

UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

Design and testing of test rigs for fault detection in energy systems

**María José Jácome Moreira
Pedro David Reina Dávila
Sebastián Alejandro Espinosa Gordillo
Ayrton Marcelo Franco Rivadeneira**

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UNIVERSIDAD SAN FRANCISCO DE QUITO USFQ

Colegio de Ciencias e Ingenierías

HOJA DE CALIFICACIÓN DE TRABAJO DE FIN DE CARRERA

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**María José Jácome Moreira
Pedro David Reina Dávila
Sebastián Alejandro Espinosa Gordillo
Ayrton Marcelo Franco Rivadeneira**

Calificación

A

Nombre del profesor, Título académico

Juan Sebastián Proaño, PhD.

Quito, 13 de mayo de 2020

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Nombres y apellidos: Pedro David Reina Dávila

Código: 00130383

Cédula de identidad: 100396852-4

Lugar y fecha: Quito, mayo de 2020

Nombres y apellidos: María José Jácome Moreira

Código: 00134004

Cédula de identidad: 131270239-0

Lugar y fecha: Quito, mayo de 2020

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Nombres y apellidos: Ayrton Marcelo Franco Rivadeneira

Código: 00129907

Cédula de identidad: 100407068-4

Lugar y fecha: Quito, mayo de 2020

Nombres y apellidos: Sebastián Alejandro Espinosa Gordillo

Código: 00130689

Cédula de identidad: 172087187-8

Lugar y fecha: Quito, mayo de 2020

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RESUMEN

Este portafolio resume el desarrollo de un sistema automatizado capaz de detectar fallas operacionales en sistemas energéticos. El sistema incluye transporte de agua, calentamiento y refrigeración. Múltiples sensores monitorean los subsistemas en el prototipo. Por ejemplo, al calentar agua, se midió la temperatura para identificar desviaciones de un valor en estado estable. Las posibles causas de la desviación podrían ser daños en la estructura eléctrica o en los sensores. Para ambos casos, la medición de temperatura será incorrecta. Un control PID intentará mantener la temperatura del agua a 40°C. Los problemas seleccionados que deben abordarse en el sistema de transporte de agua son los que se encuentran comúnmente en la industria: cavitación, válvulas atascadas, fugas y bombas que dejan de funcionar. Debido al tamaño del modelo del proyecto, el sistema de refrigeración incluye solo cambios de temperatura inesperados. Los datos enviados por los sensores se guardan en un código Python que usa algoritmos de regresión lineal, método K - de vecinos más cercanos (KNN) y programación de declaraciones "if". Cuando se detecta cualquier falla, se envían mensajes de advertencia al operador del sistema. Tanto los sensores como el código de programación se validaron correctamente y se concluyó que todos los problemas propuestos se detectaron como se esperaba.

Palabras Clave: Detección de fallas, sistemas energéticos, automatización, fallas operacionales, Python.

ABSTRACT

This portfolio summarizes the development of an automated system capable of detecting operational faults within energy systems. The system includes water transport, heating and refrigeration. Multiple sensors monitor the sub-systems in the prototype. For example, when heating water, temperature was measured to identify deviations from a steady state value. Possible causes of the deviation could be damages in the electric structure or the sensors. For both cases the temperature measurement will be incorrect. A PID control will attempt keeping the water temperature at 40°C. The selected problems to be addressed in the water transport system are ones commonly found in the industry: cavitation, stuck valves, leaks, and pumps that stop working. Due to the project's model size, refrigeration system includes only unexpected temperature changes. The data sent by the sensors is saved into a Python code that uses a linear regression algorithm, K – nearest neighbors method (KNN) and “if” statements programming. When any fault is detected, warning messages are sent to system's operator. Both the sensors and programming code were correctly verified, and it was concluded that all the proposed problems were detected as expected.

Key words: Fault Detection, Energy Systems, Automation, Operational Faults, Python.

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Notation*Thermo-physical variables*

FDD = fault detection and diagnosis

T_a = ambient temperature ($^{\circ}C$)

T_{in} = water inlet temperature ($^{\circ}C$)

d_1, d_2 = internal and external diameters (m)

L = length (m)

\dot{V} = volumetric flow rate (m^3/s)

ρ = density (kg/m^3)

C_p = specific heat ($\frac{kJ}{kg \cdot K}$)

l = latent heat ($\frac{kJ}{kg}$)

U_o = overall heat transfer coefficient ($\frac{W}{m^2 \cdot K}$)

A = area (m^2)

V_{water} = water volume (m^3)

F_1 = correction factor for the heat provided by walls and floor

F_2 = correction factor for air circulation space

P_g = gage pressure (m.c.a)

μ_{H_2O} = water's dynamic viscosity ($\frac{N \cdot s}{m^2}$)

γ_{H_2O} = water's specific weight ($\frac{kN}{m^3}$)

ϕ_{nozzle} = nozzle's diameter (mm)

t = time (s)

m = mass (kg)

\dot{Q} = power (W)

l_a, l_b = 1'' and ¾'' pipe lengths, respectively (m)

D_a, D_b = 1'' and ¾'' pipe diameters, respectively (m)

Re = reynolds number

v = velocity $\left(\frac{m}{s}\right)$

h_a = head rise (m)

h_L = head loss (m)

z = reference height (m)

f = friction factor

ε = relative roughness

a_x = acceleration on the X axis $\left(\frac{m}{s^2}\right)$

a_y = acceleration on the Y axis $\left(\frac{m}{s^2}\right)$

a_z = acceleration on the Z axis $\left(\frac{m}{s^2}\right)$

Loss coefficients

κ_v = fully open globe valve

κ_{vr} = union threaded

κ_c = elbow

κ_s = exit

κ_R = reduction section

κ_{vp} = swing check forward valve

κ_{vb} = ball valve

κ_f = line flow threaded tee

Control variables

$E(s)$ = error signal

$B(s)$ = feedback signal

$Q(s)$ = heat in Laplace domain

$T(s)$ = temperature in Laplace domain

$H(s)$ = PID system

$G(s)$ = system function

K_p = proportional constant

T_i = integrative constant

T_d = derivative constant

SSR = solid state relay

J = average square error

1. INTRODUCTION

Energy systems are the heart of modern society, involving buildings that need HVAC, industries that use pumps, boilers, cold rooms, among others. Likewise, these systems represent one of the highest costs on the monthly bill assuming that the systems are working fine. The problem arises when the faults in the systems produce a reduction in the efficiency, increasing the monthly energy cost. These failures are difficult to detect in an early stage which triggers the need of designing an adaptable fault detection system that can detect them on time.

The purpose of this report is to detect and notify faults that occurs in common energy systems among Ecuadorian industries. Moreover, a test rig that adapts failures in the design is required in order that a programed algorithm detects each fault one by one.

A set of algorithms that learn by themselves are designed to detect faults having a given time to acquire enough data, then process it and do predictions. Samples in the learning part is given by taking the arithmetic mean between ten data points for each sensor every 12.5 seconds (having four per second) and this mean value is one data for the learning algorithm array. The more data is taken, the more accurate the prediction will be.

This algorithm will work in multiple energy systems and application scales, due to its adaptability. This project included sensors for water flow rate, temperature, vibration in three axes and water level. These sensors feed the algorithms to detect faults. The system relies on the correct selection of the sensors and their location in the system. All the components used are automated with Arduino.

A Laplace transform and energy balances allow finding a transfer function for an electric water heater tank. Moreover, this function permits calibrating a PID controller to keep the water temperature at 40°C. A temperature sensor feeds back the PID in a close loop controller.

