice for device to indicate flowrate was chosen to be cubic meter per second [m3/s] which is the SI unit for flowrate and it's the unit we will use in our calculations.

However, the maximum flow rate that our pump can achieve is 0.001975 m3/s which is two zeros after the decimal point, since the instrument shows maximum two decimals, our flowrate will always show as 00.00 m3/s which was the problem.

Therefore, we switched our unit choice to cubic meter per hour [m3/h], which was the other half of the solution to this problem.

In the early days of this problem we tried changing the unit, but since the cutoff problem was already there, we didn't see any change, so we went back to [m3/s] and decided that this was not a unit problem.

In another word we did one step at a time not two which made us go far from the solution and look somewhere else, this cost us a lot of time and effort, but this is how a man learns, isn't?

The electromagnetic flowmeter had to be also modified so the converter can obtain correct signals from the electrodes.

In order to obtain that, the converter had to be referenced to the same potential as the pumped water. as a result, two earthing rings had to be designed, built and added to the system in addition to two more rubber gaskets that were also introduced to the system.

The two sensor wires of the flow meters were connected and fixed to the earthing rings via screws.

After all of previous the flow meter was ready to be tested for verification of correct measurements and to be calibrated with the pump through the frequency regulators.

(Appendix C P10 - P13)

3.1.5. Safety backlines:

Each of the two lines were connected to their own tank to discharge in case of a sudden flow.

These two lines were already built before the start of this work only a long meterstick was added beside the water back line to measure the hydrostatic pressure of the water column.

3.1.6. Mixing unit entry:

From the early days of this project the loop had a problem with the mixing unit entry, since water is pumped from the water line and nothing has been pumped from the oil line. Some of the water started to travel back through the oil line. This not only will lead to false flowrate calculations and pressure losses, but it will also be harmful for the Coriolis flow meter in the oil line. This instrument might store some water inside of it which by time will lead to rust.

Figure 3.8. Safety backlines.

With that being said, re-designing the mixing unit entry was one of our first priorities, a U joint with an arm length of 170 cm had to be designed and introduced vertically into the system in order to avoid the reverse flow and to help with the damping.

Proceeding with experiments we realized that our U joint was successfully able to stop the unwanted reverse flow, but it introduced a huge quantity of air into the system, and it created sort of a periodic oscillations that affected the flow rate and the pressure in the loop which made it impossible to record useful data. (Figure 5.12)

To solve this problem, we closed the nearest valve in the oil line which limited the amount of air in the system but as a final solution, a plastic led were designed and built with 7.6 cm diameter and 3 mm wall thickness to close the oil inlet for now and to focus only on the water line.

This plastic plate had to be replaced with 8 mm wall thickness plate afterwards so it can be equipped with a nipple that allowed the injection of air into the system in order to study the air water flow.

At some point during the project a vertical transparent pipe was needed instead of the led to study the U effects on the loop. As a result, a vertical transparent pipe was also designed and built.

(Appendix C P14 - P22)

3.1.7. Mixing Unit:

The oil pipe (which later was switched to the air pipe) and the water pipe were united together using a Y joint that included a thin horizontal plate on the inside that separates the oil (air) and the water from the entry point up to 250 mm into the mixed section pipe.

This thin plate is centered in the middle of the pipe and it cuts the cross sectional area of the pipe into two equal half circles and its purpose is to minimize the interfacial mixing at the entry point so the oil (air) and water could flow as layers into the mixed section pipe.

(Appendix C P23)

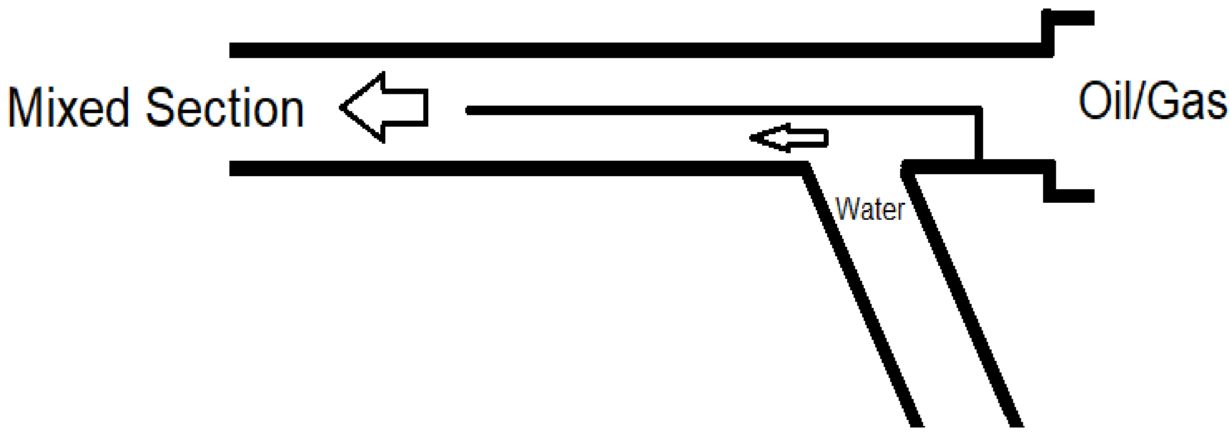

Figure 3.9. Mixing unit.

3.1.8. Mixed section pipe:

This section is a 520 cm long acrylic pipe with 52 mm inner diameter and five tiny holes equipped with five small nipples for the purposes of differential pressure measurements.

The first nipple positioned half meter away from the end of the mixing unit. The second nipple positioned half meter away from the first one. Same applies with the third nipple with half meter distance away from the second one. The fourth and the fifth nipples were one meter and two meters away from the third nipple.

Figure 3.10. Mixed section during restoration.

This section wasn't redesign but it needed to be taken down and go through a complete restoration since all the nipples were leaking fluids.

(Appendix C P24 - P27)

3.1.9. Test section

This section comes after the mixed section pipe with length 105 cm and its mainly for taking pictures of the flowing fluids. Due to the round shape of pipes, it's impossible to take clear and quality pictures through them alone, With this in mind an optical box was designed and built to be put around the test section pipe in order to take good quality pictures of the flow regimes. The optical box was designed to be movable which is very unusual optical box in the lab facility and it's the first of its kind.

Figure 3.11. Test section pipe.

A four-sided metal frames which are connected by the help of eight threaded steel rods and 16 nuts had to be designed to make the box seal around the test section pipe.

Two nipples with conic threads were introduced one at the base and one at the top surface of the box for filling and draining purposes. (Appendix C P28 - P35, Appendix D F1 - F2)

3.1.10. Temperature sensor holder:

Even though that the effects of temperature change to water density and viscosity is not relevant in the loop at this point, there was a real need to observe how much heat the pump is bringing to the system, especially after facing some problems with pump, we decided to design and build a small dead-end cylinder with conic threads at the top crowned by a hexagon shape which makes it easier to grip and rotate it. this cylinder can be sunk into the loop and have a direct connection with the fluids from the outside, while a temperature sensor recording the temperature change in the inside.

Figure 3.12. Sensor holder.

We made two cylinders with the help of the mechanical staff at Uis. A short cylinder will be used when the pipes are full of water while the long one will be used when air is injected if we still want the box to touch the liquid.

An adapter between the brass box and the acrylic pipes was needed, a plastic adapter was designed, built and threaded with a special conic NPT thread.

(Appendix C P36 - P40, Appendix D F3 - F4)

3.1.11. Separators:

Even though it was two separators which were planned in the original design, we have decided to design and build only one. That was due to the complexity of a well-functioning separator. we wanted to start very simple and then add more components along the way for testing purposes, to solve separation problems and/or for optimization reasons.

The separator had to be designed and built. Two lids and a plastic transparent cylinder were provided by school. The cylinder has an outer diameter of 50 cm and inner diameter of 48 cm.

Eight threaded steel rods where used to connect between the two lids with the help of nuts from both sides, when the nuts were tightening up the two lids were closing on the separator from both ends resulting a sealed separator.

the two lids had to be drilled around the circumference eight times to allow the rods to pass through them. In order to be sure that the rods wont rotates with the nuts, two rods were used to connect each hole from one led to its equivalent parallel hole on the other lid. a smart connection between each two rods had to be introduced with the help of two nuts around it. This connection prohibits any clockwise rotation of the rods and ensure that the sealing process will be performed smoothly.

one of the lids had to be designed to have two holes, one as an inlet for the fluids that are coming from the loop and the other one as an outlet to the tanks.

During the design period of the inlet and the outlet, it became very clear from the beginning that we needed a mechanism which allow us to seal around the two holes without the usage of any screws and nuts, due to possible rust problems, extra turbulence around the inlets and the outlets along with appearance reasons.

Two identical pieces were designed and built using a combination of two acrylic pipes, two PVC joints, two PVC nuts and two rubber gaskets.

The inlet and the outlet were connected to the loop and the tank respectively via semi-transparent plastic hoses with the help of hose clamps.

After testing the separator and running some experiments an urgency to know the separator pressure and its effect on the whole system rose very quickly, two other holes had to be introduced one to have a valve on it to close and open the separator to the atmospheric pressure and the other hole was to be connected to a pressure sensor to monitor the pressure of the separator.

A valve was added to the outlet of the separator to control the liquid level in it.

A hose extension was added to the separator outlet valve and was sunk into the water tank later on during the experiment phase to prevent bubbles from traveling up the outlet and into the separator when a differential pressure existed. (Appendix C P41 - P47, Appendix D F5 – F7)

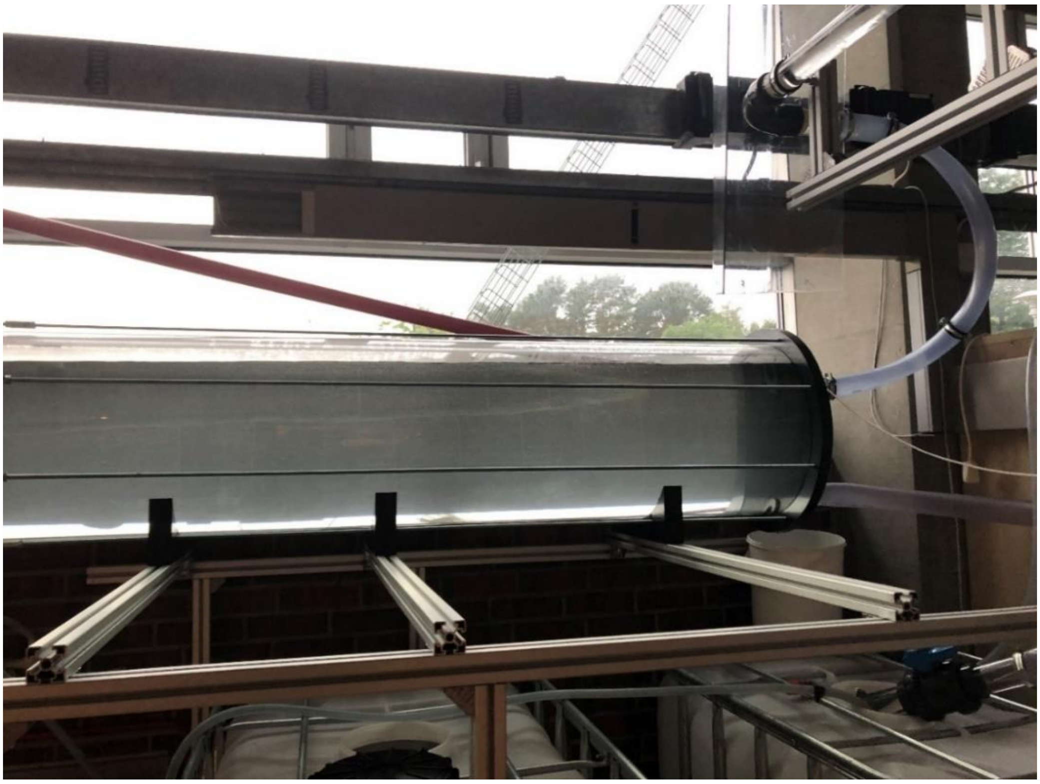

Figure 3.13. Separator, final stage.

3.1.12. Separator table:

A six-legged table that will carry the two separators was designed and built with aluminum profiles.

These aluminum profiles have square shapes with 4.5 cm side length. on each side of the square there is a one-centimeter width path in the middle followed by a two centimeters width path underneath it. These paths together have a depth of 1.45 cm and are used for fixing the table parts together with the help of screws, nuts and special subs.

Three legs were designed to stand in one line representing the frontage of the table while the other three legs stood by another line which is parallel to the first line representing the backend of the table. Two Horizontal aluminum profiles were used to connect between each three legs while three profiles were used connect each leg from the frontage with its equivalent parallel leg on the backend, these three profiles were called the arms of the table.

All the six legs had to be threaded from the inside at their ends so they can be equipped with a special connection that makes it easier for them to stand on the ground. these connections also allowed us to control the elevation of each leg, consequently the elevation of the separator and the degree of inclination if needed. these connections were called the feet of the separator's table.

(Appendix C P48 - P53)

3.1.13. Separator support (cushions)

During the design of the separator and the separator's table we were wondering about the shape of the body that must stand in between that allow a strong grip to both table and the separator.

Three plastic cuboids with a concave top surface were ordered, their concavity perfectly matches the convexity of the separator's outside diameter. As the separator rested on these three cuboids, we started to call them the cushions of the separator.

evidently the separator's steel rods had to pass through the cushion's bodies, therefore two paths have been made in each cushion so the rods will move through them smoothly.

three holes on the base of each cushion were drilled and threaded and three screws were slightly modified to go through these holes and to slide into the arms of the separator's table making these cushions a reliable part of the body system.

(Appendix C P54 - P56 Appendix D F8)

Figure 3.14. one of the cushions during building phase

3.2 Subsequent jobs

Alongside rig construction there were various jobs that had to be performed during this work

3.2.1. Based on Safety observations

During the finishing phase of loop building and before the beginning of experiments an urgent need for a written start protocol “starting procedures” was obvious. In another word a simple guide on what to do before running the pump was needed to be written.

A simple guide including a figure of the loop and a few written steps was printed and hanged beside the on/off switch.

Following up on this but later in time, during the experiments phase, the control valves in the water line had to be open and closed many times which raised a safety concern.

What if one of the values left closed by the end of the experiment and the person who will perform the next one will simply forget to follow the starting safety protocol.

Our pumps are positive displacement pumps which can build up an enormous pressure in case of a closed valve.

From two safety barriers prospective we can say that the back line which is already in the system is our first barrier and the valves that are before the back line is open all the time regardless of the type of the experiments that is being run. this is due to the duties of these valves. These valves are mainly to stop the flow of the liquid in case of the need to change the pump or the tank and they were not meant to be used during runs.

on the other hand, the actual valve of the back line can be involved in some experiments, which will make our second barrier in this case a primary one, enough being said a secondary barrier is a must.

To solve this issue a weak point far away from electricity sockets and sensitive instruments was created in the system where in case of a sudden huge increase of pressure, this point will fail not any other unexpected element in the loop.

On a different safety issue, during working on one of the early risk assessments reports for this project, we have noticed that a high voltage circuit is positioned very close to the loop outlet and any failure in the outlet hose can be catastrophic.

Figure 3.15. Start protocol.

After discussion we have decided to redesign the loop outlet and replace the hose with a 90-degree PVC fitting and the risk of the hazard have been reduced to a very low stage.

In this regard but later in time before introducing pressured air into the system, a plastic shield that covers the high voltage circuit were designed, built and introduced to the rig.

(Appendix C P57 - P59)

Figure 3.16. The weak point with fairly loose hose rings.

3.2.2. Instrumentation setup

The measurement's instruments had to be chosen and mounted on the rig body.

3.2.2.1. PASCO 850 universal interface and its sensors.

This was our main instrument for measurements of pressure in loop, differential pressure along the mixing pipe, temperature in the loop and pressure in the separator.

The instrument included the 850 Universal Interface where the sensors can be mounted directly or indirectly through cables.

The instrument offered a variety of sensors for different measurements. two sensors were chosen.

1. Differential dual pressure sensor was used to measure the pressure in two different spots along the mixing pipe and to measure the differential pressure between them. This sensor has two inlets for pressure measurements. These labeled with 1 and 2 on the sensor's cover.
2. Absolute pressure temperature sensor was used to measure the temperature in the loop and the pressure in the separator. This sensor has one inlet for pressure measurement and one inlet for temperature measurement.

While the interface was mounted on the desktop table, the sensors had to be mounted on the loop body and connected to the interface via cables. tapes were mainly used for fixing purposes.

VWR silicone tubing with inner diameter of 3mm and outer diameter of 5 mm were used to connect between the nipples and the PASCO pressure sensors.

A small wired temperature sensor was used to connect between the PASCO temperature sensor and the place of interest.

Figure 3.17. PASCO 850 universal interface

The sensors had to be calibrated for both temperature and pressure. This was made to make sure that the sensors are working flawlessly.

(Appendix C P60 - P65)

3.2.2.2. Desktop computer

A desktop computer was needed to record and analyze the instruments signals, a desktop was provided by the university. A table for mounting the desktop was already in the lab.

PASCO Capstone software was needed to be installed on the Desktop in order to use the PASCO interface in our project. The PASCO interface was connected to the computer via USB cable.

(Appendix C P66)

3.2.2.3. Rosemount pressure transmitters

Four Rosemount 3051 were introduced to the loop. Due to their heavy weight, these devices needed a separate strong plate to be mounted on, this plate had to be electrically isolated. An aluminum stick has been chosen for that purpose, with small modification on the stick, the transmitters were fixed firmly to it, a rubber plate were used to isolate the stick and the transmitters from the rig body.

These devices weren't used in our project, but their installation was part of making the loop ready for future projects.

(Appendix C P67 - P69)

Figure 3.18. Rosemount transmitters.

Figure 3.19. Validyne transmitter and transducer.

3.2.2.4. P 55 Validyne pressure transmitter and transducer

These devises were originally mounted on an aluminum plate. the plate was fixed to the rig body with the help of heavy-duty zip ties.

Like the Rosemount pressure transmitters these devices weren't used in our project, but their installation was part of making the loop ready for future projects.

(Appendix C P70)

3.2.2.5. Atmospheric pressure and room temperature measurements

The lab was already equipped with a Rosemount 2088 Gage and absolute Pressure Transmitter and the 3144P Rosemount Temperature Transmitter, they showed a direct measurement of atmospheric pressure in bar unit and temperature in Celsius in case atmospheric pressure and room temperature values were needed (Appendix C P71,P72)

3.2.3. Air system:

Later during the project, air had to be pumped into the system. The multiphase lab at the university of Stavanger already had a system for compressed air.

The multiphase lab also had a compressed air dryer, a Swaglok pressure regulator, a crystal engineering xp2i digital pressure gauge indicator, and Alicat Scientific MCR gas mass flow controller. While the pressure regulator allowed us to open and close the air flowing, the flow controller provided us the flowrate value of the passing air on its screen. 3-way valves were used to make sure no water will reach the Air flowmeter incase no air was being injected.

All the previous instruments were ready to be used.