In the previous system, the first fault appears when the resistor is burned or disconnected. In this scenario the Arduino code sends a signal to turn on the relay but it is not working. This is represented as a not so steep temperature drop, but it can be mistaken for damage in the sensor and in the last scenario the temperature drop will be bigger.

In water supply system, the problems will be more complex like cavitation. To detect it a six degrees of freedom sensor will be used. The first step is to design a model to force cavitation causing that the pump starts vibrating. This deviation will be detected by using a machine learning algorithm to classify the behavior by using nearest neighbors' technique. Another fault that is commonly reported by pump users is that the foot valve is damaged and allows the water to flow out of the pipe. This can be detected by using a water flow sensor. If there is no water, there is no flow, and the algorithm sends a warning message to stop the pump. Other problems will be detected like stuck valves, pump is not working and leaks in water tank.

In a refrigeration cycle exists problems that are very difficult to detect like leaks or fouling problems inside the components. Given that the present project is a scale model, the only problem to be detected is the unexpected change in the temperature. This change can appear because of the people that are opening and closing the door of the cold room. If the door lasts more than 30 minutes open, a warning will appear.

In order to demonstrate the real operation, when faults are forced to happen, the algorithm starts to work by using linear regression model for heating, k-nearest neighbors for cavitation and if statements for the others. Both linear regression and k-nearest neighbors are used in machine learning and are available to do predictions after to be trained with previous data set.

1.1. Problem Statement and Project Specification

The ASHRAE 2020 applied engineering challenge consists on designing a system that can detect operational faults and send messages to the building operator. “The system should identify issues and provide solutions and/or next steps to solve these problems” (Applied Engineering Challenge ASHRAE, 2020). Therefore, this project concentrates on the development of a fault detection and diagnosis methodology (FDD).

To solve this problem, it is necessary to build a set of test rigs for each energy system taking into account as the main point for the design the implementation of faults. Data recorded from sensors is stored into a vector in Python and then filtered in order to be improved before it will be treated (fitting process).

Another objective is to safeguard the machines integrity by giving a warning. To achieve this purpose, it is important to sample the analog signal given by the sensor to treat the data by using machine learning algorithms or if statements to compare the projections over this dataset behavior. This is a simple and scalable way to take, filter and compare data.

One requirement is to put all test rigs and components into an ordered place. To do it three floors of a scale building are going to be developed. In the same way a support that holds the pump over the building is important. The model size depends on the cold room dimensions since these are going to be calculated depending on the available components.

In order to generate faults, it is needed to change the normal status of the components. For example, to force cavitation is required to drop the pressure of the system under the vapor pressure in the suction part by closing the valves. For the heating system is necessary to develop a PID that works inside the right parameters. If the PID is well designed, it only

remains to damage the components to force temperature out of its normal range. This can be achieved by disconnecting the relay or the temperature sensor.

For the refrigeration cycle was not possible to assemble the parts and take real data, but it will be simulated in order to train the algorithm. This will be possible by using a dataset for a similar designed system to make ice. These values will be used to train the model, and then to simulate the fault inside the data array for the test section.

After achieving a good fault detection, the next step is to send warning alerts to the operator and clearly communicate where the faults are located. This facilitates the maintenance or act over the components in an easy way knowing the problem.

The state of the art referred to this subject involves a wide variety of research approaches for HVAC data management and processing. Machine learning techniques and statistical models applied to HVAC systems are relatively recent research lines and still in development (Cheng & Lee, 2019). However, there are already some products available in the market that implement these methodologies for HVAC. For example, Nest (Google's smart device company) has developed an automatic climate control thermostat system that uses algorithms to learn the user's habits over time and self-optimize (Lavars, 2015).

Related to air conditioning systems and using the data given in the ASHRAE Project 1043-Rp, typical water-cooled centrifugal chillers have more than 20 types of common faults. Also, ASHRAE Project 1312-Rp shows that a typical air handling unit has 68 types of common faults. This represents a considerable amount of money in training data and filters, and also in space in the cloud for processing data. It is still in an early stage (Zhao et al., 2019). Nevertheless, HVAC systems will continue to grow smarter, more reliable and energy efficient.

1.2. Design Concepts and Selection

In order to address the previously specified problem, a heating, water supply and refrigeration systems are designed, built and monitored. To stay within budget, using recycled components becomes a must. Calculating the correct dimensions for the pipelines, refrigeration components and others is also key in order to buy just what is necessary. It is also important to highlight that the size of the building should not exceed the dimensions of a standard table, which is 150 cm long and 80 cm wide.

Figure 1 shows the configuration for the heating/water supply systems. It is divided into three main distribution lines (supply, cavitation, and delivery) and the heating portion itself.

The temperature sensor, solid state relays, electric resistance and various other components work together with a PID to properly control the water's set point temperature. The developed FDD algorithm feeds from the recorded data and analyzes possible common fault scenarios. The water heater storage tank on the top floor of the building model is scaled to an appropriate size (5.2 liters container).

In order to locate the systems is necessary to make other adaptations like a table that supports the weight of the pump (5 kg) and the vibration when cavitation starts. The whole water delivery system is connected to the heating part through a fish pump to supply water to heating system tank. Then, this hot water will return into the main storage tank to be used by the big pump (APm37), helping to force cavitation. This is within the temperature range that the manufacturer allows. The cost for the heating/water supply system is of \$180.

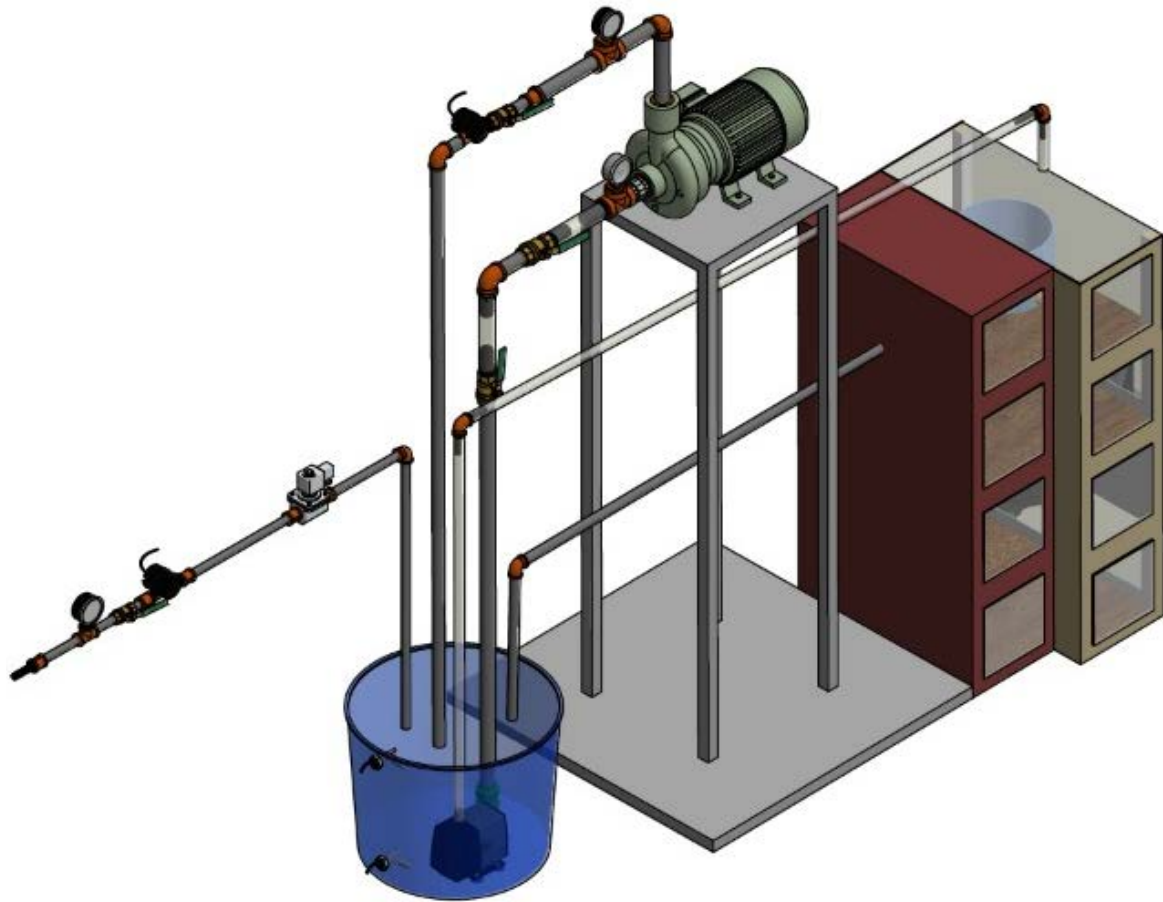


Figure 1: Water supply and heating system CAD.

Similarly, the refrigeration system is based on temperature control. Therefore, its FDD algorithm will act on the same principles as the one for the heating/water supply. Its design is also on a full-scale model where all its components are regular size parts found in the market ($\frac{1}{4}$ hp compressor, evaporator, and condenser). In this case all the components are limited by the compressor specifications which are for low temperature settings and uses R-134a as the refrigerant, as shown in Figure 2. However, the model is not built but simulations will be done with a dataset from a similar refrigeration cycle (Ajav & Mankinde, 2015). The total cost for the system is of \$55 (assembly costs not included).

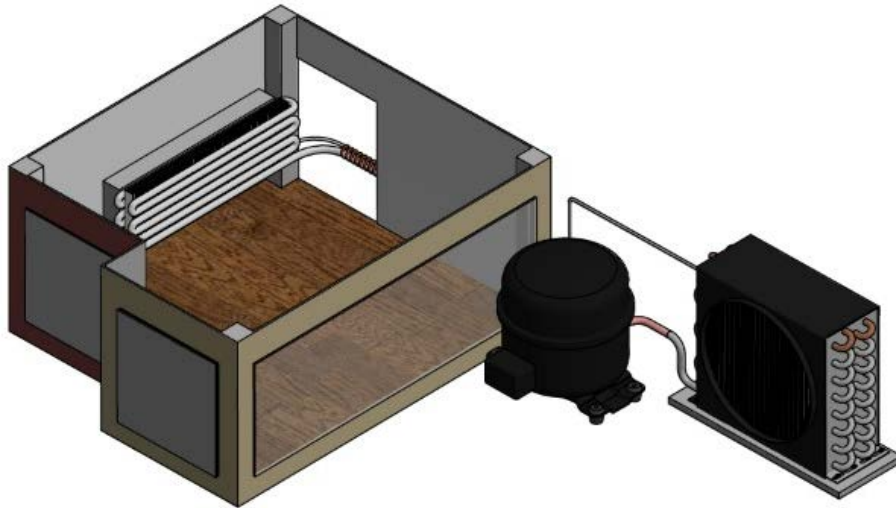


Figure 2: Refrigeration system CAD.

1.3. Project Management

This project has a maximum budget of \$300, so in order to stay within the range it is necessary to define which components can be recycled and which ones need to be new. For example, compressor, pump and fish pump were donated components. Some of these donated materials and equipment were obtained from Ecuadorian companies that are related to the area of study (Megafrio, SeingPro). New accessories are required for the water delivery section. The final expenses were close to the available budget and are detailed in appendix F. Additionally, appendix G contains a full Gantt diagram where all the project progress is reported on a weekly basis. The majority of the tasks were able to be done in a week or less. However, most of the algorithms' development took around a full month to be completed.

1.4. Engineering Standards

Applicable technical standards

- ASHRAE Standard 135-2016

This will help to learn about data communication protocols for building automation and control networks using BACnet.

- ASHRAE Handbook

This manual considers the four volumes with practical knowledge on the various topics inside the field of heating, refrigerating, air conditioning and ventilation. Here can find topics like maintenance of equipment, typical faults, and automatic control, among others. This will be important for the project because here it can found a lot of information or at least the basis for starting the design of energetic systems.

- ASHRAE Standard 188-2015

Since it is going to use a delivery hot water system, this standard is needed in order to know the risk for managing it.

- PIP PIC001 Piping and Instrumentation Diagram

This practice manual provides requirements for designers preparing Piping and Instrumentation Diagrams (P&IDs). Useful to know the correct order of the components and the symbology too.

- Normas y convenios del dibujo arquitectónico

The model scale building has components that needs to be specified where are exactly located like glass, columns, doors among other by using different symbols and colors. This manual is going to be used to know these constraints and how to draw them.

2. MATERIALS AND METHODS

2.1. Material and component selection

The problems to be tested were selected by industry recommendations. To maintain the idea of making test rigs akin to real life, the components selected need to be closest than the used in the industry. For each system, the components are the following.

2.1.1. Heating.

In this system, the fault is related to a wrong measure of temperature. The system to be built needs a water storage tank, heater, water pump, temperature sensor, and a pipe to allow water flow. All of them are selected to facilitate the calculation of the transfer function of the system.

To simplify the calculations the shape selected for the water heater tank is circular and it needs to allow a volume of 2 liters, this value is selected as a reference data. With this volume and doing an experiment using a little water pump available for fish tanks, the water flow found is 6.897×10^{-6} cubic meters per second. It has an output section of $\frac{1}{4}$ inch and for this reason the pipe is selected with the same size. At the output section of the water heater tank, the pipe which allows water out has the same dimensions but with a valve that controls the flow.

There are several options to heat the water, but the most common and simple are an electric immersion resistance, electromagnetic induction, thermal energy, and thermo electric tank. All of them achieve the goal of increasing the water temperature. In the industry, the most used is the third option using a burner. The selection of the water heating system will be carried out by the ordinal method corrected by weighted criteria, considering that the model to be built will be of a reduced scale.

- Solution 1, Electric immersion resistance. These are designed to be in direct contact with the fluid that in this case is water; in addition, this is a process that allows to control the water temperature through sensors or thermostats (Lennox & Aloï, 1960).
- Solution 2, Electromagnetic induction is a physical phenomenon that is caused by a voltage exposed to a magnetic field (Xue et al., 2018).
- Solution 3, Thermal Energy is the most used domestic system, this is given by the combustion of liquefied gas managing to heat any fluid type (Raluy & Dias, 2020).
- Solution 4, Thermo electric tank, basically it is a cistern which will consist of a resistance that will heat the fluid and by means of sensors or thermostats the temperature of the fluid is controlled, providing comfort to the user (Çağlar, 2019).

2.1.1.1. Selection methodology.

The most important selection criteria were: (To see the applied method refers to Appendix H.1.)

The valuation criteria considered are:

- a. Energy consumption, amount of energy used for specific operation.
- b. Construction price, amount of money needed to prepare the construction of the heating system.
- c. Thermal efficiency is the relationship between energy consumption and heat input.

The results are expressed in Table 1:

Table 1
Result Table of alternatives for heating water.

RESULTS					
Solution 1 > Solution 2 > Solution 3 > Solution 4					
Conclusion	Price	Energy	Efficiency	$\sum+1$	Weighting
Solution 1	0.2000	0.1333	0.0333	1.3667	0.273
Solution 2	0.1500	0.1000	0.0500	1.1300	0.260
Solution 3	0.1000	0.0667	0.0167	1.1833	0.237
Solution 4	0.0500	0.0333	0.0667	1.1500	0.230
			Average	5.0000	1.000

It has as a result that option 1 is the most optimal for the requirements of the construction for the model scale building.