A transparent plastic hose with 2mm inner diameter were used to connect the outlet of the flowmeter to the air inlet of the loop. (Appendix C P73 - ,P76)

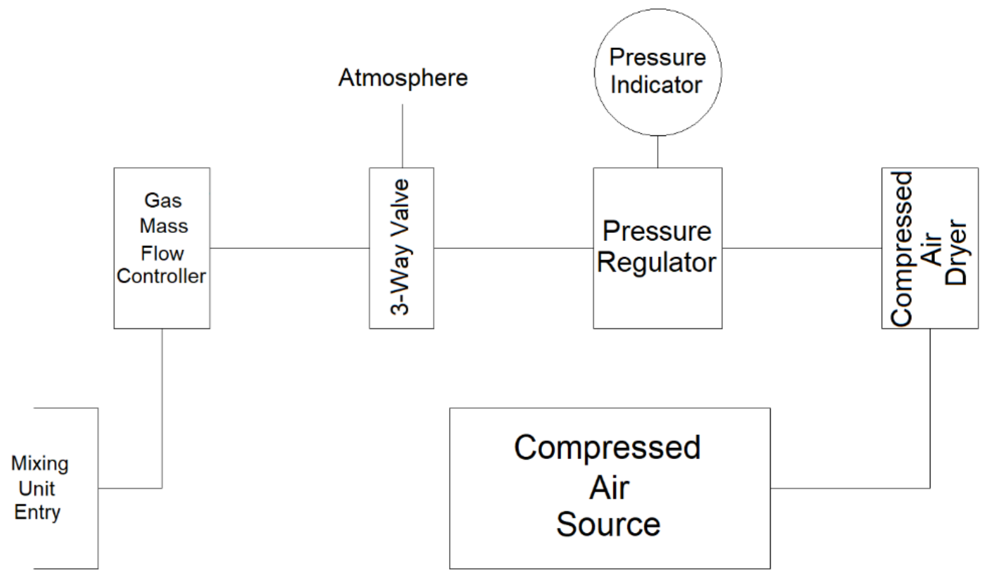

Figure 3.20. Air System

3.3 Calibration Processes.

All of the instruments had to go through calibration processes in order for us to gain full understanding of the instruments and to make sure that these instruments work accordingly.

3.3.1. Flow meter:

It goes without saying that the aim of this work was to study air-water flow in pipes therefore the main concern here was electromagnetic flowmeter.

In order to make sure that the sensors for electromagnetic flow meter works properly, a simple test was made.

We fill the tank with 100 liters of water, we pumped it through into the system, obviously through the electromagnetic flowmeter and observed the volume reading. At the end of the run when all the 100 Liters were pumped into the system, we altered the flow by closing valve number six. the electromagnetic flow meter showed 0.10 m3 volume reading which is exactly a hundred liters. Figure 3.21.

On a different note the pump frequency regulators allowed us to run the pump from 0 to 50 Hz per second, and by calibrating it through the flowmeter, we were able to distinguish our possible flowrates and link them to the pump frequencies.

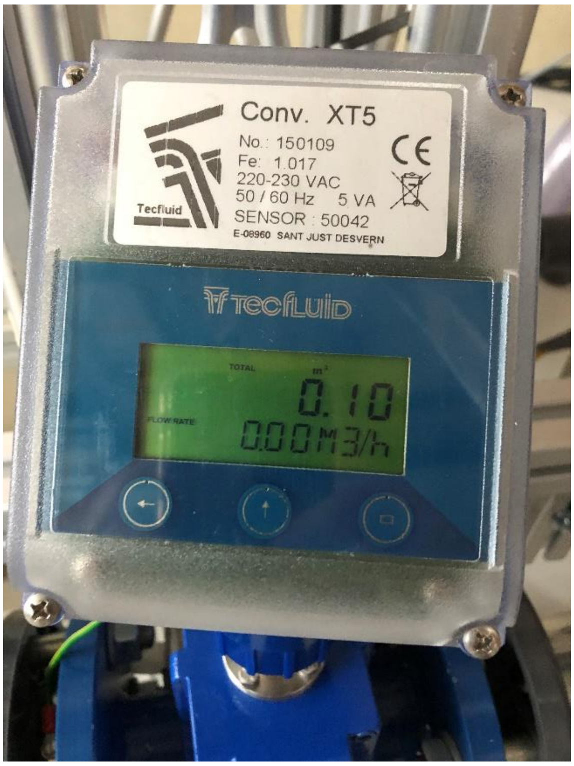

Figure 3.21. Flowmeter after test.

we sat the pump pump frequency regulators to 50 Hz, and we observed the flowmeter, a record for all the readings were documented. Every five minutes a 5Hz were taken down from the pump frequency regulators and the readings were recorded again.

As a result, a very handful data was recorded, (see Appendix A) and plotted on (figure 3.22). using the least square regression method, we were able to reach equation (3.1) that linked our pump frequency regulator to its equal flowrate.

$$Q\,[m3/h] = 0.1436*Freq + 0.0203 \qquad (3.1)$$

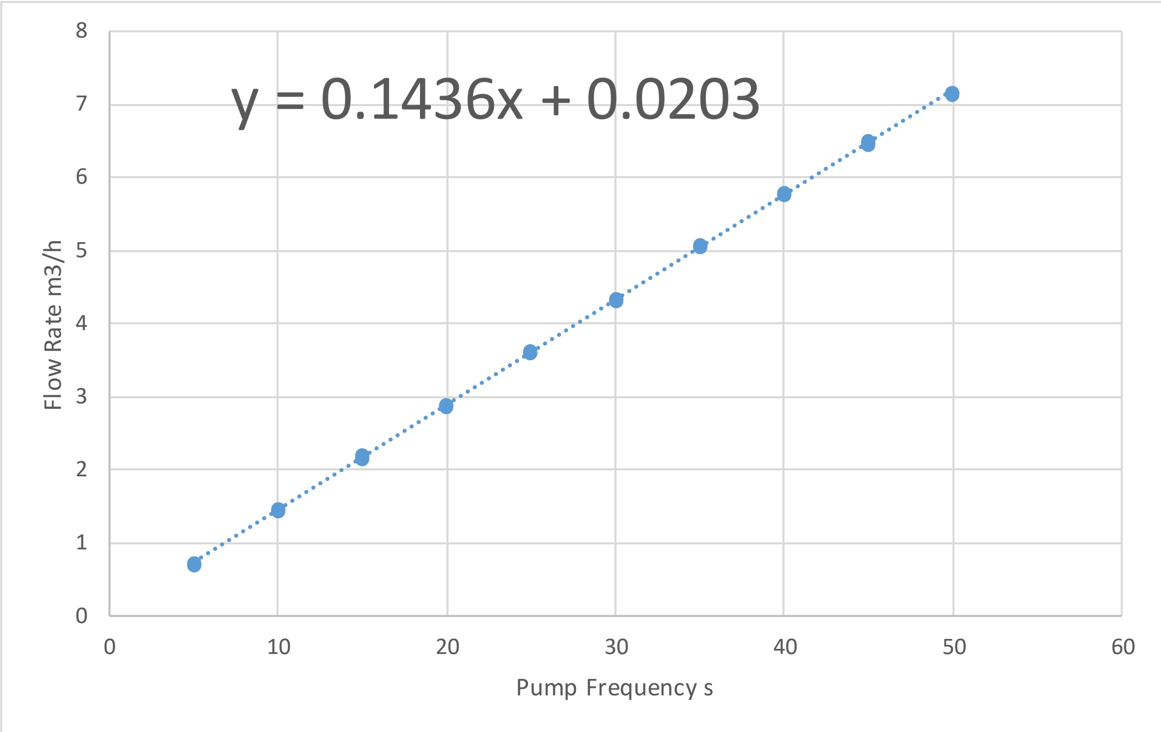

Figure 3.22 Flow Rate – Pump Frequency

3.3.2. PASCO Sensors Calibration

3.3.2.1. Pressure sensors.

We needed to test the sensors with different known pressures to confirm their accuracy. A 2.75-meter-long transparent hose was set vertically, opened to the atmosphere and filled with water. the first pressure sensor was connected to its end. A pressure measurement was recorded and saved. we decreased the water level to 2.50 m and another measurement were taken and recorded. we kept decreasing the water level inside of the hose by 0.25 meter each measurement until we reached 0 meters which is the atmospheric pressure.

This process was repeated with all the pressure sensors. The theoretical values of pressure at each water height were calculated using equation (2.38.) and then added to the atmospheric pressure.

(see Appendix B)

Figure 3.23. was made from the data.

We can note that the tiny difference between the pressures was due to the accuracy of measuring the water level in the hose in each run.

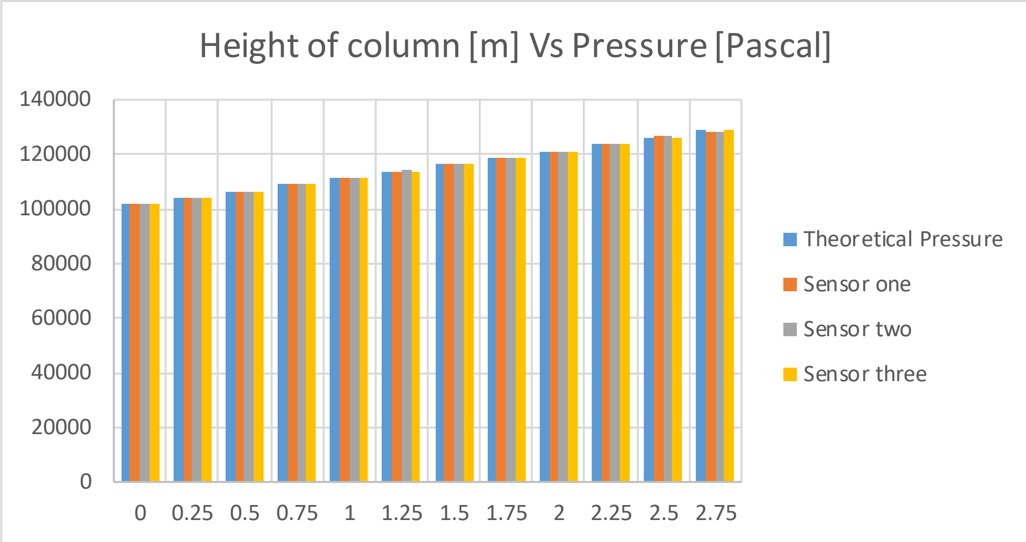

Figure 3.23 Pasco Pressure sensors calibration

3.3.2.2. Temperature sensor.

To confirm the accuracy of the temperature sensor, FLUKE 9102S Dry-Wells device were used, this is a temperature calibration device. It has the ability to generate stable known temperature degrees.

The sensor was connected to the fluke device when the fluke device reading was 15 c. a record of measurements with time was continuously running. we raised the temperature of the fluke device to 35 c and then down to 20 c, up to 30 c, 40 c and finally down to 25 c.

The measurement record showed a correct value from the temperature sensor with the temperature change.

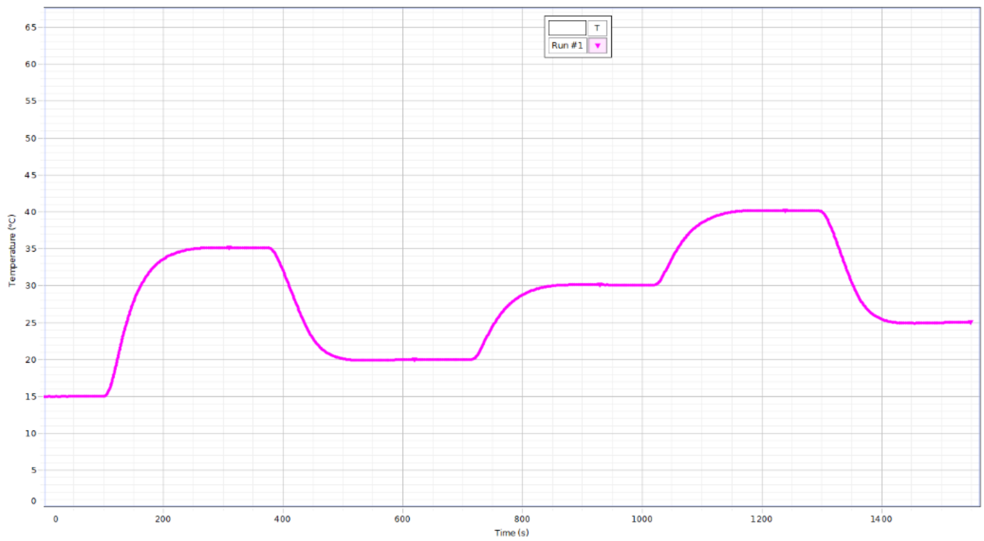

Figure 3.24 PASCO temperature sensor calibration.

4.Experiments

This chapter include a detailed description of the experiments that have been done with the loop.

4.1. One-phase experiments (Water)

Using the PASCO interface and its sensors, we were able to monitor the pressure alongside the mixing pipe and the separator using the nipples that were built for this purpose.

Since the pressure differences between the nipples alongside the mixing pipe are expected to be small, we were interested in measuring the differential pressure along the longest available distance. on the other hand, we tried to avoid using the first two nipples due to their close position to the mixing unit where extra turbulence occurs. Therefore, we used the third nipple to be our first pressure point while the fifth nipple was used as a second pressure measurement point.

A differential dual pressure PASCO sensor was fixed on the rig body exactly between the two nipples with the help of a tape and then connected to the interface USB via cables. Two silicone tubes with same length connected the nipples with the pressure sensors. Plastic adapters were used to connect the silicone tubes with the sensor's inlets.

The silicone tubes had to be filled of water almost up to the sensor inlet, while a tiny air gap was left to be sure that water won't reach the sensor's inner circuit. the position of the sensor had to be higher than the mixed pipe, for the same reason.

An absolute pressure temperature sensor was also fixed to the rig body close to the separator and the temperature sensor box.

While an air-filled silicon tube connected the separator to the pressure inlet of the sensor, a USB cable connected the sensor to the PASCO interface.

A small temperature sensor was put in the temperature box and connected to the PASCO sensor via a thin electric wire.

4.1.1. PASCO Capstone software configuration.

Certain procedures were done using the Pasco Capstone software. We divided these procedures into two groups. Procedures that were done at the beginning of every day and Procedures that were done at the beginning of every run.

4.1.1.1. Beginning of everyday procedures

Through the Capstone software a small calibration process for the pressure sensors were done at the beginning of every day.

We make sure that the pressure sensors are disconnected from the silicon tubes and open to the atmosphere. Afterwards we open the Capstone software, go directly to the calibration option, and choose pressure. We click next and choose the differential pressure sensor that we wanted to calibrate and then perform a one standard calibration were the real value of the atmospheric pressure is taken from the lab barometer.

Now we are back to the main display menu. we drag one table into our page. The table usually contain two columns, at the top of the first column an option for inserting more columns is available. after adding three more columns, we select the desired measurements for each of the five columns in the table. The desired units for each column are automatically chosen but can be changed simply by clicking on the displayed unit.

First column will be for time, the second column will be for absolute pressure 1, the third column will be for absolute pressure 2, the fourth column will be for the differential pressure between absolute pressure 1 and absolute pressure 2 and the fifth column will be for the absolute pressure 3.

We click record wait for one second and stop recording. We choose a time step and compare the values. While the absolute pressures values must be equal, the differential pressure value must be zero.

Later, we go through the safety start protocol and we run the loop on 50 Hz, wait until it stabilized then connect the silicon tubes to the PASCO sensors.

The third nipple on our mixed pipe must be connected to the first inlet of the PASCO differential pressure sensor while the fifth nipple must be connected to the second inlet. The separator nipple must be connected to the absolute pressure temperature sensor.

Next, we stop the loop and wait until it stabilized then measure the differential pressure for one more time. The differential pressure must equal zero again.

This was all done to ensure quality of measurements during the day.

4.1.1.2. Beginning of every run procedure

Similar to the previous step we drag tables according to our interest and we select the desired measurements and the desired units for each column in the table. We also drag a graph this time and select its axes and units in a similar way so we can see a live representation of the measured data.

While an option of one measurement at a time is available on the X axes, the option of adding many Y axes is always available by clicking on the black arrow at the top of the graph.

4.1.2. Differential pressure between two nipples, experiment in steps:

After making sure that the daily procedures have been done in the morning. we do the following.

1. Make sure all the valves are set according to the start protocol.
2. Make sure that the separator valve is open to the atmosphere.
3. Turn on the electricity.
4. Choosing of the initial flowrate by using equation (3.1).

We always started with 50 Hz pump frequency.

5. Push the run button and wait until the loop stabilized.
6. Open capstone and apply the procedures for the beginning of every run.
7. Choose the frequency recording rate. We used 20 Hz per second
8. Click on record and observe the measurements at least for one minute.
9. Go down with the flow rate according to equation (3.1)
   We decrease the pump frequency with 5Hz at every step.
10. Observe the measurements at least for one minute not including transition time.
11. Repeating steps 8 and 9 until we record the 25Hz pump frequency measurement.
12. Stop the recording.
13. Save the recoded data in a PASCO file.
14. Choose between step 15 and step 16.
15. Choose an initial flowrate and repeat the steps from six to twelve or jump to the 16th step.
16. Go down to zero pump frequency, stop the pump and turn off the electricity.
17. Copy the data from the PASCO file to an excel sheet and calculate the average differential pressure for each flow rate.

4.2. Two-phase experiments (Air-Water)

After introducing air to the system, we wanted to observe and document the flow regimes that we can achieve through the loop.

We simply connected the air system to the mixed unit entry and opened the pressure regulator valve to the max. The 3-way valve had to be turned slowly towards the flow controller direction, by doing so we have established an air flow to the loop.

The flowrate values of the flowing air which were shown on the flow controller screen were documented.

Afterwards we observed the flow regimes in the loop with different water flow rates and different air flowrates.

4.3. Other experiments

There have been some special runs that were performed for specific experimental reasons like monitoring the oscillation in the loop and in the separator or runs for identifying noise sources and many other reasons.

The steps for these experiments are quite similar to the 4.1.2 and will be explained through the discussion part if needed and not here.

5.Discussions and Observations

This chapter will include a discussion about the experiments and the observations we have made during this project.

5.1. One-phase experiments (Water).

In order to gain more understanding of the loop behavior, many experiments had to be run and analyzed. afterwards some elements in the loop had to be redesigned and more experiments were made. Interesting observations were noted along the way in order to find explanations to their existence.

5.1.1 Differential pressure between two nipples.

After stable system was established in the loop, many runs have been made. Then, eight runs were chosen to be studied. Their data were compared together with the theoretical measurements using two different friction factors. (Table 5.1)

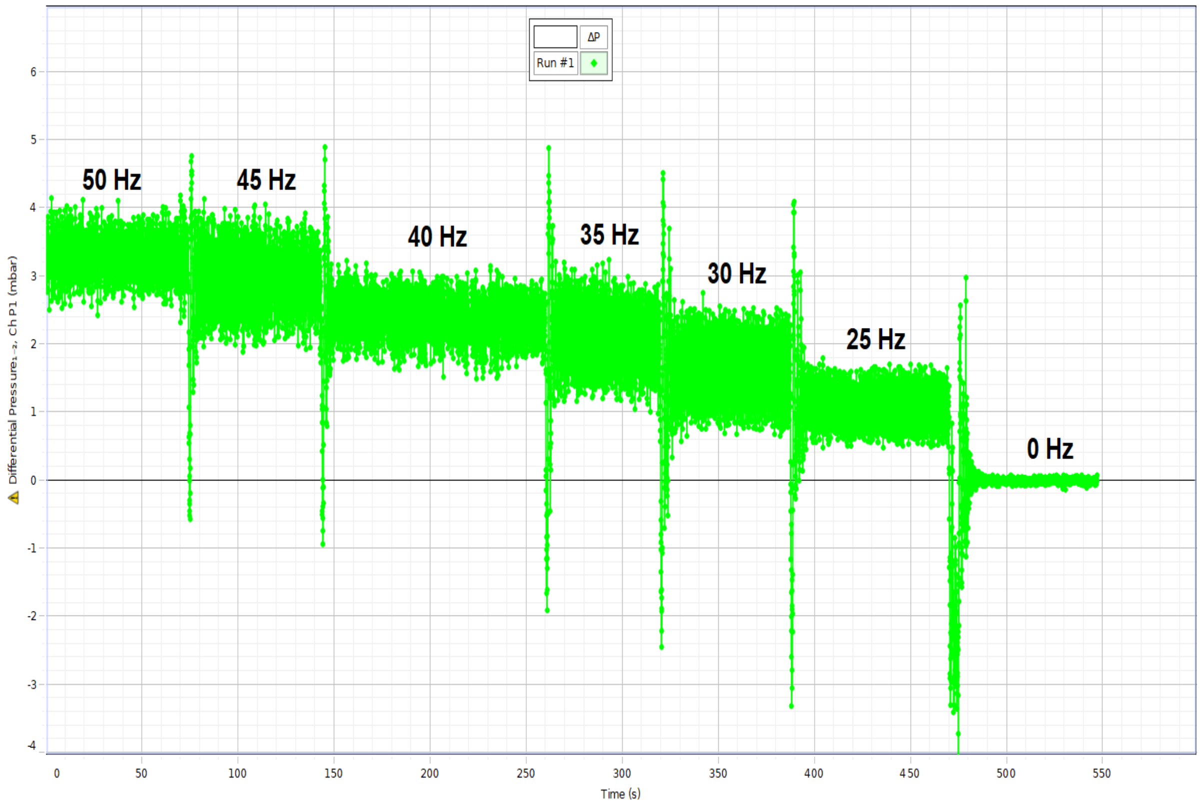

Figure 5.1 Differential pressure measurements, random loop.

An average value at each pump frequency were calculated and noted in table 5.1

Zero frequency results weren't taken into consideration in measurements, but they were observed to make sure that the sensors are well calibrated.

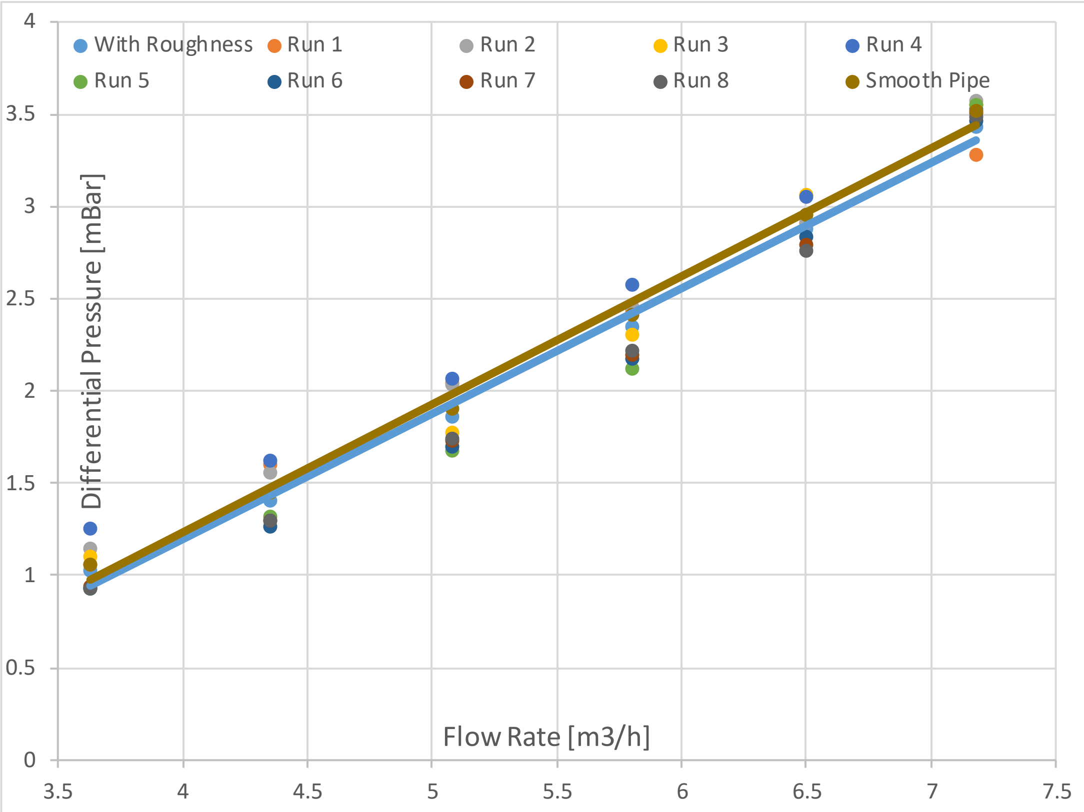

Figure 5.2. Data from all the runs compared to the theoretical measurements.

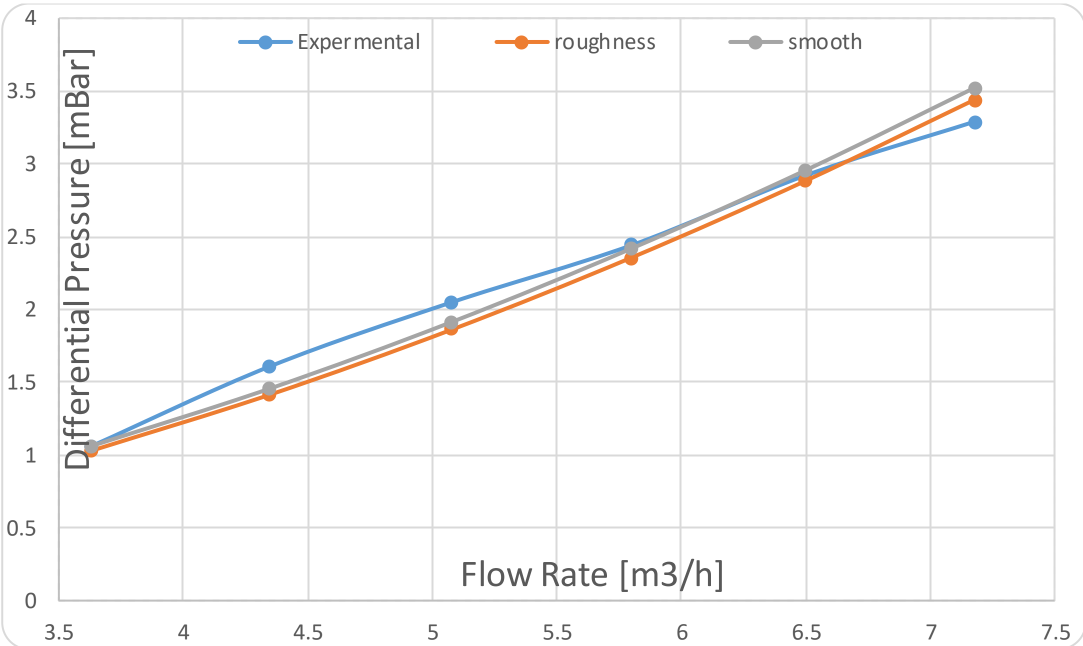

Figure 5.3 least square fit for all the runs compared with the theoretical measurements.

Pump frequency [Hz]	flow rate [m3/h]	Velocity [m/s]	Theoretical differential pressure [mBar] based on Drew,Koo and McAdams. [Smooth Pipe] Friction factor	Theoretical differential pressure [mBar] based on Haaland Friction factor. [Roughness included]	Expermental differential pressure [mBar] (Avarage)							
					Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8
50	7.18	0.94	3.52	3.44	3.29	3.58	3.56	3.53	3.56	3.47	3.51	3.49
45	6.5	0.85	2.95	2.88	2.92	2.92	3.07	3.06	2.96	2.84	2.8	2.77
40	5.8	0.76	2.41	2.35	2.44	2.46	2.31	2.58	2.13	2.18	2.2	2.22
35	5.08	0.66	1.91	1.86	2.05	2.04	1.78	2.07	1.68	1.7	1.74	1.75
30	4.35	0.57	1.45	1.41	1.61	1.56	1.45	1.63	1.32	1.27	1.3	1.3
25	3.63	0.47	1.06	1.02	1.06	1.15	1.11	1.26	0.93	0.93	0.95	0.94

Table 5.1. Differential pressure results and comparison.

The data from table 1.5 were plotted in figure 5.2 and 5.3 where we compared between the experimental and the theoretical data.

Since our pipes are made from acrylic which has a lot of similarities to glass. It is important to mention that we have used the glass roughness value during the calculation of the Haaland's friction factor. This made our theoretical measurements for the differential pressure in a smooth pipe bigger than the theoretical measurements for the differential pressure of a pipe with roughness.

5.2. Two-phase experiments-observations (Air-Water).

5.2.1 Separator Oscillations.

Our interest in the possible effects of the separator on the system and the vice versa was quite early. There were some oscillations that were happening in the separator and we wanted to neutralize these effects in order to gain more accurate results.

In order to study the separator pressure and the separator oscillations, a valve was added to the separator. by opening this valve to the atmosphere, the separator pressure become simply constant and equals the atmospheric pressure, a nipple was also added to the separator so it can be connected to a pressure sensor to monitor the pressure inside of the separator. (Check 3.1.11)

After observing the separator for many hours, it was obvious that understanding the oscillation starts from understanding water level at each flowrate.

With having no instrument to measure the flow rates of the liquid that is going out of the separator and back into the water tank, we were looking for a method to estimate the flow rate.

In theory having a constant liquid level in the separator is an indication that the flow in equals the flow out.

We built a model based on the Bernoulli equation (2.37). the model predicts the water level in the separator for each flow rate we are pumping in, the model took into consideration the pressure in the separator and the pressure of the outlet, the results were plotted in figure 5.4.

Studying water level was a challenge, a correct measurement from a visual monitoring of the liquid level to compare it with the theoretical data was almost impossible. They were many oscillations, waves and bubbles which made the differences in water height from a flow rate to another very hard to distinguish.

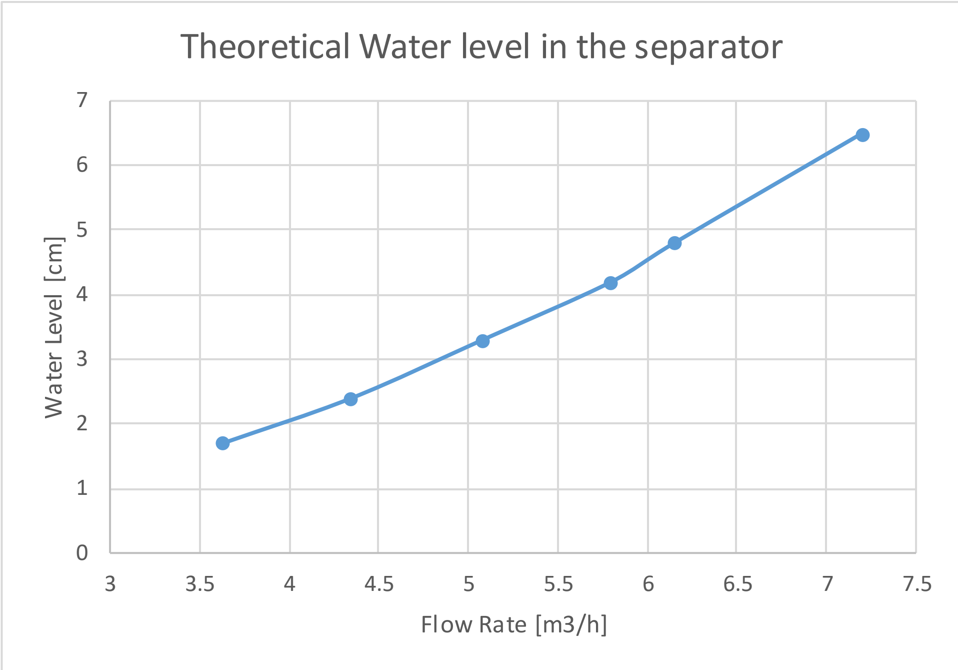

Figure 5.4. Theoretical Water level in the separator, P Sep and P Tank equals P atm.

A main reason for the existence of bubbles was the water that is flowing into the separator from the inlet. The inlet is higher than the water level which created a lot of bubbles due to the crash between the falling water and the surface of the liquid in the separator. Figure 5.5.

Figure 5.5. Bubbles in the separator.

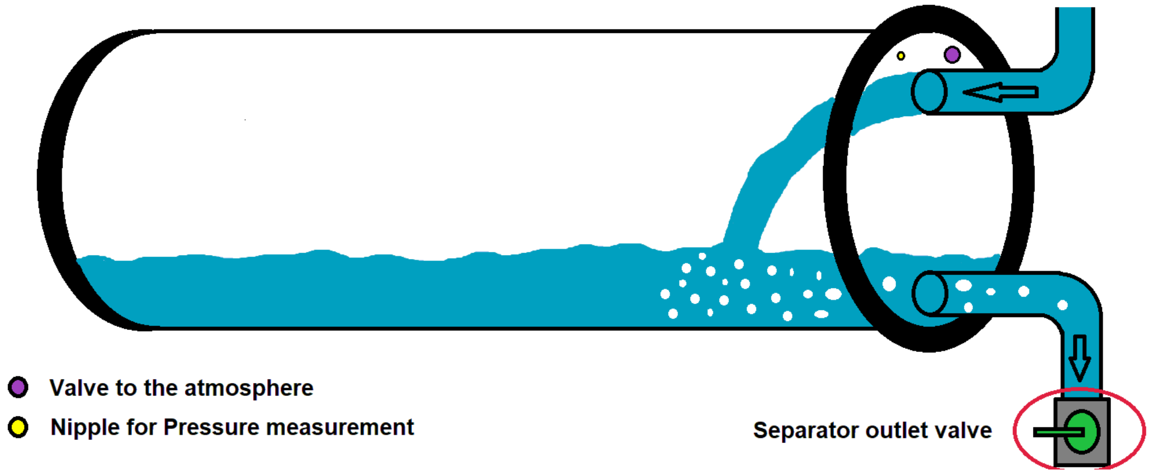

Figure 5.6. separator valves.

In order to raise the liquid level in the separator we made sure that the valve to the atmosphere was open and then we closed the separator outlet valve.

We waited until the liquid level was close to the inlet. Afterwards we closed the valve to the atmosphere and open the separator valve simultaneously. Doing so allowed us to keep the water level constant in the separator.

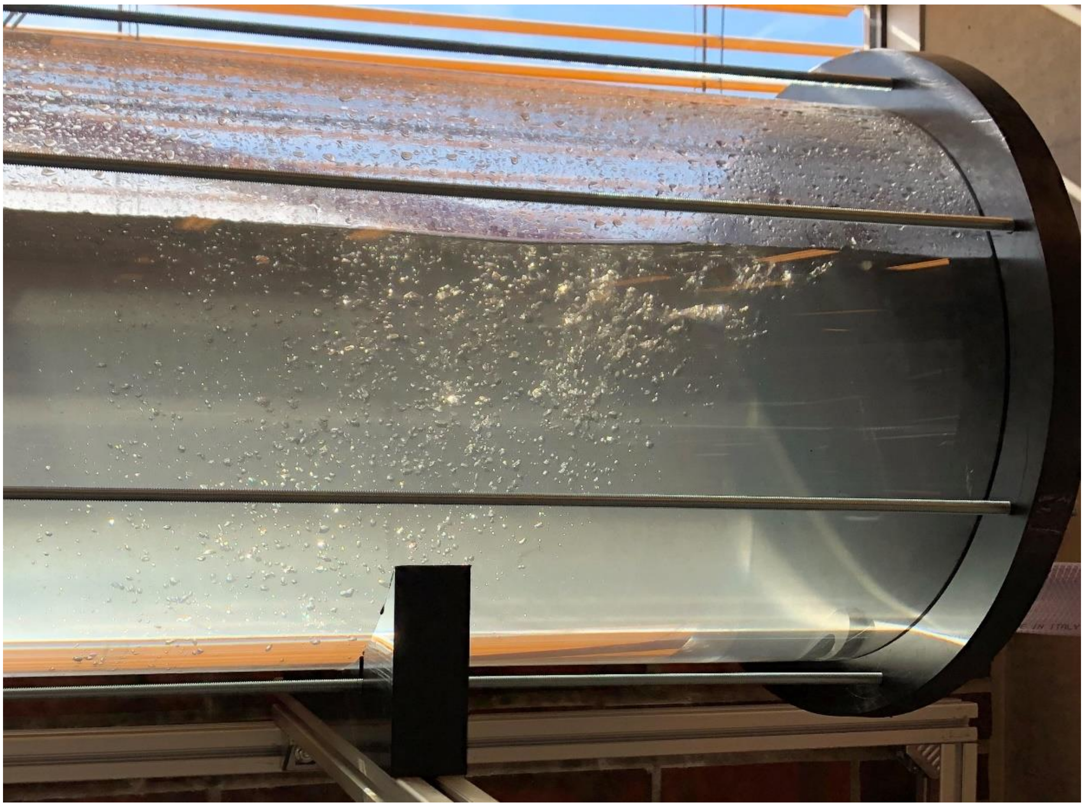

Figure 5.7. Water level close to the inlet.

It is obvious that the amount of bubbles has decreased which led to a decrease in the oscillations in the separator.

We decided to raise the water level more until it covers the entire inlet, figure 5.8.

Figure 5.8. water level higher than the inlet.

As a result, we have achieved zero bubbles in the separator. now let's look at what we did through the PASCO recordings.

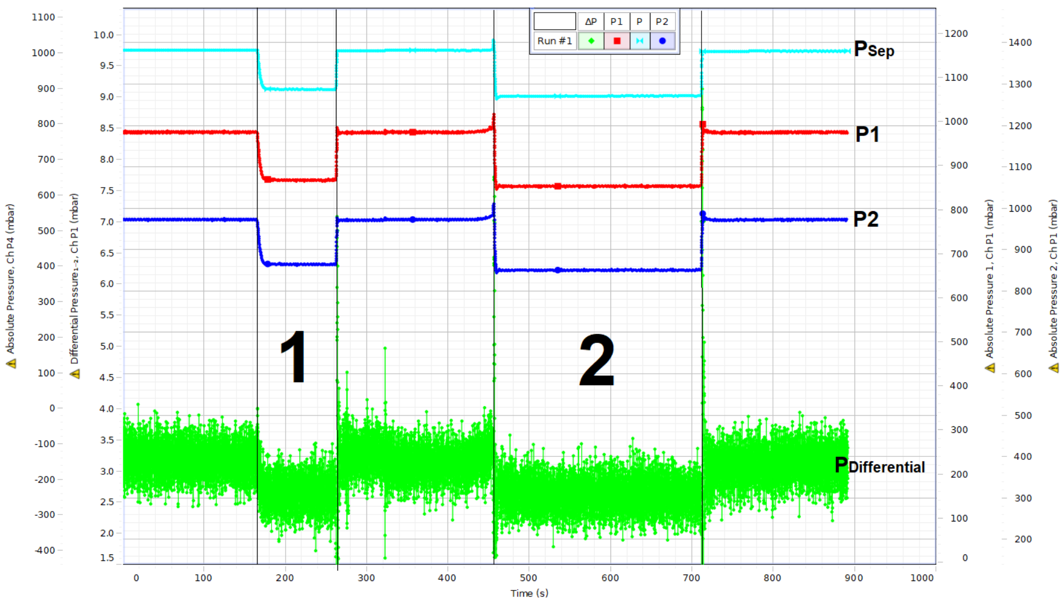

Figure 5.9. Effect of Pressure separator on the system.

The effect that the separator pressure has on the system is quite clear in figure 5.9

While in both time periods 1 & 2, the valve to the atmosphere was closed. In period one the water level was close to the inlet while in period two the inlet was covered with water.

It was noted that during the first period the pressure of the separator was decreasing with time while it was constant during the second period.

To understand this more a longer run has been done with different liquid levels and different flowrates. Figures 5.10. & 5.11.