The electrical heater was selected by calculating the necessary power to heat a certain volume of water in a determined time. In this case it is set as 30 seconds and the power given is 5.57 kW. In the market is found two options for this case, 5000W or 7000 W resistor, both with 120V of operation. A decision is needs to be made between, use less power than required and increment the heating time, or the other way around, it means more power and less time. For this work, the heating time is not necessary, the goal is to achieve the set point temperature, with this idea is selected the 5000W heater.

The heater needs a way to control on-off statements and allows PID to work. It is required a solid-state relay with an input signal between 3V and 32V DC that will be controlled by Arduino and an output AC between 24V and 380V to turn on or off the resistor. Similarly, the temperature sensor is essential to do a PID control system. For this purpose, the thermocouple needs to send signals to an Arduino that acts like the brain of the automation process, so this component only needs to achieve this goal, measure the temperature, and send the signal. The Figure 3 shows the components of the heating system.

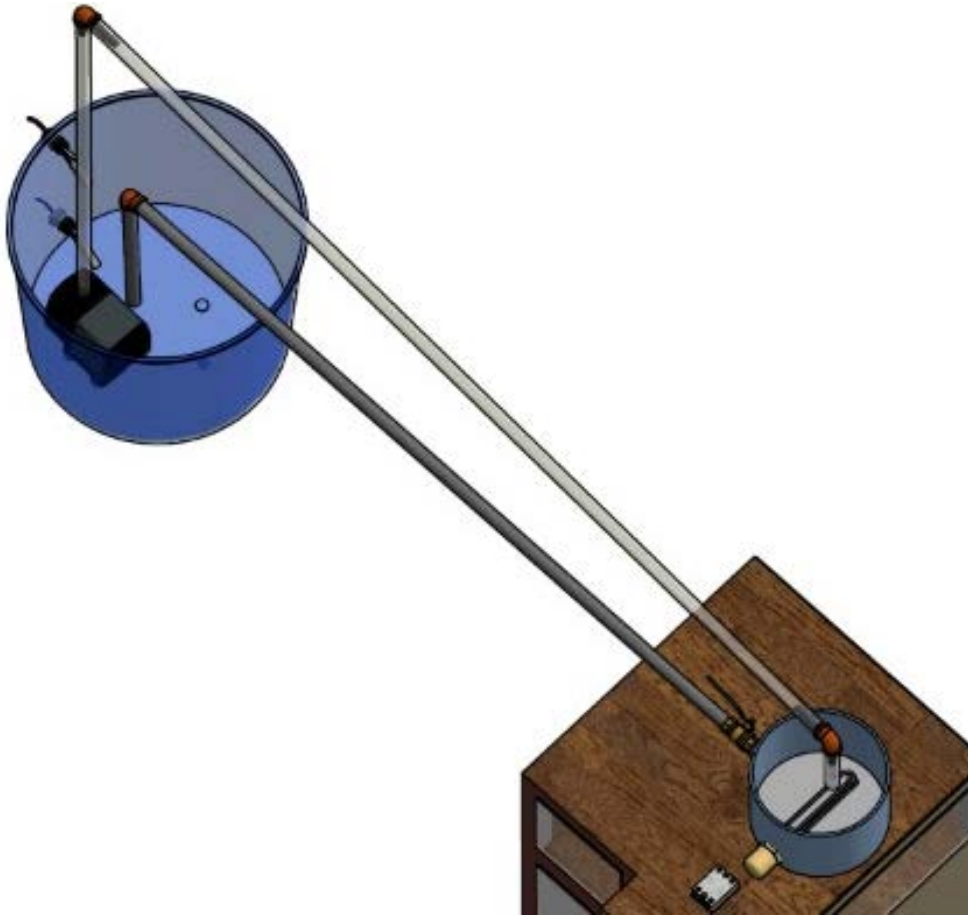


Figure 3: Heating components.

2.1.2. Refrigeration.

For this case, it is needed to take into consideration the fault that will be detected in this system: the unexpected temperature change. The components that are going to be used are a compressor, an evaporator, a condenser and a capillary or an expansion valve. These are the usual components that the industries use to refrigerate a cold room.

Since this project is going to simulate common problems that can happen in real life, common components like refrigerator compressors will be used. The available compressor that was selected has $\frac{1}{4}$ HP of power and because of this the evaporator and the condenser were chosen given the compressor data. Therefore, a $\frac{1}{4}$ HP evaporator and condenser were chosen. Also, the sensor that is going to be used for measuring the temperature of the cold room could be the same as the selected in heating part.

For cooling a cold room, it is necessary an expansion valve or a capillary; to complete the refrigeration cycle. If this component is not used, the pressure of the refrigerant cannot go down and it is not going to regulate the flow of the refrigerant, making that the fluid does not become liquid and can enter the evaporator. The selection will be made using the same method as in the heating system:

- Solution 1, Expansion valve. It regulates the injection of liquid refrigerant to the evaporators. This injection will always be regulated by a thermostatic element that is located at the top of the expansion valve, which is controlled depending on the overheating of the refrigerant. The use of this component depends on the pressure drop across the valve, internal or external pressure equalization, refrigerant, evaporator capacity and evaporation pressure and condensing pressure (García del Valle et al., 2020).
- Solution 2, Capillary. The difference with the expansion valve is that the coolant goes through a fixed hole. It cannot regulate or control the amount of refrigerant entering the evaporator. It is used in small equipment as in air conditioning applications and home refrigerators (Parmar & Atrey, 2020).

2.1.2.1. Selection methodology.

The most important selection criteria were: (To see the method applied refers to Appendix H.2.)

The valuation criteria considered are:

- a. Price, the cost of the component that is going to be used.
- b. Size, the size that the system has, and the component can cover.
- c. Pressure drop, the enough amount of pressure that the fluid has in the system.

The results are expressed in Table 2:

Table 2
Results for the refrigeration system.

RESULTS					
Solution 2 > Solution 1					
Conclusion	Price	Size	Pression Drop	$\Sigma+1$	Weighting
Solution 1	0.0556	0.1111	0.1667	1.3333	0.4444
Solution 2	0.1111	0.2222	0.3333	1.6667	0.5556
			Average	3.0000	1.000

The best solution that can be used is the Solution 2. It is necessary to use a capillary to complete the system and make it work the right way. This solution is the one that adapts better to the conditions that the system has. The most important conditions are the pressure drop and the space that is going to be refrigerated.

The pressure drop is low because is a small system, so the pressure obtained is not going to work with an expansion valve. So that to select the diameter and the length of the capillary the heat load of the system and the temperatures of evaporation, condensation and return gas must be considered. To do this selection, a program where the capillary can be selected is used, having as results that the length must be 1.51 meters and the inner diameter must be 0.044 inches. Figure 4 shows the refrigeration components that were selected.