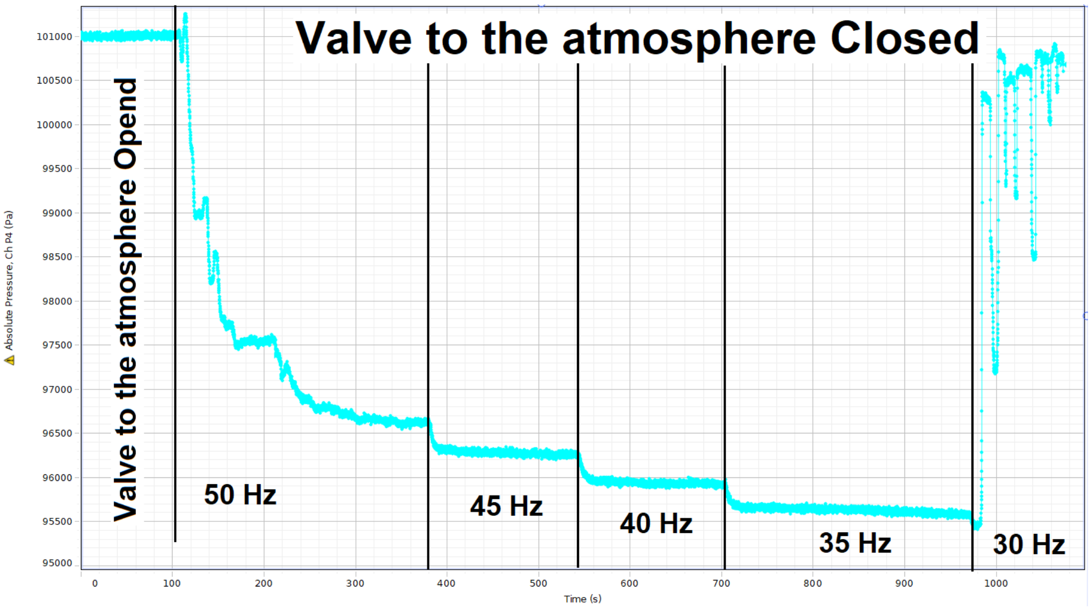

Figure 5.10. Pressure variation with low liquid level in the separator

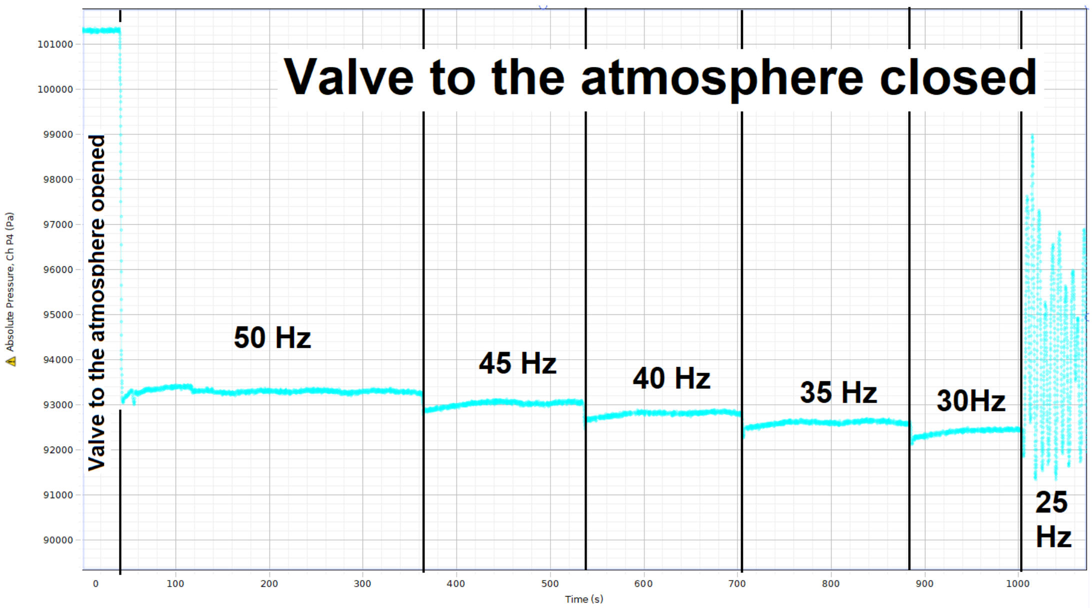

Figure 5.11. Pressure variation in the separator with liquid level covers the inlet.

When the level of water is low in the separator, the water falls from the inlet through the air phase to break the water surface and join the water, during this process the falling water grabs some of the air molecules down into the water phase. While some of the bubbles go back up and rejoin the air phase, others escape the separator through the water outlet. This ongoing process leads to the continuous decrease of pressure since there is no source of air to equalize the volume of the escaped air.

However, it was noted that the amount of bubbles that escapes the separator decrease with the decrease in the separator pressure.

While the decrease in pressure in figure 5.11 reflects the relation between the flowrate and the water level in the separator, the decrease in pressure in figure 5.10 reflects the same relation but in addition to the escaped air effect.

On another note, the ongoing process of decreasing flow rate thus pressure in the separator led eventually to pressure differences between the separator pressure and the atmospheric pressure which is the pressure of the outlet. This difference reached a value that allowed bubbles to travel up the outlet and into the separator, these cases can be seen in figure 5.10 during the 30 Hz period and in figure 5.11. during the 25 Hz period.

The hydrostatic pressure of the liquid was responsible for delaying this event in figure 5.11.

As a solution the outlet hose was extended and sunk into the water tank which made it harder for the bubbles to travel through the hose up to the outlet.

5.2.2. U joint effect on the loop.

After introducing the U joint as it was mentioned earlier in (3.1.6) we started to run so we can measure the differential pressure along the mixed section. Our high hopes were immediately restrained by periodic oscillations inside of the loop caused by the air that was introduced by the U joint.

These oscillations effected the flow rates and the pressure values along the loop.

Figure 5.12. shows a differential pressure reading between two nipples along the mixed section where it is impossible to get a reliable value of the pressure difference.

Figure 5.13. illustrate the water movements that we observed after the U joint was introduced. The water apparently found an easier path to flow through, after a certain height h was established, water goes back to the original flow direction leaving air behind it to fill its place.

The air dragged in the pipe for a certain distance like the third part of the 5.13 figure shows. Along that distance, a stratified flow is created in the pipe. Afterwards a number of slugs is created and then a reverse flow is happening again in the pipe replacing the air with water by pushing the air back into the U joint until the height h is established again in the U joint and so on.

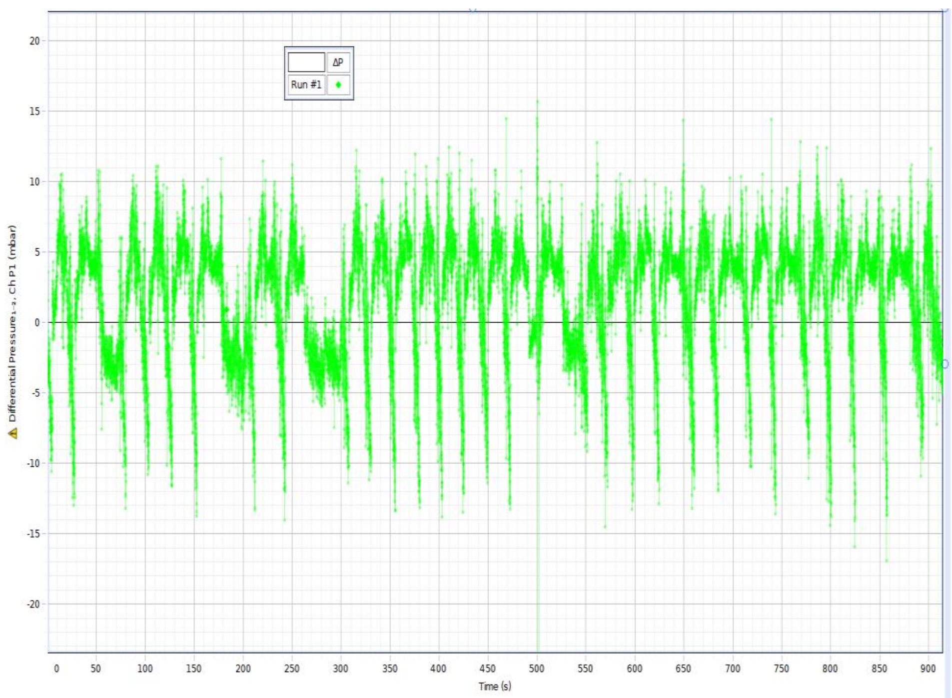

Figure 5.12 U joint effect on Differential pressure readings with time.

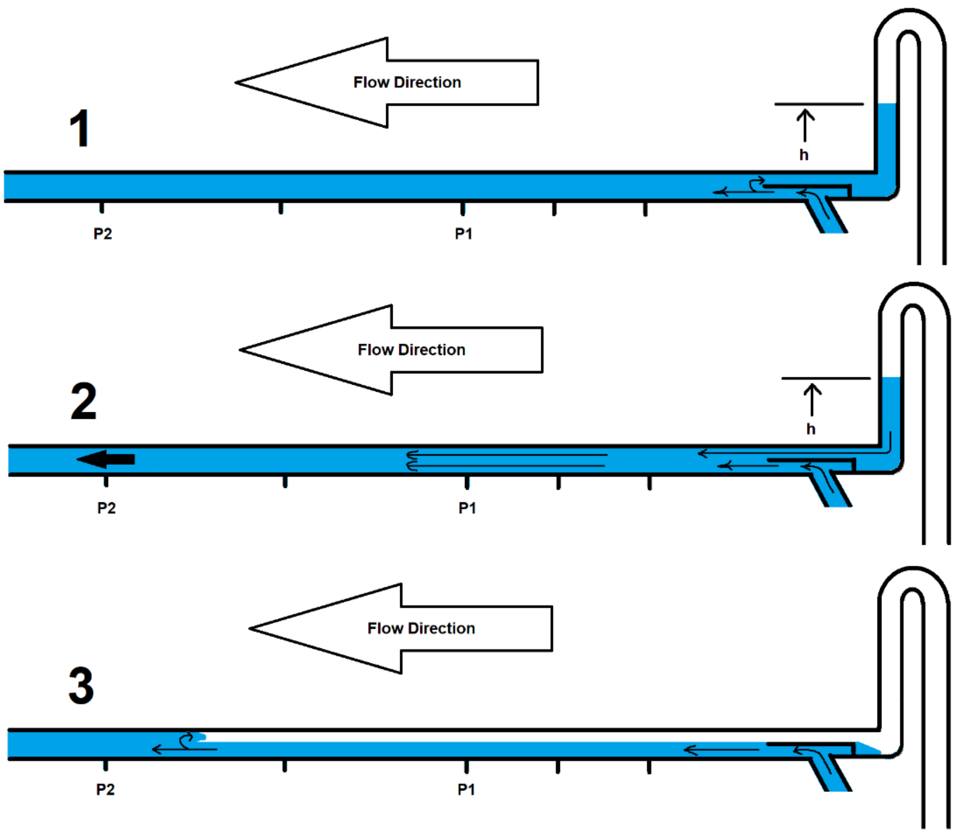

Figure 5.13. Effects of U joint on water flow.

To get an understanding of this case we had to eliminate factors that made our situation more complex.

The separator was opened to the atmospheric pressure while the U joint was replaced with a vertical transparent pipe that is open to the atmosphere as well. Figure 5.14. illustrate the new system with important pressure points to study.

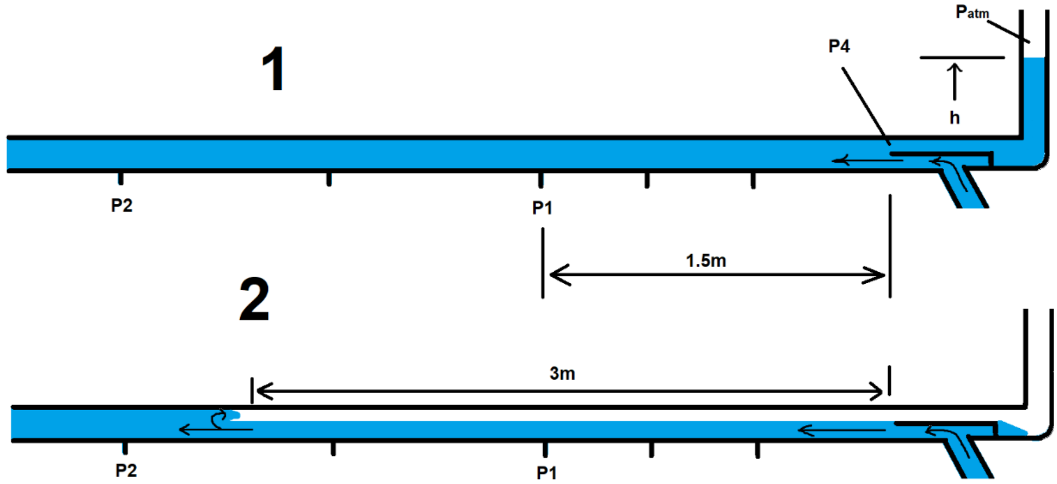

Figure 5.14. loop after modification.

We run the loop again on 50 Hz frequency and focus rather on the absolute pressure values P1 and P2 instead on the differential pressure between them.

To make sure we observe all changes in the system, the water back line valve (Valve number 4 in figure 3.4.) had to be closed. this will prevent any damping action.

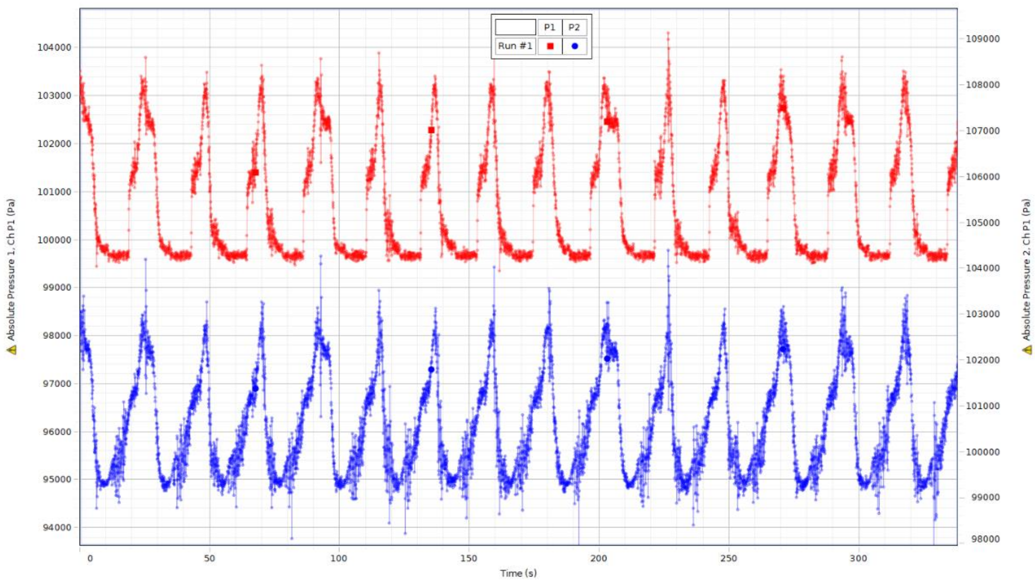

Figure 5.15 Absolute pressures P1 and P2 with the U effect

Figure 5.15 shows that the periodic oscillations happens approximately every 22 seconds. The pressure sensors record the maximum pressure values during the end of the reverse flow when the water height in the vertical pipe is maximum. While they record the minimum pressure values just before the slugs starts to happen.

While the lab barometer reads an atmospheric pressure of 100640 Pascal we started to record. The water height h was at its maximum, i.e. 0.34 m. at this exact moment the water level is constant which means the flow in the upperpart of the mixing unit is zero, P1 reads 103500 Pascal.

Our pump frequency is 50 and according to equation 3.1 the equivalent flow rate will be 7.20 m3/h.

To measure P4 we add the pressure lost due to friction in the 1.5 m to the value of P1. According to equation (2.27) and (2.29), the differential pressure lost is 265 Pascal.

$$P4 = 103500+265= 103765 \text{ Pascal} \qquad 5.1$$

If we ignore the frictional pressure drop in mixing unit, we can also say:

P4 = P atm + P hydrostatic weight of h.

P hydrostatic = 9.81*997*0.34 =3325 Pascal (According to equation 2.38)

$$P4= 100640 + 3325 = 103965 \text{ Pascal} \qquad 5.2$$

Comparing 5.1 and 5.2 values together we can argue that the 200 pascal pressure differences between them is due to the friction that we ignored in the calculation.

So, we can say that 5.1 and 5.2 approximately equals each other’s values.

However, this equilibrium in pressure doesn’t last too long and the oscillations continues.

If we get a closer look to the mixing unit during the pressure equilibrium, Figure 5.8. two points can be defined.

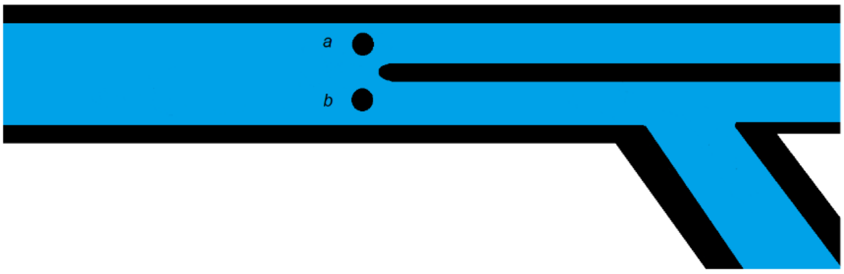

Figure 5.16. mixing unit velocities

Point *a* belongs to the static water layer where the velocity of the liquid is Zero and point *b* belongs to the moving water layer where the velocity of the liquid is the velocity of the flow.

It is most probably due to friction between the two layers, the moving layer drags with it the static one along with the air behind it forming a stratified flow in the pipe for a certain distance.

Along this distance the water level is rising gradually and by the end of it, it hits the upper surface of the pipe forming numbers of slugs with the dragged air and then forming a reverse flow due to pressure difference towards the mix joint and so on.

Before going any further, it is important to clarify the point of the maximum distance which the stratified flow reach. It is happening half a meter before the last pressure nipple where P2 measurements are taken and one and a half meter after the third nipple where P1 measurements are taken. See Figure 5.14

Now, if we scale all of the axes together in figure 5.15 and zoom into the first period where minimum pressure values occur, we will get figure 5.17. where special areas can be identified.

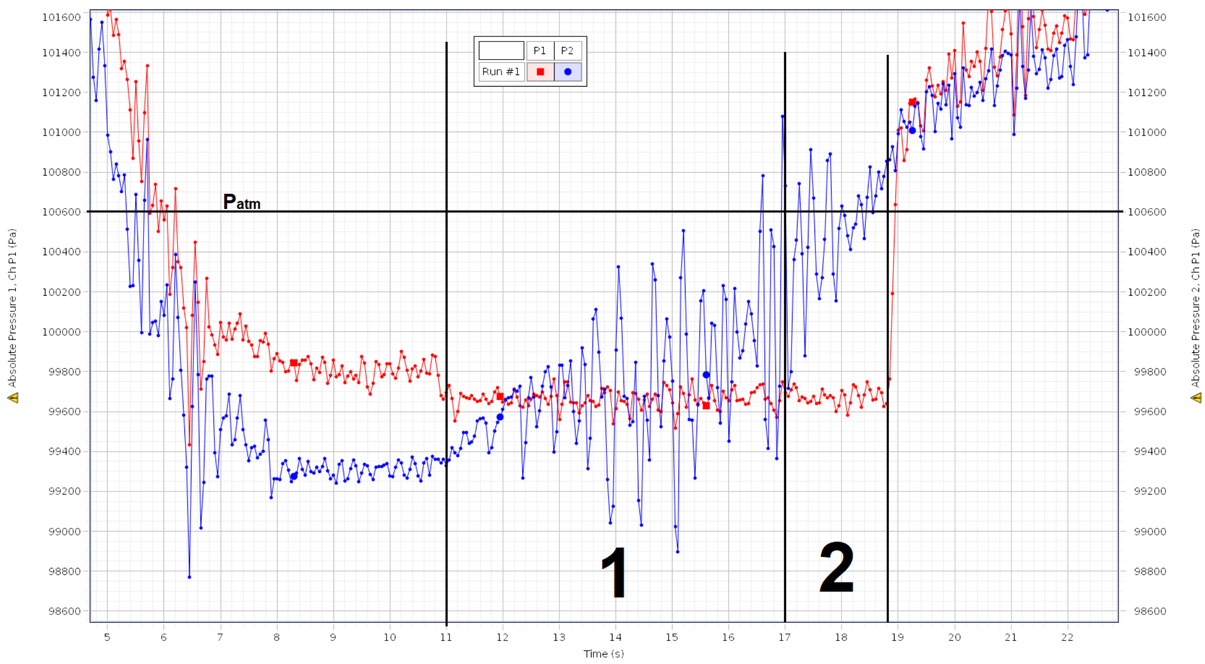

Figure 5.17 Absolute pressures 1 and 2 during slugs and revers flow.

<u>Area number 1:</u>

At the eleventh second the water hits the upper surface of the pipe, small slugs start to appear and gradually getting bigger, the effects of big slugs can be seen clearly on P2 measurements after the twelfth second and up to the eighteenth second.

<u>Area number 2:</u>

At the seventeenth second the reverse flow begins. The P2 finish recording the effects of the last slug on the eighteenth second. On the second 18.8 the reverse flow reaches P1 and its effect is clearly seen on P1 after the second 18.80. We can also clearly see the negative pressure difference at the moment the reverse flow is formed.

It's was interesting to observe the behavior of the loop under the U effect with different flow rates, figure 5.18. shows that.

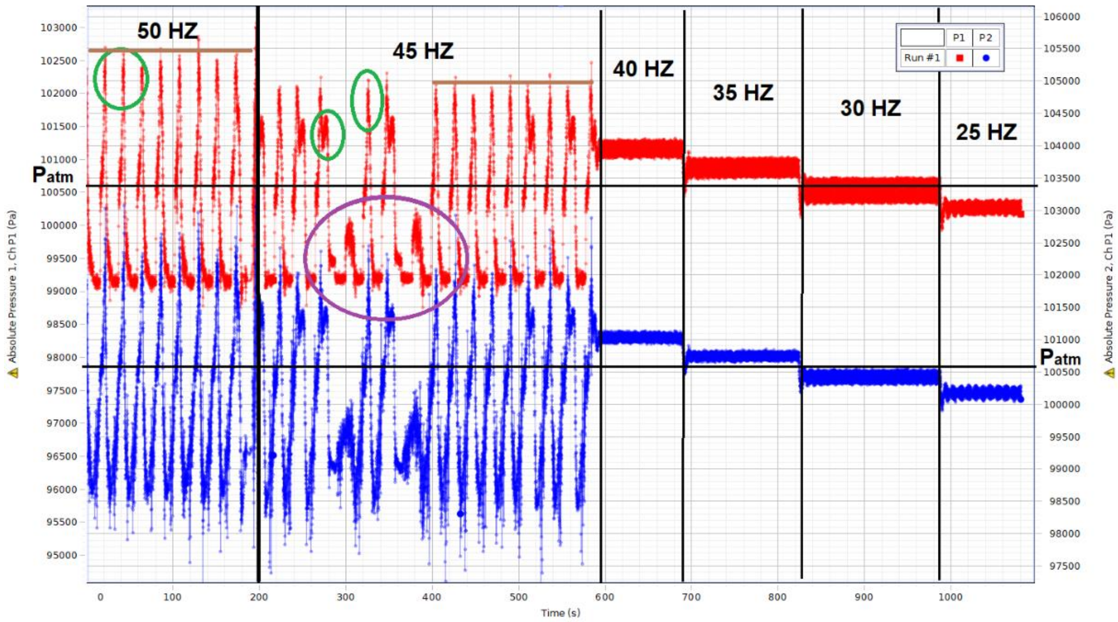

Figure 5.18. Absolute pressures with different flowrates under the U effect

From figure 5.18. we can note that the periodic oscillations happen only on 45 Hz pump frequency and above. we have observed that the liquid level in the vertical pipe at a 45 Hz pump frequency is less than its level when the pump frequency is at 50 Hz, but the liquid stays longer at a constant level during the 45 Hz Pump frequency. While the brown lines on the figure 5.18. confirms the liquid level differences, the green circles show that sometimes the liquid spend more time at a constant level during the 45 Hz than during the 50 Hz pump frequency. The purple circle shows that partially periodic oscillations (not complete period) has happened twice during the 45 Hz pump frequency.

5.2.3. Different flow regimes in the loop.

Introducing air to the system enabled us to discover the flow regimes that could happened in the loop.

Using the maximum available flowrates for both air and water we started to run the loop and observe the flow.

We divided the mixed section pipe into two theoretical parts, the first part is the distance d which starts from the end of the thin plate in the mixing unit and ends when the stratified flow regime ends. While the second part starts at the end of the stratified flow and ends by the end of the test section pipe. (figure 5.19)

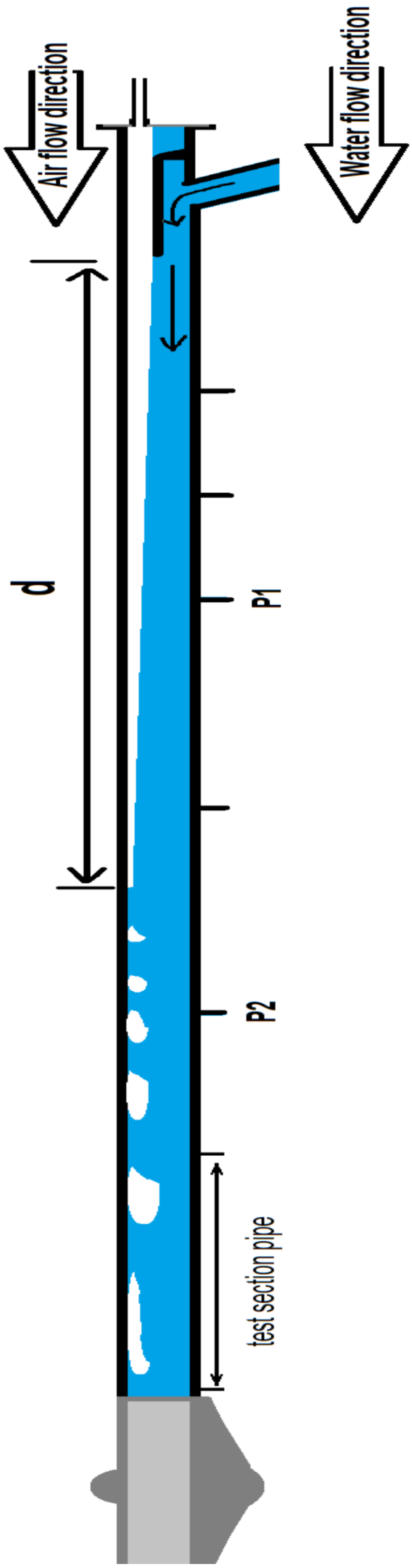

Figure 5.19 the mixed pipe section with two phase, air-water.

qL [L/m]	qg [L/m]	d length [meter]	Part 2 length [meter]
7220	4.76	3.6	1.9
6520	4.76	3.4	2.1
5820	4.76	3.1	2.4
5090	4.76	3	2.5
4450	4.76	2.8	2.7
3740	4.76	2.1	3.4

Table 5.2. length of flow regimes areas where qg is 4.76.

qL [L/m]	qg [L/m]	d length meter	Part 2 length meter
7220	1.84	3.6	1.9
6520	1.84	3.4	2.1
5820	1.84	3.1	2.4
5090	1.84	3	2.5
4450	1.84	2.8	2.7
3740	1.84	2.1	3.4

Table 5.3. length of flow regimes areas where qg is 1.84.

With constant air flowrate injected in the loop, the Loop behaved quite like its behavior under the U effect but without the reverse flow.

While a stratified wavy flow is happening always along the d distance, part 2 distance experience slugs flow almost all the time, but with the difference in shapes and the speeds of the slugs according to the water flow rate.

Since the huge difference flow rates between water and air in the loop, the borders of our two hypothetical parts d and part 2, didn't change with the change in the air flowrate, it only changes with the water flowrate changes.

5.3. Noise observations.

During the usage of the PASCO device, there were noises from different sources that affected the quality of the signals, we tried to identify the noise sources.

5.3.1. Noise caused by the pump:

It was experienced on many occasions that the pump was unstable on low frequencies which made us take a decision to limit the use of the pump to the frequencies between 25 Hz and 50 Hz only. Figure 5.20 shows how the pump noise increase with decreasing frequency.

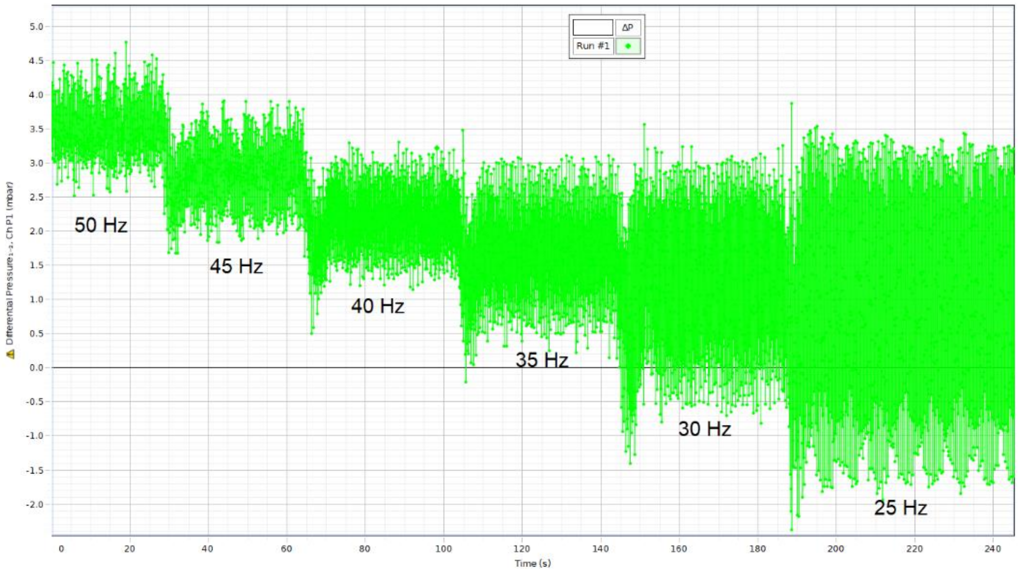

Figure 5.20 Pump noise with decreasing frequency.

5.3.2 Noise caused by the separator pressure.

It was experienced on many occasions that the separator pressure not only effect the pressure of the whole system, but it affects the noise level as well.

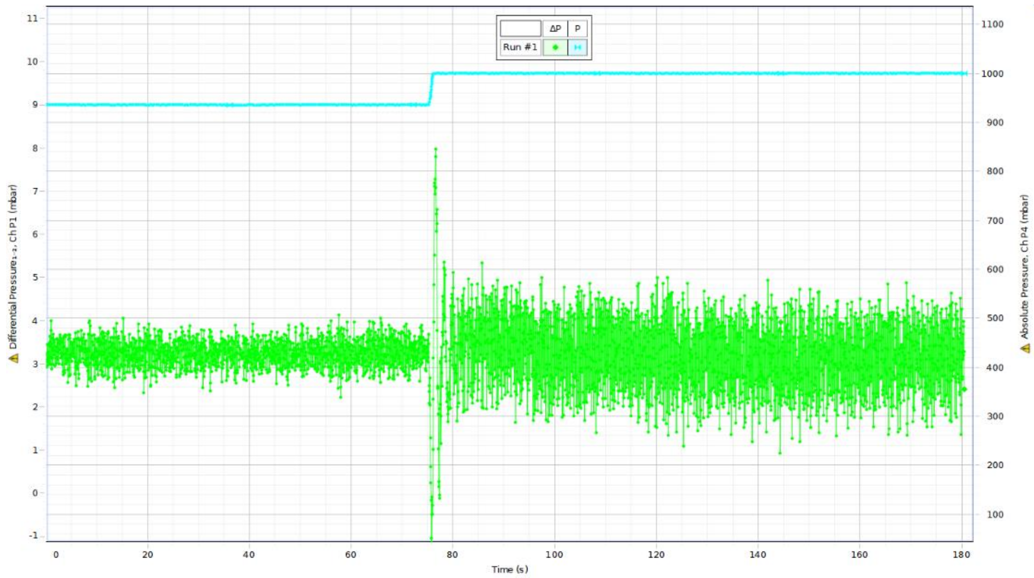

Figure 5.21. Valve to the atmosphere closed and then opened. 50Hz pump frequency.

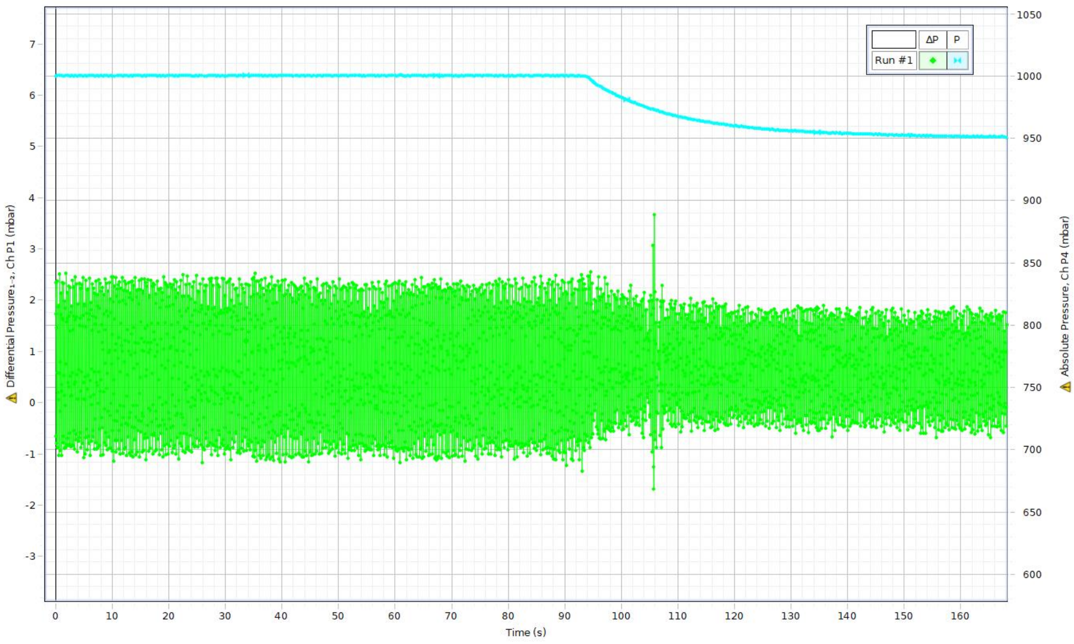

Figure 5.22. Valve to the atmosphere opened and then closed. 25Hz pump frequency.

5.3.3 Noise caused by electrical potential and electromagnetic waves.

We noticed that the rig doesn’t have a proper electrical grounding, this can be a source of error for electrical potential reference point.

Pump frequancy regualtors and the ON/OFF switches are very close to the mesuring instruments and can cause an elctromagnatic noise.

6. Conclusion and future recommendations

The main aim of this work was to build a multiphase flow loop and confirm its validity with the theory by measuring the frictional pressure drop between two points along the loop.

In addition, experiments and observation have been made regarding flow oscillations in the loop, the instability of the liquid level in the separator along with other observations including observations for air water flow.

6.1. Differential pressure between two nipples

- Despite the fact that our experimental data is orbiting very close around the theoretical ones but very seldomly equal them, we can definitely say that our loop was giving us results which are close enough to the theoretical measurements.
- Stating that confirms that the loop works according to the fluid dynamic principles and we can move on with more experiments.

6.2. Separator Oscillations.

- The separator pressure affects the pressure in the whole loop.
- Low liquid level in the separator can create a lot of bubbles and oscillations.
- Low liquid level in the separator can decrease the separator pressure in case the separator was closed.
- Closed separator creates less noise in the measurements.
- Low pressure in the separator helps with decreasing the number of bubbles in the separator and force the bubbles to join the air phase faster.
- Big pressure differences between the separator and the outlet can create a vacuum pressure in the separator that will help air to travel through the outlet into the separator.

6.3. Flow oscillations in the loop.

- Open spots in pipes can lead to flow regime changes and possibility for reverse flow problems.
- More analyzing to figure 5.17. combining with proper video recording equipment we can measure the initial velocity of the reverse flow.
- One of the reasons for the reverse flow is difference in pressure.

6.4. Different flow regimes in the loop.

- With constant air flowrate injected in the loop, the Loop behaved quite like its behavior under the U effect but without the reverse flow.
- Stratified wavy flow and slug flow can be easily achievable with our loop.
- Our loop is water flow dominant and while the presence of air flow is important to create a two-phase flow in the loop, the changes in the air flowrates doesn’t have a huge effect on the flow regimes.

6.5. Other conclusions and different recommendations.

- In order to study the separator more, fixing a flow meter on the out will be very helpful.
- Our pump is a helical progressing cavity pump which needs lubrications Thus, the pumped water should be treated.
- Due to safety reasons and to avoid probable electromagnetic noise, a box or a closet must be built where all of the on/off switches and the frequency regulators can fixed inside of it, the box must be fixed away from the loop and must be provided with an external main on/off electricity switch in case of an emergency.
- A box with a hose should be made to cover the weak point in the system.
- The lighting conditions must be enhanced in order to use the optical box for photos and video recordings.
- A stand should be made so lab workers can stand on it and monitor the flow through the optical box.
- The mixing unit with the thin plate has an unknown effect on the flow. This should be studied and mixing units with different designs can be introduced.
- The loop should be electrically grounded.
- Using flexible hoses can affect the pressure drop due to acceleration. This can be studied
- In case a better air system was introduced, it can allow us to monitor the changes with air flowrate changes. And maybe achieve more flow regimes in the loop.

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Appendix A

Pump frequency s	Flow Rate m3/h	Flow Rate m3/s	Velocity m/s
5	0.7	0.000194444	0.091558564
	0.71	0.000197222	0.092866543
	0.72	0.0002	0.094174523
	0.73	0.000202778	0.095482502
10	1.44	0.0004	0.188349045
	1.45	0.000402778	0.189657025
	1.46	0.000405556	0.190965004
	1.47	0.000408333	0.192272984
15	2.17	0.000602778	0.283831547
	2.18	0.000605556	0.285139527
	2.19	0.000608333	0.286447506
	2.2	0.000611111	0.287755486
20	2.88	0.0008	0.37669809
	2.89	0.000802778	0.37800607
	2.9	0.000805556	0.379314049
	2.91	0.000808333	0.380622029
25	3.6	0.001	0.470872613
	3.61	0.001002778	0.472180592
	3.62	0.001005556	0.473488572
	3.63	0.001008333	0.474796551
30	4.32	0.0012	0.565047135
	4.33	0.001202778	0.566355115
	4.34	0.001205556	0.567663094
	4.35	0.001208333	0.568971074
35	5.05	0.001402778	0.660529637
	5.06	0.001405556	0.661837617
	5.07	0.001408333	0.663145596
	5.08	0.001411111	0.664453576
40	5.77	0.001602778	0.75470416
	5.78	0.001605556	0.756012139
	5.79	0.001608333	0.757320119
	5.8	0.001611111	0.758628098
45	6.47	0.001797222	0.846262723
	6.48	0.0018	0.847570703
	6.49	0.001802778	0.848878682
	6.5	0.001805556	0.850186662
50	7.15	0.001986111	0.935205328
	7.16	0.001988889	0.936513307
	7.17	0.001991667	0.937821287
	7.18	0.001994444	0.939129266

Appendix B

Height of column [m]	Theoretical Pressure	Sensor one	Sensor two	Sensor three
0	101703	101703	101703	101703
0.25	104148.1425	104058	104199	104139
0.5	106593.285	106598	106524	106518
0.75	109038.4275	108940	109089	109261
1	111483.57	111488	111427	111611
1.25	113928.7125	113768	113991	113897
1.5	116373.855	116283	116482	116319
1.75	118818.9975	118869	118752	118892
2	121264.14	121199	121255	121176
2.25	123709.2825	123723	123650	123620
2.5	126154.425	126979	126833	126046
2.75	128599.5675	128581	128506	128654

Appendix C

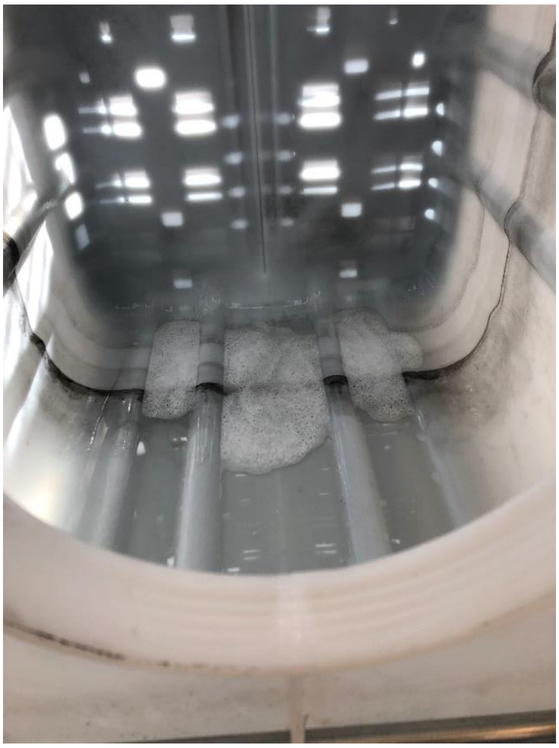
Picture 1. Loop body.