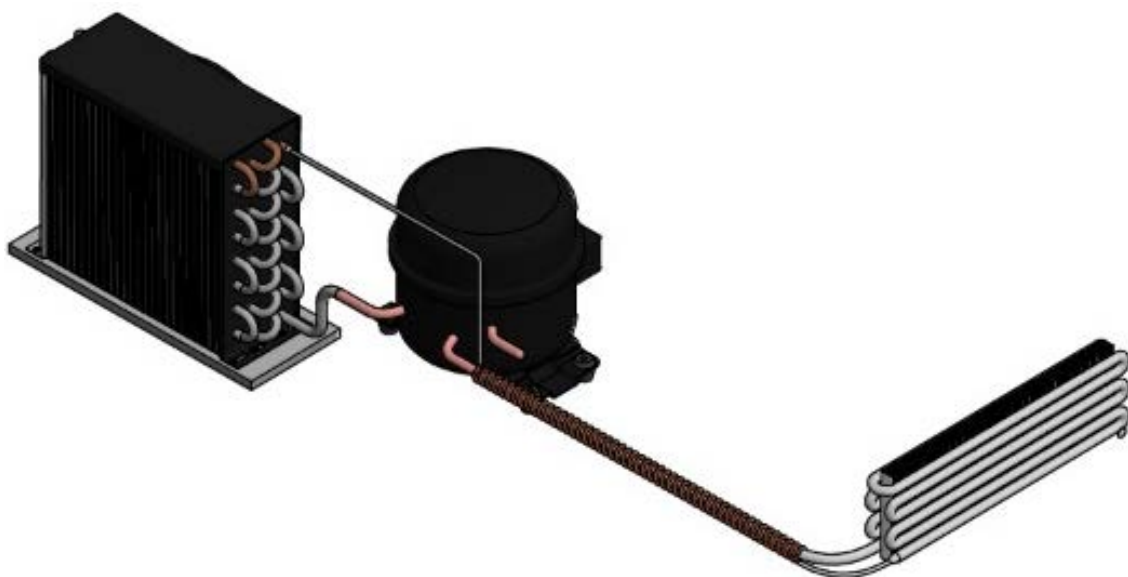


Figure 4: Refrigeration components.

2.1.3. Water supply.

For this system should be considered that five problems will be detected. The main component in this system is the pump. The one to be used is part of Leo Group (APm37) and given the budget, this was not selected, it was taken between some components available to use. It is working well, and it is in perfect conditions but before using it, maintenance was required. It is a peripheral pump of 60 Hz; another detail is that it has inlet and outlet of 1 inch. Therefore, it is a condition to select the pipe. For all water supply system, the material for the pipes is PVC with relative roughness of zero (smooth pipe).

The first problem to be detected is when the pump stops working. For this it is needed to have a flow sensor at the outlet of the pump. If the flow meter prints zero something is happening in it. This sensor also helps to detect another problem related with the foot check valve because if this valve is working well, the pipe at the suction is always full of water, and when the system starts, the water immediately is going to go through the sensor. If this component has a fault, the water goes down and the pipe will be emptied. If one minute passed since the pump is turned on and the sensor marks zero or a flow value different from the expected, it means that this foot valve is failing.

Given that, the diameter of suction is 1 in, all the components along this portion should be the same size. The third problem is cavitation. To achieve it, throughout the pipe is needed to have two ball valves closed at 2/3. In this part exists other accessories like a 90° elbow, and a tee for the suction manometer, also is used a threaded union to facilitate the assembly of this section. Thus, all components selected before are threaded and made of PVC, except the manometer.

In the outlet part that is delivery of water from the pump, there is no more faults to be detected, thus it is not necessary to put extra components. Pipe and all components are one-inch size. This section has a flow sensor $\frac{3}{4}$ in, that helps in problem detection, so it is needed

a diameter reduction to join the pipe with the sensor. This portion has a 90° elbow, a tee for the manometer, and a diameter reduction for flow sensor.

The next problem are the leaks in the tank that stores the water that will be suctioned by the pump. In this case to detect this problem two sensors of water level are located on the tank, and it controls a solenoid to allow the flow. When the solenoid is open, the low-level sensor starts a timer that stops when the high-level sensor is on. If this time is more than the normal, it means that there exists a leak in the tank.

Water delivery section needs to be calculated in order to have a constant flow through this part. When these calculations were made, the value found was between two options of pipe sizes: the first one is ½ inch and the other is ¼ inch. Using weighted criteria like described below.

2.1.3.1. Selection methodology.

The most important selection criteria were: (To see the method applied refers to Appendix H.3.)

The valuation criteria considered are:

- a. Availability in the market.
- b. Lower price.
- c. Accuracy in the calculated result, shown in the section water delivery in engineering analysis.

The results are expressed in Table 3:

Table 3
Results for the water supply system.

RESULTS					
Solution 1 > Solution 2					
Conclusion	Availability	Price	Accuracy	∑+1	Weighting
Solution 1	0.3333	0.2222	0.1111	1.6667	0.5556
Solution 2	0.1667	0.1111	0.0556	1.3333	0.4444
			Average	3.0000	1.000

The solution 1 related to ½ inches size is the best option because is the cheaper one and the most available in the market like the components that will be used. Also, the value is closest to the calculated given an accurate result.

All the next components in the system must have the same size, a manometer, a ball valve to regulate water flow, 90° elbow and joins, flow sensor and two water level sensors to measure and calculate the tank fill time as shown in Figure 5. Another fault is that the solenoid is stuck. To do it is necessary to send the sensors signals to the solenoid, using electronic components described in the next section.



Figure 5: Water supply components.

2.2. Electric components and connections

2.2.1. Heating.

For the heating system, the input signal will be the seventh port of Arduino. This is given by the temperature sensor that will be submerged into the water heater tank at 1 centimeter to the base. The output will be the sixth port and it depends on the PID code programed. At the output of the solid-state relay (SSR), the heater resistor will be connected

by cutting one wire and making a bridge on it. When the Arduino sends the signal to the SSR, the contact will be closed, and the resistor will start to work. Refer to Appendix P.1.

2.2.2. Water supply.

This system has two different connections. One is for cavitation that has an independent connection because the sampling frequency is bigger than the other sensor signals. To achieve a different signal processing, a separate Arduino is required. To measure the vibration signal in each axis a sensor with six degree of freedom (MPU-6050) is going to be used. Refers to Appendix P.2. The remaining components will be connected to the same breadboard used for the heating system.

For this case, the MPU-6050 sensor is connected like described in the appendix referred above. To do the water level sensor connection push buttons will be used but can be replaced for water level sensors because both act-like logical operators. Below the push button a 10 kilo-ohms resistance is required to maintain the logic state when the buttons are not being pressed. Specifically, for this case a pull-down resistance is going to be used because when the button is not powered, the state is low and when it is pressed, it changes to high (Blauvelt, 2004).

Then these buttons send signals to the Arduino's port number four for the low-level sensor and five for the high-level sensor. The next step is to connect the solenoid due to this component requires more voltage than the given by the Arduino. It is necessary to use an external voltage source of 9 volts or 12 volts, and it will be handled by a transistor T1P122 and a diode to polarize the signal. All this information was taken from an Arduino forum. For the same reason described for push buttons, the transistor is going to use a resistance pull-down of 10 kilo-ohms.

The flow meter sensors are very easy to connect. It only needs to connect one pin to ground, another to the voltage source of the Arduino and the last one is connected to an Arduino's port. In this case the flow sensor for the pump is connected to the port number three and the sensor for water delivery to the port two. The Appendix P.3 describes all the connections for the water supply system. Table 4 shows a detailed list of the components, which system is related to and the function that fulfills.

Table 4
Electronic components with input and output ports.

Component	Related to	Input port	Output port	Actuate
Thermocouple	Heating	6	-	Send signal
SSR	Heating	-	7	On-off Resistor
Flow sensor 1	Water delivery	3	-	Send signal
Flow sensor 2	Pump outlet	2	-	Send signal
Solenoid	Water delivery	-	9	Power the solenoid
Water level low	Water supply	4	-	Step signal
Water level high	Water supply	5	-	Step signal
MPU 6050	Cavitation	2 (A.UNO)	-	INT
MPU 6050	Cavitation	A4 (A.UNO)	-	SDA
MPU 6050	Cavitation	A5(A.UNO)	-	SCL

2.3. Design for Manufacturing

Since this project consists of a test rig for energy systems rather than a one item or piece fabrication, there is not only one fabrication process that will be required. Therefore, various parts and materials will be purchased to be processed and assembled by hand as much as possible. What cannot be done by hand, a third party will be in charge.