Picture 2. Loop body.

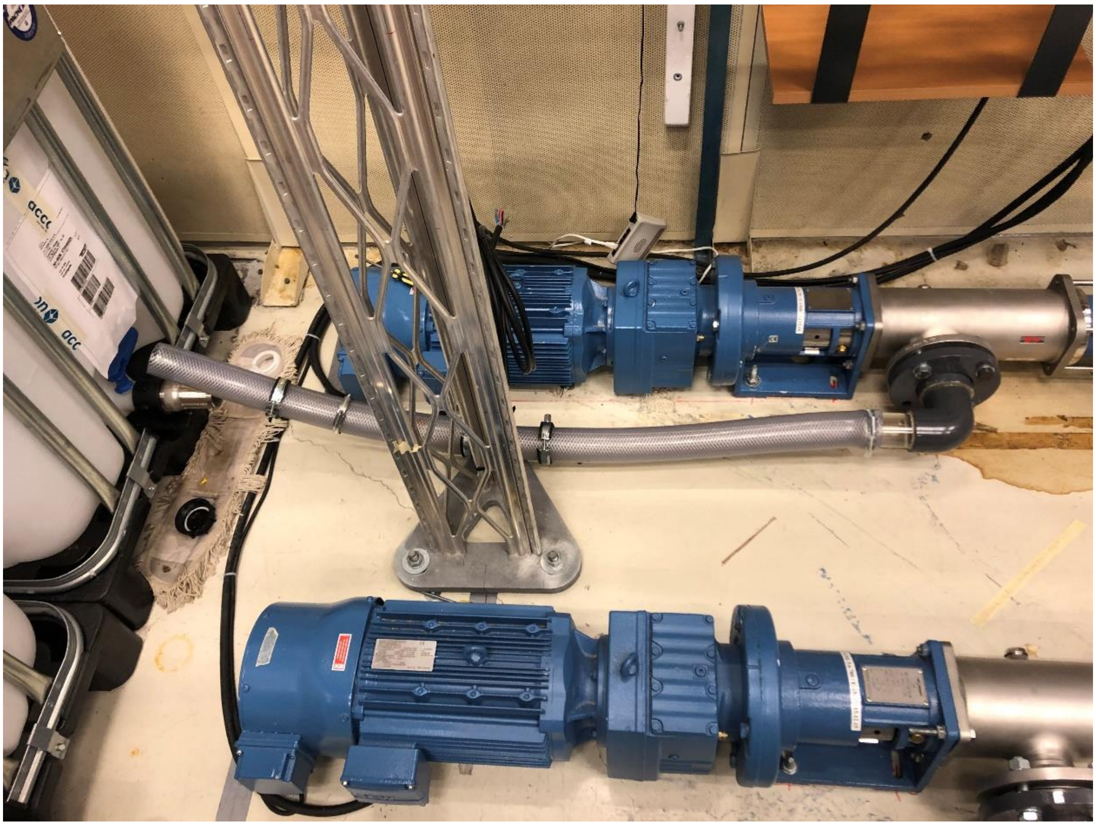
Picture 3. Tanks.

Picture 4. Tanks old outlets.

Picture 5. Tanks new outlets.



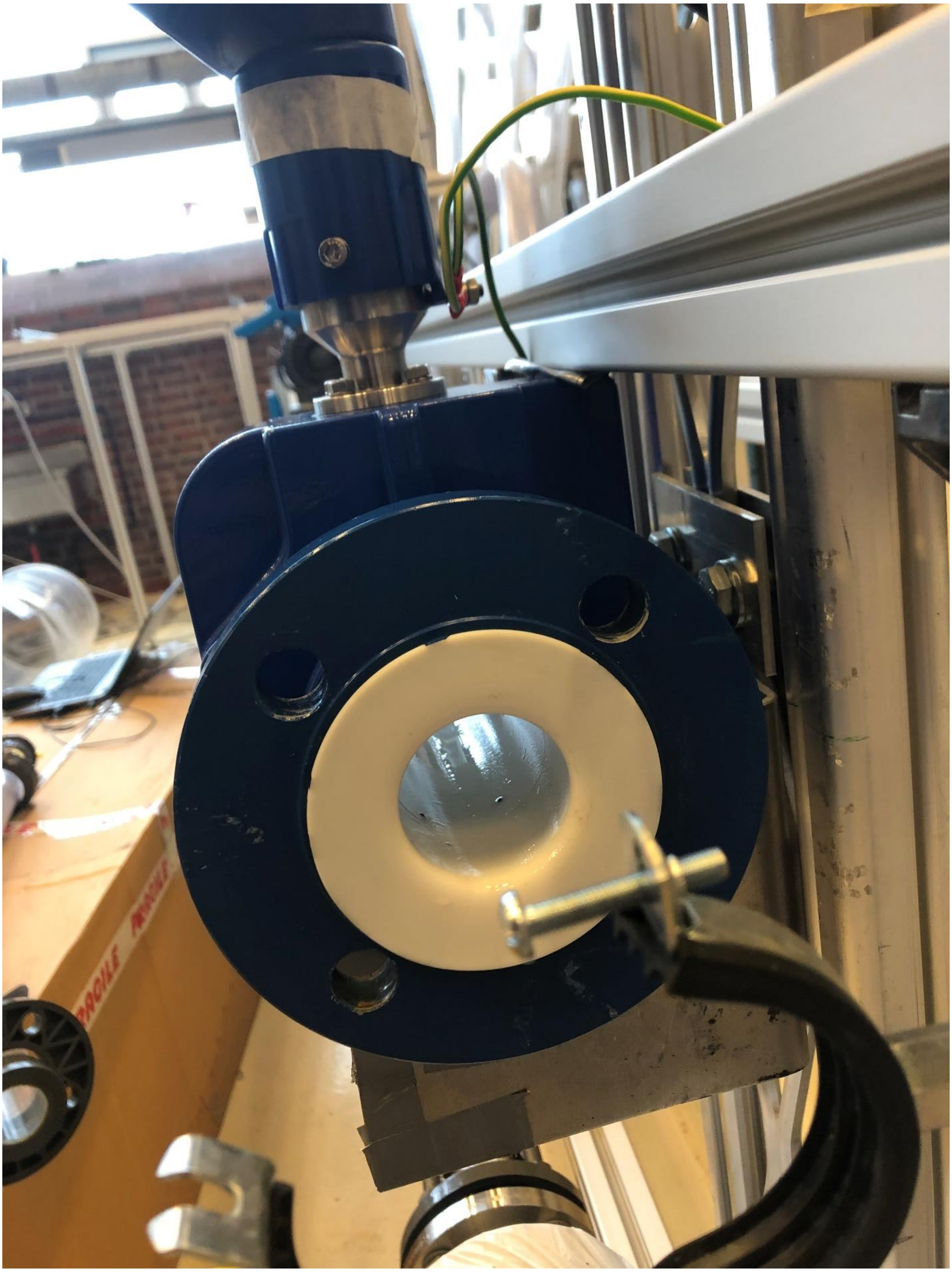
Picture 6. Dirty Tank.



Picture 7. Pumps.

Picture 8. Pumps.

Picture 9. Pumps.



Picture 10. Electromagnetic flowmeter.

Picture 11. Electromagnetic electrodes.

Picture 12. Earthing rings.

Picture 13. Rubber gaskets.

Picture 14. Mixing unit entry.

Picture 15. Mixing unit entry U joint.

Picture 16. Mixing unit entry U joint.

Picture 17. Plastic plate during construction.

Picture 18. First Plastic plate done.

Picture 19. Second Plastic plate.

Picture 20. Second Plastic plate.

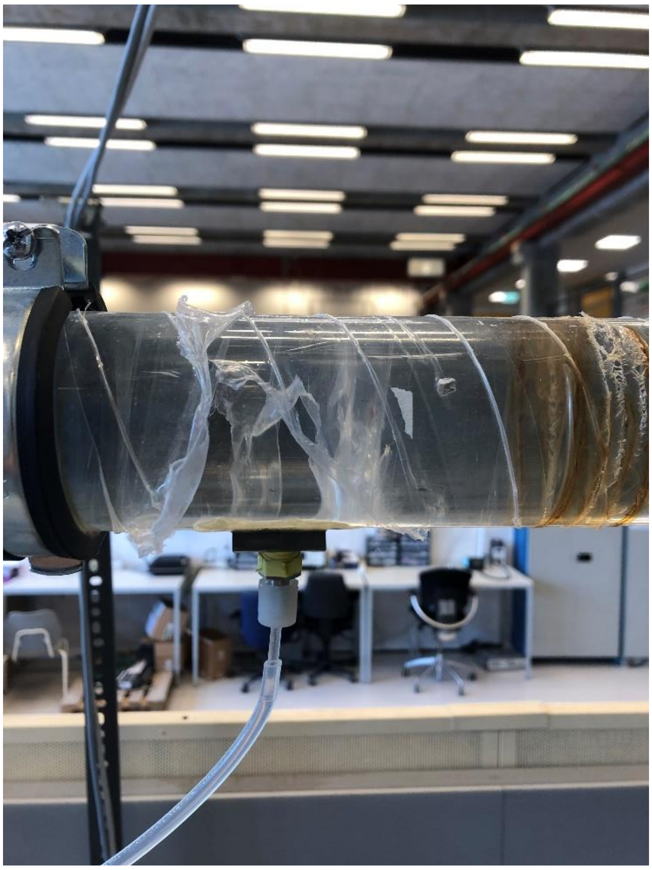
Picture 21. Second plastic plate.

Picture 22. Vertical pipe.

Picture 23. Mixing Unit.

Picture 24. Mixed section during repairing.

Picture 25. Mixed section.

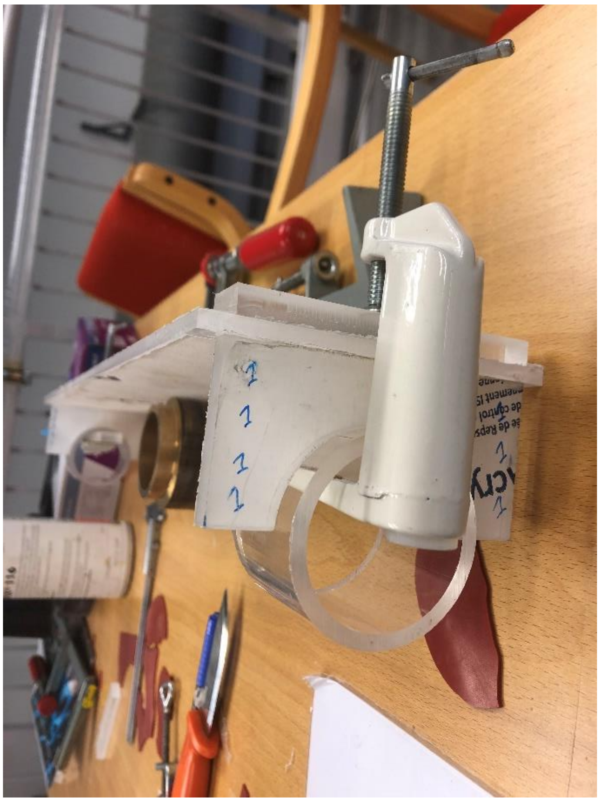


Picture 26. Mixed section nipple connected to a silicon hose.

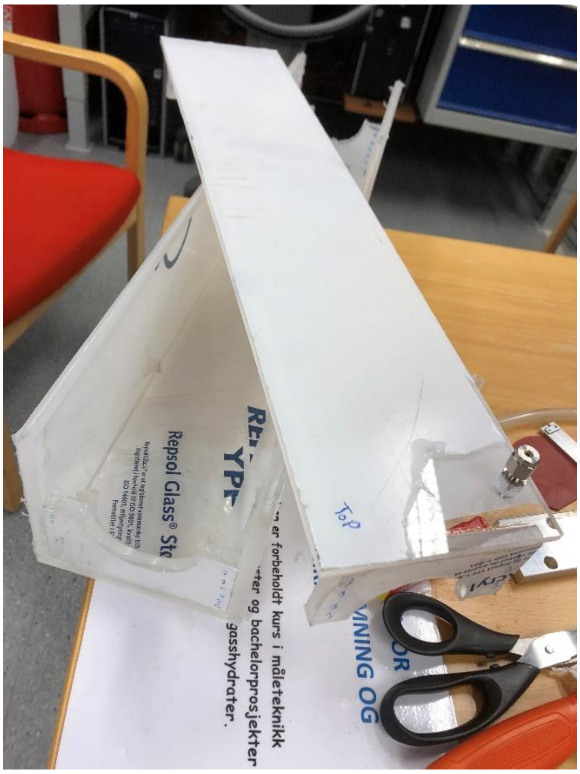
Picture 27. Mixed pipe before fixing the nipples.

Picture 28. Optical box during construction.

Picture 29. Optical box during construction.

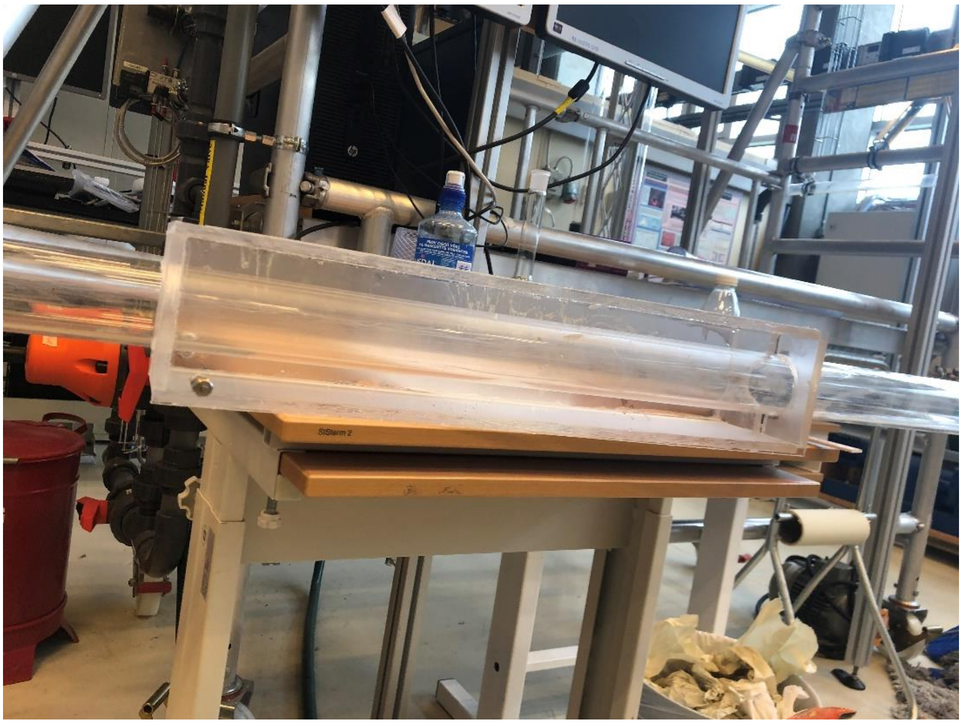


Picture 30. Optical box during construction.



Picture 31. Optical box during making.

Picture 32. Optical box during construction.



Picture 33. Optical box ready.

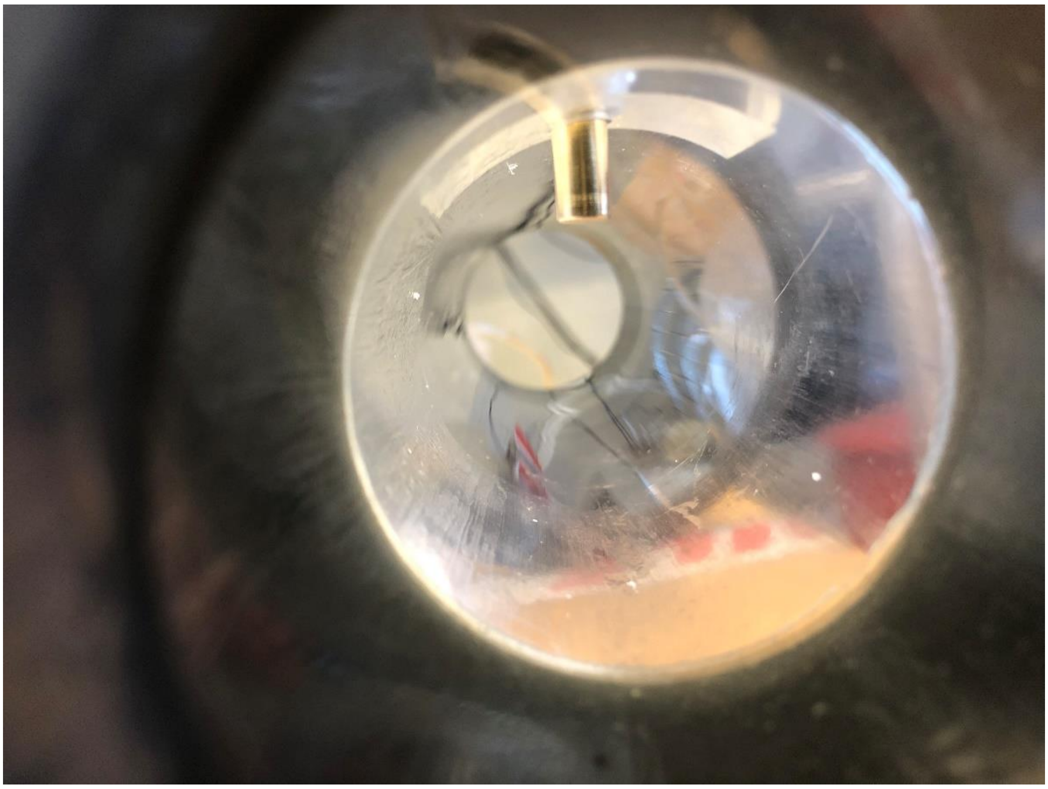
Picture 34. Optical box frames during construction.

Picture 35. Optical box with frames.

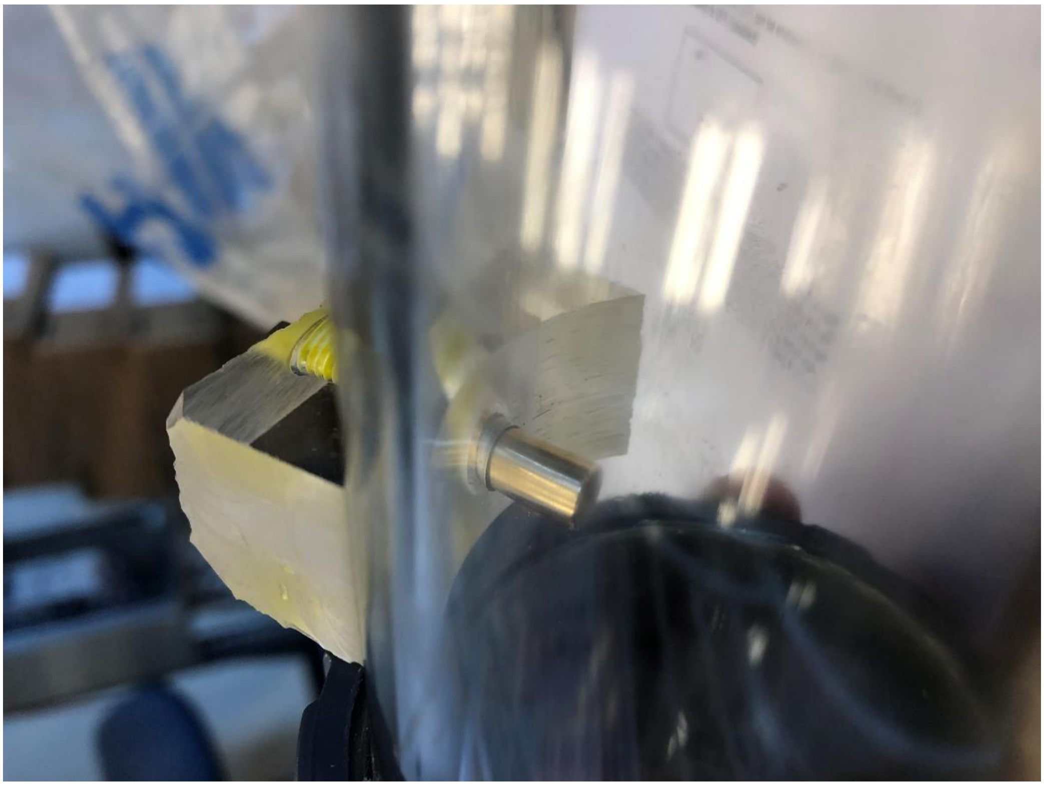
Picture 36. Temperature sensor holder during construction.