In order to reduce expenses some of the pipes are recycled from previous projects. Also, some components such as the pump, evaporator, and condenser are second-hand parts that can still be used. Additionally, assembly costs have been reduced to almost zero because it has been mainly done by team members. There are a few manufacturing and assembling tasks that need external assistance and are detailed in the following manufacturing plan diagram:

Table 5
Manufacturing plan diagram

DESIGN	MATERIALS SELECTION	PRODUCTION
<ul style="list-style-type: none"> • Building <ul style="list-style-type: none"> • CAD drawing. • Heating System <ul style="list-style-type: none"> • Cad drawing. • Design performance and behavior for: <ul style="list-style-type: none"> • Heating system. • Refrigeration system. • Building. • Calculate dimensions. 	<ul style="list-style-type: none"> • Building <ul style="list-style-type: none"> • Wooden sheets and columns. • Glass sheets. • Glue for wood and glass. • Bolts and screwdrivers. • Paint. • Heating system <ul style="list-style-type: none"> • PVC pipe. • Elbows, tees and a die for the threading. • Refrigeration System <ul style="list-style-type: none"> • Cooper tubing. • Capillary tube. • 1/4 hp compressor, condenser and evaporator. 	<ul style="list-style-type: none"> • Cut <ul style="list-style-type: none"> • Wooden sheets (hand saw). • Glass sheets and wooden columns (outsource). • PVC pipe sections (hand saw). • Threading <ul style="list-style-type: none"> • PVC pipe (die). • Assembling <ul style="list-style-type: none"> • <i>Building</i> <ul style="list-style-type: none"> • Screw wooden sheets and columns. • Glue together wooden pieces and let them dry. • Glue the glass sheets and let them dry. • <i>Heating System</i> <ul style="list-style-type: none"> • Connect all pipie sections and accesories.

The building itself consists of three levels, two identical ones and the other one with twice the height of the other two levels. Regarding its structure it only needs to hold very

light parts or objects. Therefore, it does not need great structural resistance and light materials like wood are used. All the parts that need to be cut to size are detailed in Appendix I.2. The columns need to be tightly screwed to their respective wooden sheet; no looseness should be allowed between parts. Then every wall will be joined with white glue. After the base building structure is assembled, every glass sheet needs to be glued into place. Spreading the glue uniformly over the glass and wooden surfaces is important in order to minimize space between window and wall and reduce infiltration. Enough drying time needs to be allowed to properly join every element. Appendix D contains a detailed building plan with all the expected dimensions of the assembled building.

Regarding the water transport system, all the required pipes can be cut to their respective lengths with a hand saw and threaded by employing a die. When connecting pipes to the accessories some thread sealing tape should be applied on the threads to produce high quality sealed joints. For the heating system, there are two level sensors that need to be attached to the main water storage tank. Since it is a plastic container, the tank can be easily perforated with a drill, screwed, and sealed to hold the sensors in place. Another manufactured and assembled element is the structure that holds the pump in place for the cavitation system. The main parts (base, columns) are cut out of MDF and tightly screwed together in order to assemble it as shown in appendix D. A manufacturing schedule is detailed in Appendix I.1.

3. RESULTS AND DISCUSSIONS

3.1. Design Report

3.1.1. Heating system.

A water heating system requires a heat source, a hot water tank, a recirculating water pipeline and a pump that feeds the hot water cycle. However, components have also been added to automate the system, such as the solid relay and the thermocouple.

The main storage tank has great importance in the system, it should be designed depending on the amount of water required. Another important issue is the material, but since it is a scale model that aims to indicate the operation of the diagnostic system, it is not necessary to comply with the standards that indicate good manufacturing practices. The hydraulic fish tank pump is intended to give movement to the hot water in the circuit. This is an electric pump that has the adequate capacity to move the necessary amount of fluid from the main storage tank to the tank located on the top of the building.

One of the most significant elements of the heating system is the piping circuit since it allows to increase the efficiency of the system. The correct design of the lines allows significant savings in water consumption, and even recirculation ensures that the hot water reaches the point of consumption (Ambiente, 2015).

Inside the storage tank the immersion resistance is coupled, it is designed to heat the fluid by direct contact, allowing the water to heat in a short period of time, as it reaches its maximum energy performance. Similarly, there is a thermocouple that indicates the water temperature to the system, giving the ability to indicate to the system whether or not to turn on the resistance, in order to keep the water at a certain temperature. At the end of the output pipe a ball valve has been added to control the recirculation of water from the heating cycle.

In the previous paragraphs all the components used for this system was described to expand the knowledge about how it works independent. The thermocouple and the resistor need to be separated enough allowing to take right measures. Figure 6 shows the system. All detailed calculations refer to Appendix A.1.

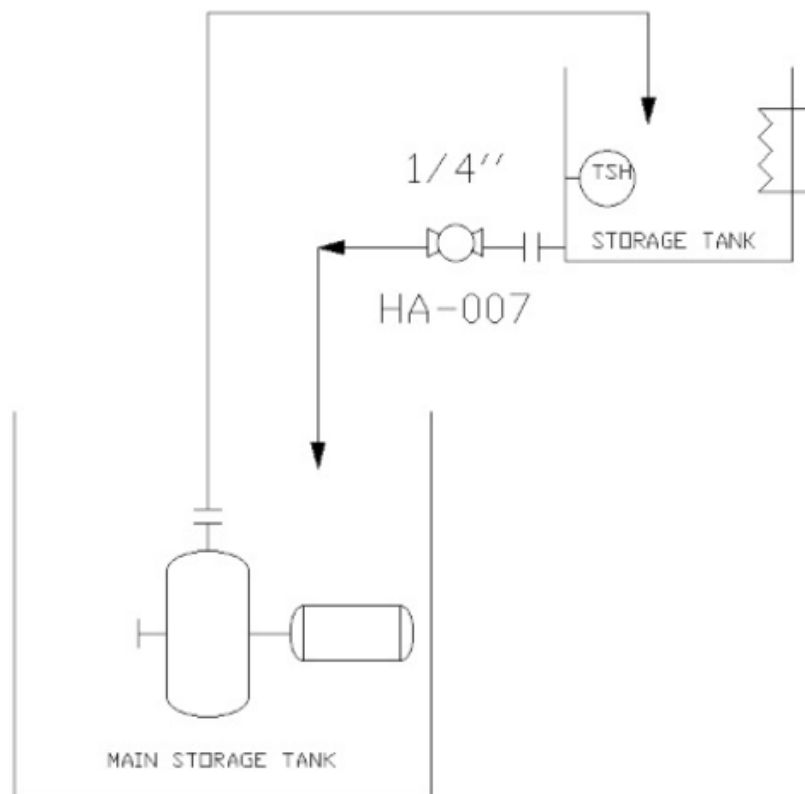


Figure 6: Heating P&ID sketch.

3.1.2. Refrigeration system.

The cold room is designed using a refrigeration cycle. This system has a hermetic compressor that allows the circulation of the refrigerant to be mechanically forced within the refrigeration cycle, creating high and low pressure zones, resulting in the ability for the fluid to absorb heat in a certain place and dissipate it in another (HVAC & R World, 2014).

The condenser is another of the main components of the cold room. This is a coil where the pressurized gas is expelled by the compressor changing its state into a liquid due to the refrigerant getting compressed. During the transport of the refrigerant through the

condenser, the cycle allows heat to dissipate through all the copper pipes to the environment in such a way that this process generates a loss of heat that is given by the compression process and by heat that was absorbed during the course of the evaporator (Franco, 2006).

The capillary creates a pressure difference between the low and high sides of the cycle. It is connected between the condenser and the evaporator because its small diameter causes a pressure drop in the refrigerant, managing to expand it for the evaporator inlet. On the other hand, it is important to have the knowledge about the function of the capillary which is the same as an expansion valve. The difference is that the valve is used for systems with a higher thermal load capacity because it has the capacity to vary the refrigerant flow depending on the need of the evaporator (Bright Hub Engineering, 2009).

The evaporator is the component that is inside the cold room. It is in charge of performing the heat exchange between the refrigerant and the room environment. The expansion given by the capillary generates changes in the fluid, causing its temperature to drop. For this reason, during the evaporation process, the fluid is at low pressure and temperature, allowing it to absorb heat from the environment. As a result of this heat transfer, the refrigerant gets vaporized when it is leaving the evaporator (Bernard Refrigeración, nd). This is the simplest assembly to refrigerate a certain space.

The next figure describes the order of the components. All detailed calculations refer to Appendix A.2.

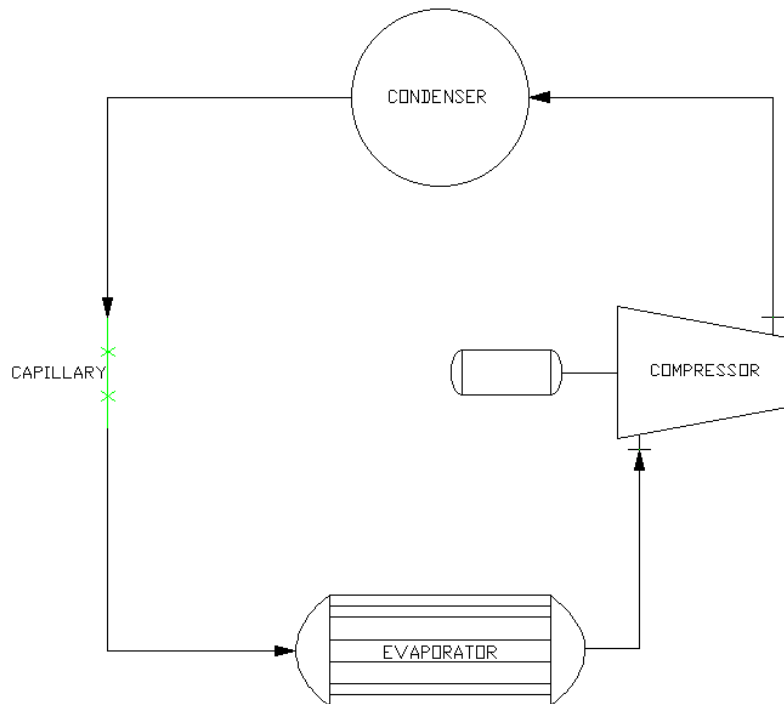


Figure 7: Refrigeration P&ID sketch.

3.1.3. Water supply system.

This section is composed of two independent lines of piping. The first is in charge of supplying water to the main tank from a water source, while the other carries water to the pump suction line.

The pipeline that is in charge of supplying water to the main tank is made up of a manometer that indicates the water pressure at the filling point. It will indicate some value only if the ball valve is obstructing the passage of the fluid. If not, it will show zero. When the valve is open the fluid will be in motion. To measure the flow there is a sensor that is responsible for sending a signal indicating the amount of water. Finally, a solenoid is in charge of allowing the passage of water depending on the water level sensors located on the main tank, which indicate if it requires water or if it contains enough to continue its functions.

The cavitation line has a greater number of accessories, in order to increase the loss of pressure and cause cavitation in the pump. It is also a line that recirculates the water from the main tank. It has a foot valve that maintains the water flow within this line so that the pump

always has water when turning it on. To increase the loss of pressure by a large amount, two ball valves are partially closed, allowing cavitation. To visualize this effect, transparent tubing has been placed, which is represented in the P&ID sketch as the green line, in which the state of the fluid caused by this anomaly can be observed. It is also necessary a vacuum gauge manometer which is located before entering the pump, which will indicate a negative pressure when the pump is having this hydrodynamic effect.

The next part of the line is characterized by the pump, being the essential equipment, which absorbs the hot water from the main tank. In the return line there is a manometer which indicates the discharge pressure of the pump, and a reduction in the diameter of the pipe from 1 to $\frac{3}{4}$ inch, due to the suction line has a diameter of 1 inch and the flow sensor available in the market has $\frac{3}{4}$. Similarly, there is a ball valve that allows the water flow to pass or not. The Figure 8 describes the right position of each component, all of them threaded. All detailed calculations refer to Appendix A.3, A.4 & A.5.

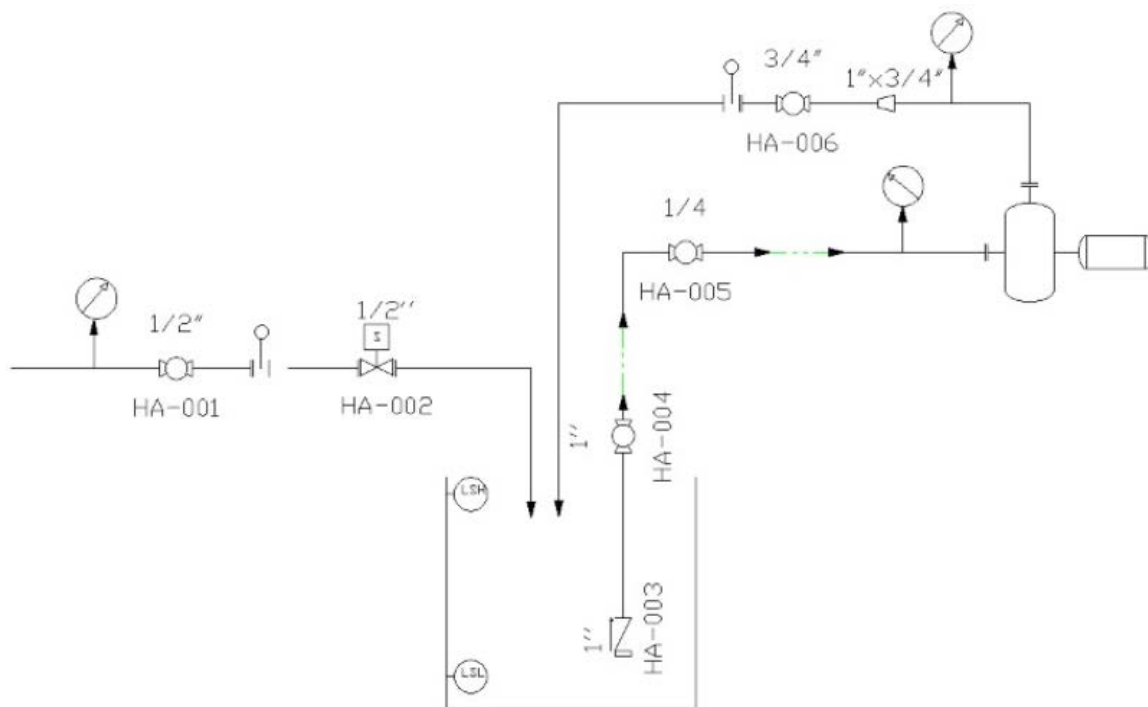


Figure 8: Water supply P&ID sketch.

3.2. Fault detection algorithm

In this section will be described one way to detect faults using machine learning algorithms to predict or classify the behavior given by the sensor. Also, if statements are going to be used to compare the status of the systems. Before to start with predictions, it is necessary to filter the data acquired by Arduino signals, it needs to be sampled with $F_s = 4 \text{ Hz}$. The data will be imported from Arduino to Python, but the signals enter mixed because the system have several sensors.