Picture 37. Temperature sensor holder during construction.

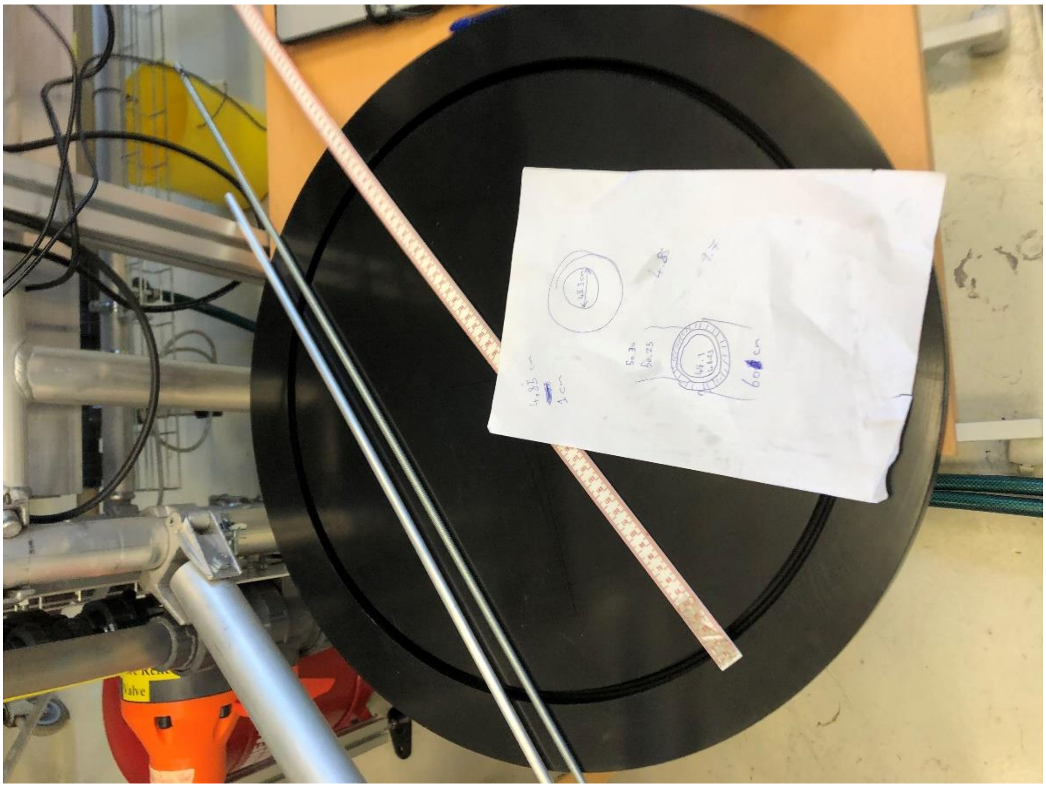
Picture 38. Temperature sensor holder ready.



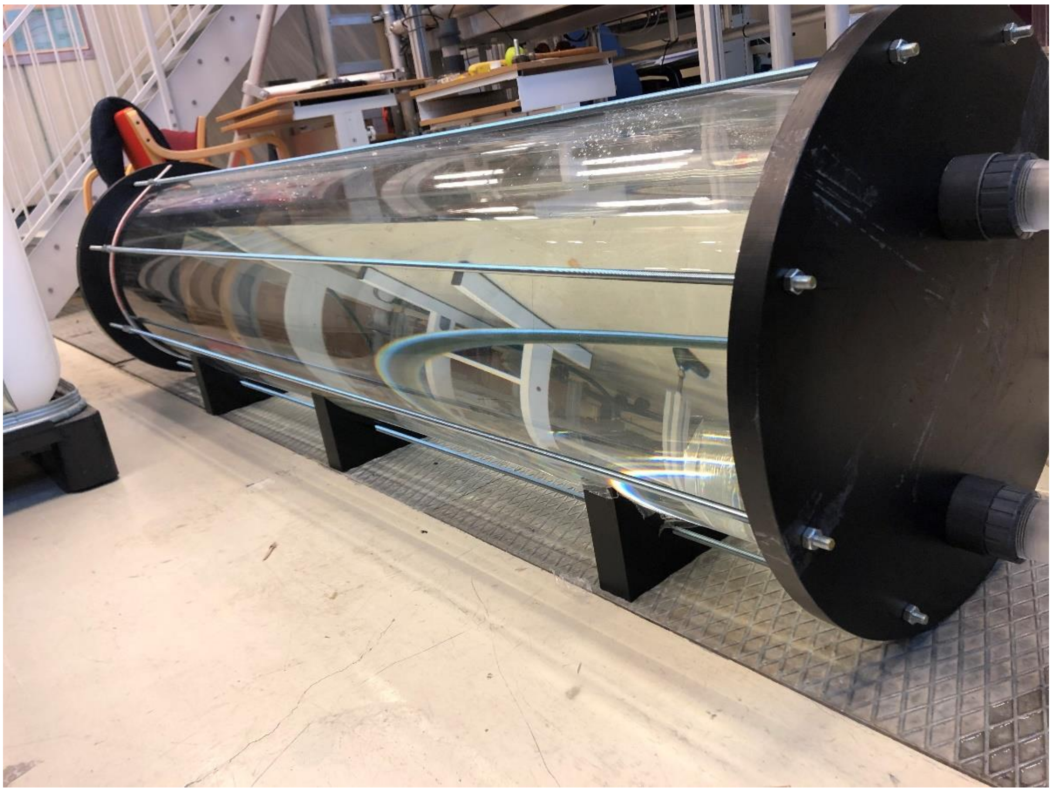
Picture 39. Temperature sensor holder.



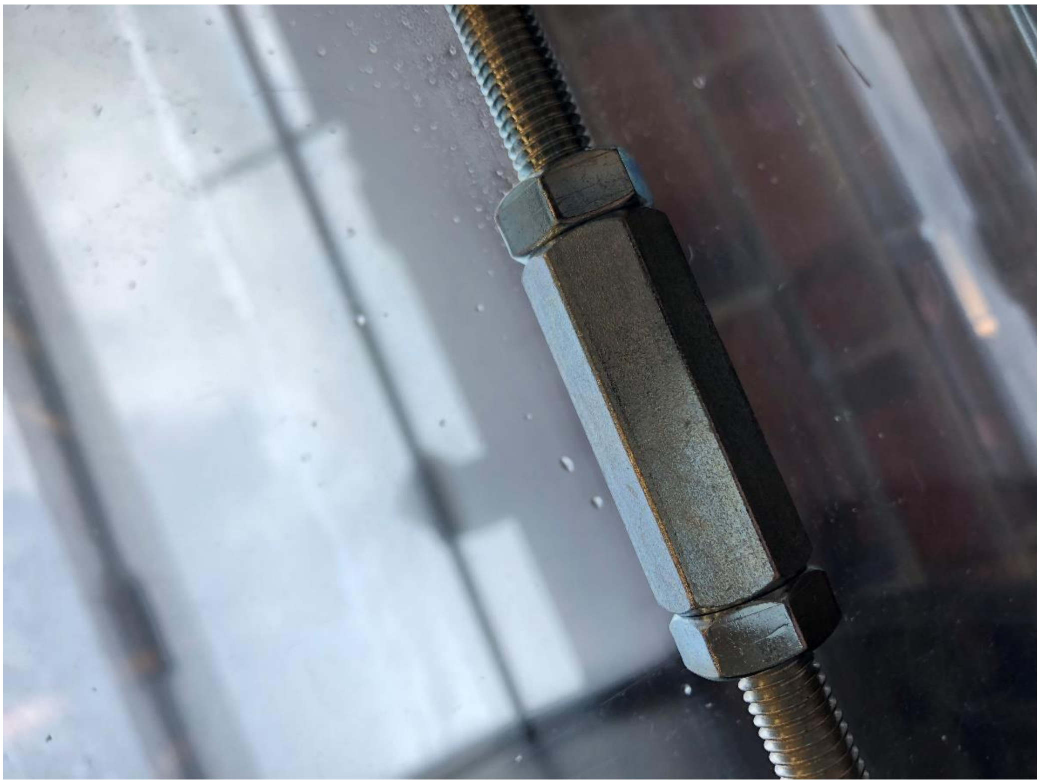
Picture 40. Temperature sensor holder



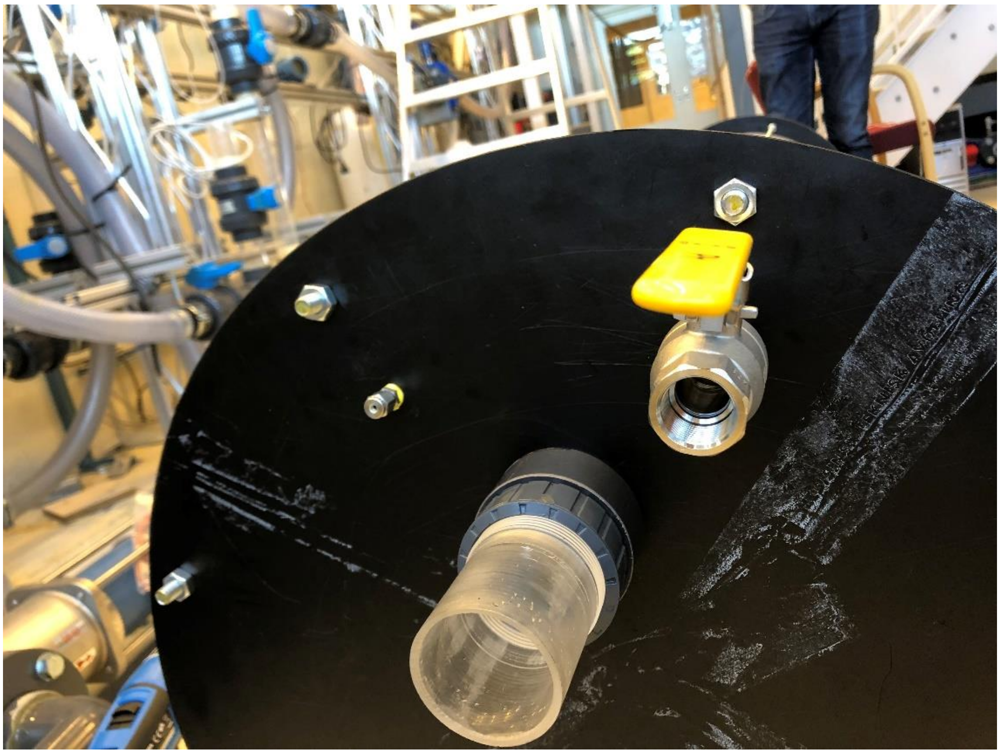
Picture 41. Separator.



Picture 42. Separator.



Picture 43. Separator smart connection.

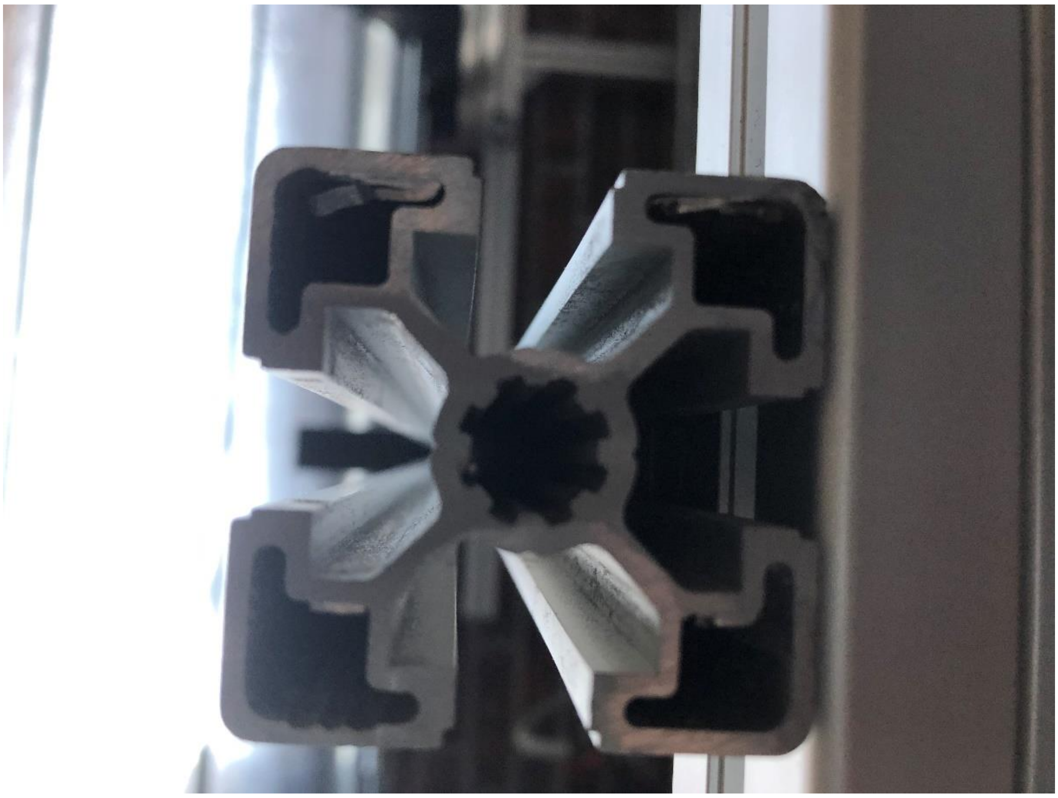


Picture 44. Separator.

Picture 45. Separator.

Picture 46. Separator.

Picture 47. Separator outlet valve.



Picture 48. Separator table aluminum profiles

Picture 49. Separator table

Picture 50. Separator table.

Picture 51. Separator table.

Picture 52. Separator table leg threading.

Picture 53. Separator table.

Picture 54. Separator support (cushions).

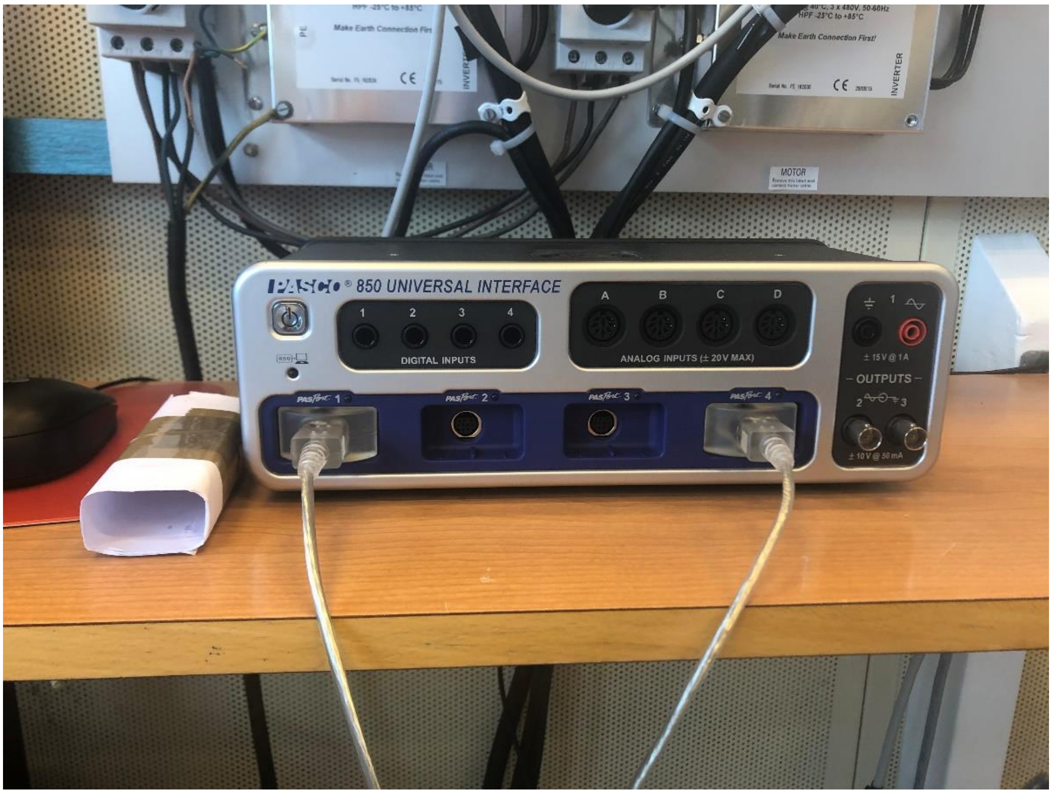
Picture 55. Separator support (cushions).

Picture 56. Separator modified screws.

Picture 57. Safety observations.

Picture 58. PVC fitting.

Picture 59. Plastic Shield



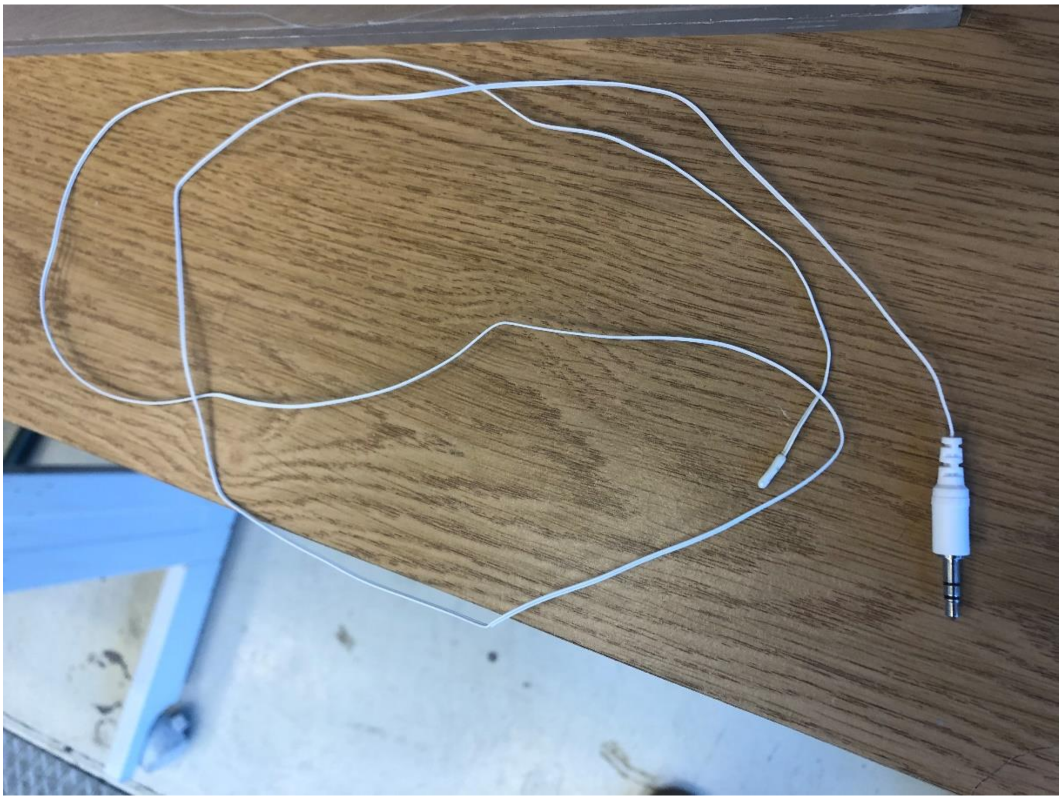
Picture 60. PASCO interface.

Picture 61. PASCO Absolute Pressure temperature sensor

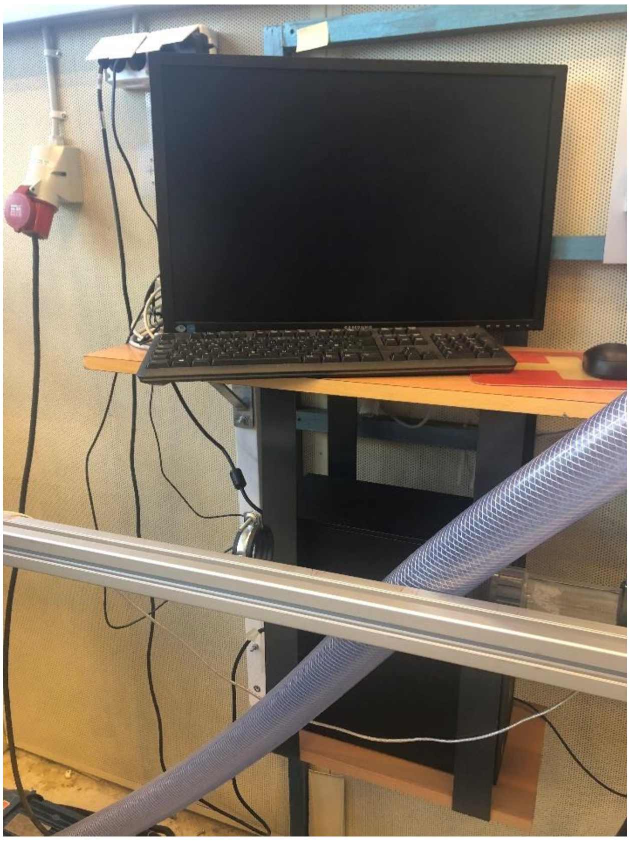
Picture 62. PASCO Dual Pressure sensor.

Picture 63. PASCO sensors.

Picture 64. PASCO sensor cables.



Picture 65. PASCO Temperature sensor.



Picture 66. Desktop computer.

Picture 67. Aluminum stick for the Rosemounts.

Picture 68. Aluminum stick for the Rosemounts.

Picture 69. Rosemount transmitters.

Picture 70. Validyne pressure transmitter and transducer

Picture 71. Rosemount 2088 Gage and absolute Pressure Transmitter.

Picture 72. 3144P Rosemount Temperature Transmitter

Picture 73. Swaglok pressure regulator and crystal engineering xp2i digital pressure gauge indicator

Picture 74. 3-way valve.

Picture 75. Air flowmeter

Picture 76. Air flowmeter.

Appendix D

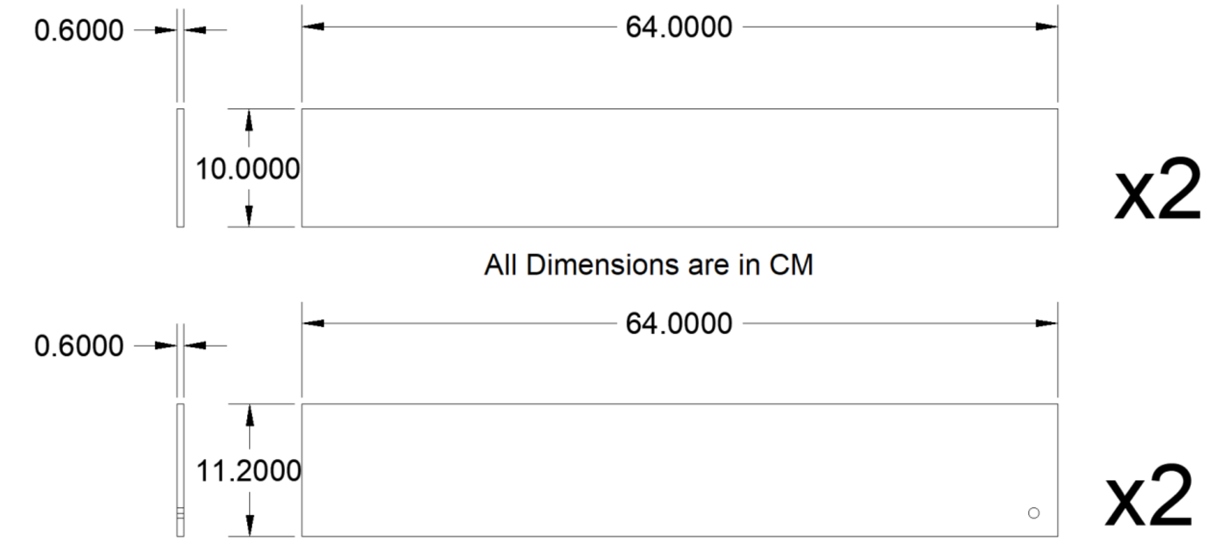


Figure 1. Optical Box

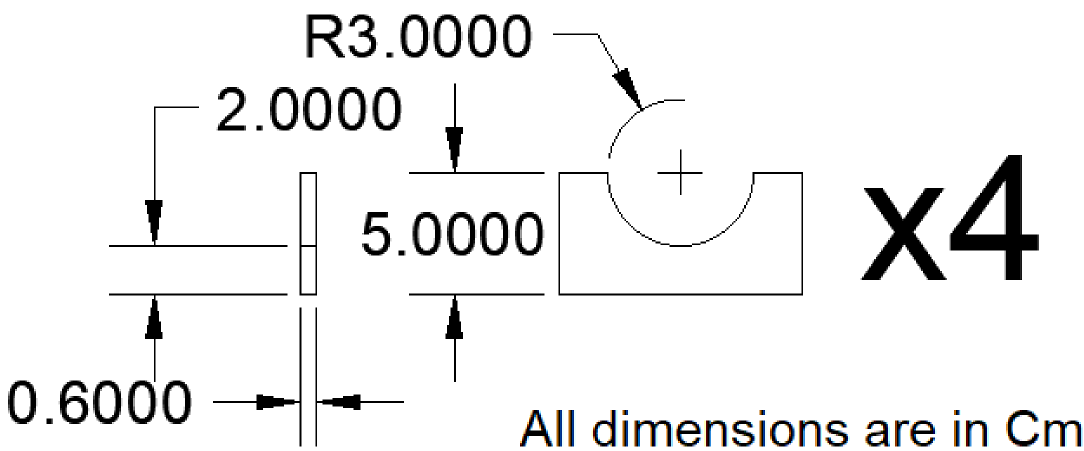


Figure 2. Optical Box

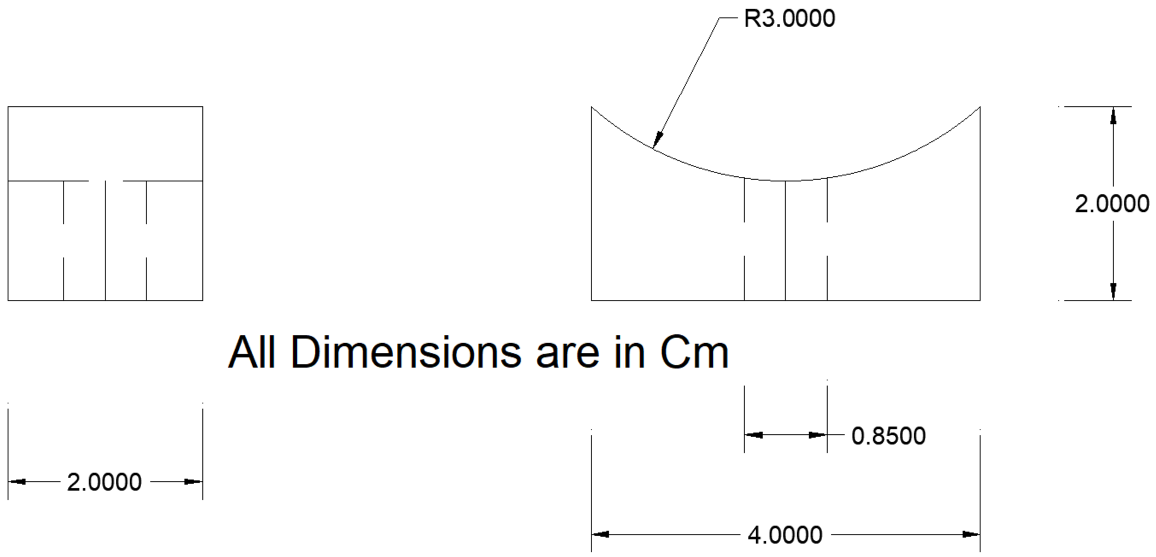


Figure 3. Adapter

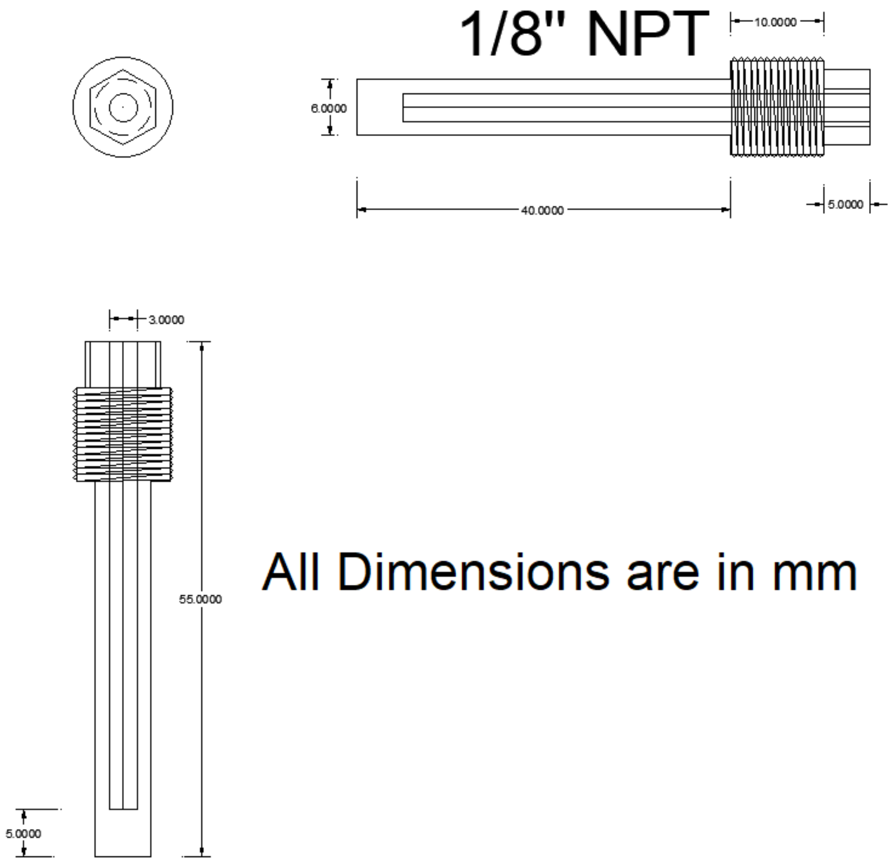


Figure 4. Brass Holder

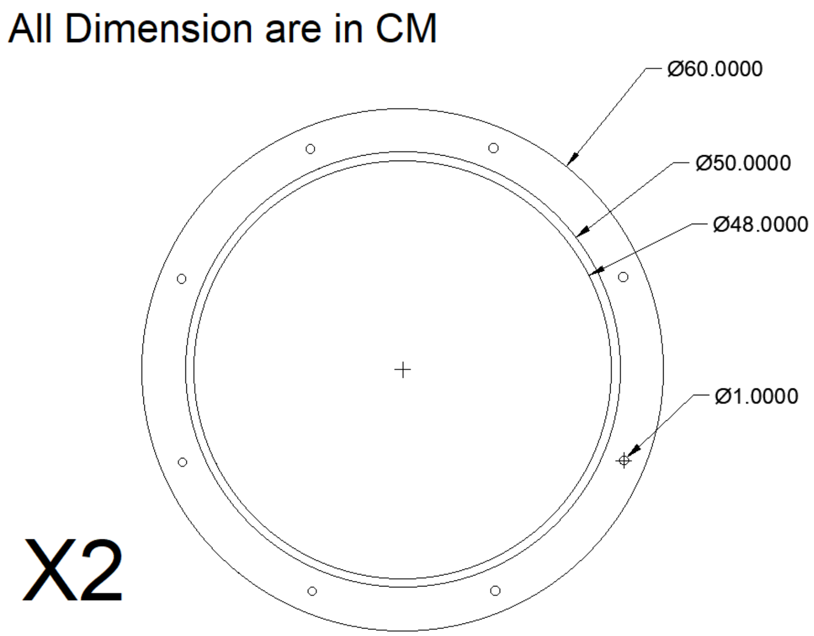


Figure 5. Lid General

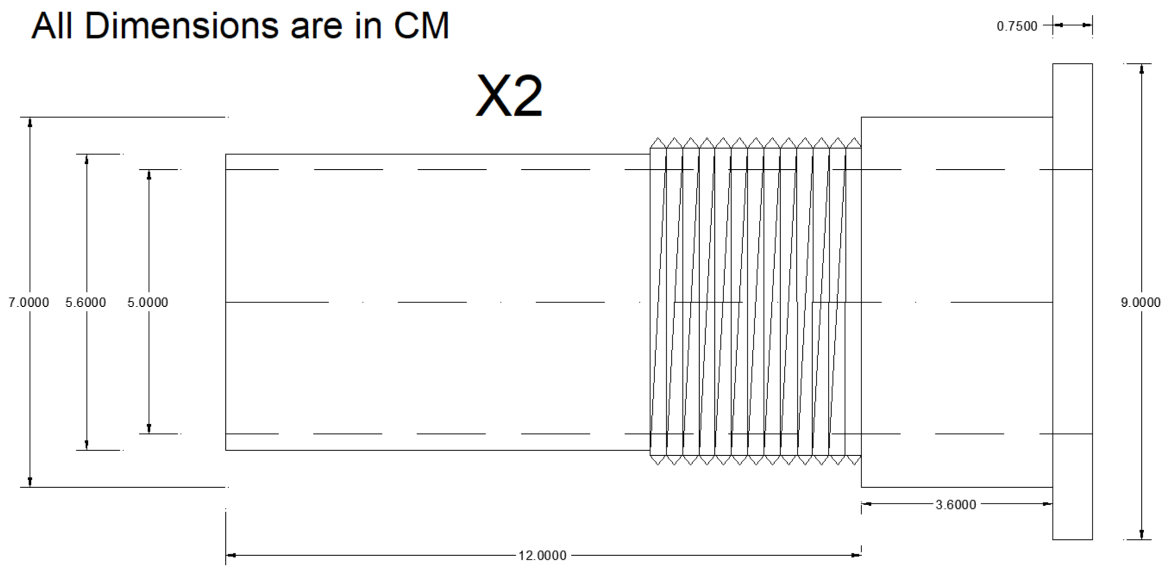


Figure 6. Inlet and Outlet

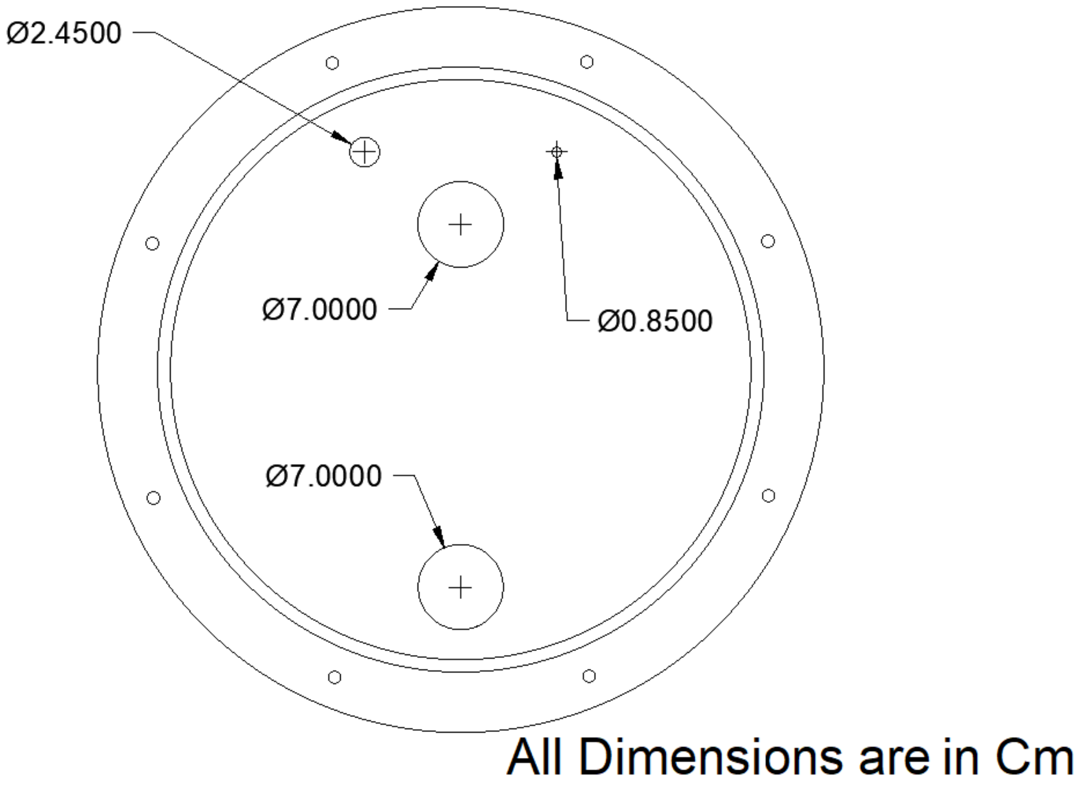


Figure 7. Led Front

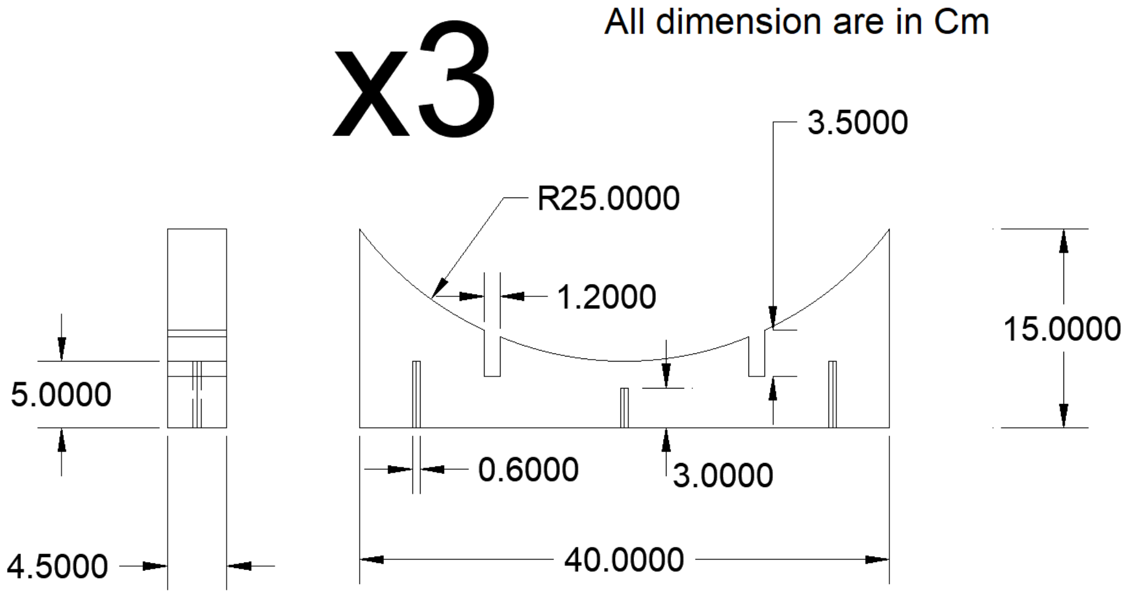


Figure 8. Cushions