The first filter needs to organize all of them with a maximum of 50 values in the master dataset. It gives a total time of $T_s = 12.5 \text{ s}$. Then, it is required to separate the signals and store one by one in an independent array for each sensor. This dataset will repeat when the number of samples for the master data set reach the maximum allowed, so it is reseeded, and the process starts again. For each sensor the dataset will have 10 data.

The master dataset has 5 signals, the first and second of them correspond to the sensors of low and high-water level. In fact, these are not signals because only send two values, zero for open sensor and one for close, representing that the water tank is full or empty. For this reason, these two values do not need to be sampled or filtered but it is essential that these have their own independent array.

The third signal is given by the water temperature sensor. The fourth correspond of water flow sensors for water delivery and the fifth for output pump section. These last three are analog signals. In the next pages, the code to solve every failure occurred in the correspondent energy systems are explained.

After assuring the correct operation of the sensors, the recorded data is accepted as valid. The data filtering methodology employed (rectangular window) correctly processed them (Ingle & Proakis, 2012). Independently of it being a simple data filtering practice, it fulfills the task of allowing values within the established limits to be recorded. It is correct to

use this filter because the sampling frequency of 4 Hz used along the algorithm (except for cavitation) is low.

3.2.1. Heating.

The fault is related to the temperature. In optimal conditions, the PID will work well and the temperature will be around 40°C. As long as it stays in this range, no faults will be detected. If something happens with the electrical heater, and it is burned or disconnected the temperature of the water will start to decrease smoothly. It means that the analog signal for the temperature sensor will not have peaks.

In this case, the PID will continue working and sending the order to SSR to activate the heater but given that is failing this will not happen. The other case is a fault in the sensor. Testing this failure if it is burned the temperature decreases considerably drawing peaks on the signal. This difference is described in the experiment section.

The first step is to filter the samples given by the temperature sensor, corresponding to the third signal of the master dataset. In order to do it, it is necessary to know the main characteristic about the transitory response of the system shown in the Figure 9.

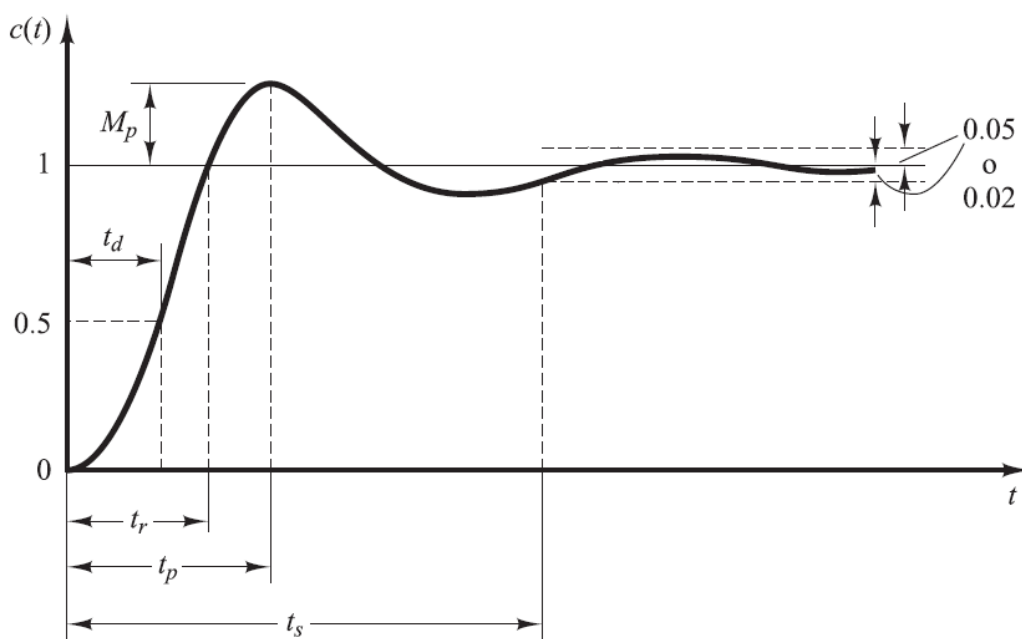


Figure 9: Curve response with unit step exemplifying PID behavior.

Source: Ogata, 2013

In the figure presented above is described the most important definitions to understand the behavior of the signal curve. In the PID design section appears terms like max over-elongation $M_p = 10\%$, settlement time $t_s = 30\text{ s}$, and the allowable tolerance that is recommended to be between 2% and 5%. In this case the value of 0.02 tolerance is going to be used, this represents the amount of temperature that can oscillate from the set point when the signal is stabilized (Ogata, 2013).

When the system is still in the transitory section, the sampled values are fluctuating, and it does not allow to take good measures about how the components are working. In this first value of raising time (t_r), it is possible to analyze if the PID reaches the set point desired in a correct range of time.

When the system is stabilized and the temperature samples are around 40°C, the components can be analyzed. The first step is to get the mean of the temperature array named “Temperature” and append it in another array (DataTemp). Each time that a new mean will be append, a counter (sd) will sum one. This helps to give a number of mean samples (NS) for learning period. The code in appendix C.1 explains how to obtain the mean of the first array and the rectangular window filter to identify when the system is stabilized.

Simple linear regression is a technique for modeling the relationship between a dependent variable (temperature) and one or more independent variables, like time. The linear equation shown below has two coefficients to be found in the best way by the algorithm (Ao et al., 2019).

$$y = a_0 + a_1x$$

In order to minimize the difference between the real value and the predicted one, it is necessary to define another concept that is related to the average square error (J) by using cost function also called mean squared error, this tends to zero when the prediction is

accurate. Also, it is usual to use R2 score, which is the percentage of variation of the response variable. If more samples are appended this value will increase and tend to one.

$$J = \frac{1}{n} \sum_{i=1}^n (\text{predicted}_i - y_i)^2$$

For this linear regression code, some libraries are called in the beginning. When NS reaches the set value, the linear regression starts by finding the constants, and then the model will be fitted, and the prediction value will be defined (y_p). To do a linear regression like the described in the code in appendix C.2 is necessary to have the number of samples taken (NS) to train the algorithm.

When the linear regression is completed means that the counter will be greater than the number of samples given to learn. This projection is useful to know how the temperature increases depending on the number of samples taken. Using this idea, after a certain number of samples, the temperature reaches the maximum allowable temperature by the PID in steady state. Then, the system will recirculate hot water so that the resistor does not need to be turned on, because there will be no immediate drop in temperature in the incoming water. Using linear regression projections, the number of samples will be found. This code can be found in appendix C.3.

Then, the error is set as an indicator for the precision between the next data and the expected in the model. In order to visualize it in a best way the decisions taken by the algorithm, the main idea will be resumed in a decisions tree based on the error of the mean and is shown in Appendix K.1.

The code in appendix C.4 is used to translate these decisions tree using the definition of percentage error and if statements. In this algorithm the fault detection is made.

3.2.2. Water supply.

This system has several problems to be detected. The first one and the easier of all of them is to detect when the pump is not working. To detect it, sensor 2 (located in the outlet of the pump) is used. This signal is the last data of the master dataset. To detect it, this sensor only prints zero values or at least three in a row, when it happens, the system assumes that the pump has stopped, or something went wrong in the system. In such case, this is going to send a warning message. The code in appendix C.5 shows this idea in a few lines.

The second problem is related to the foot check valve. This is a very common problem among high pressure pump users and can generate very expensive problems, because when the pump is turned off, this valve should maintain the pipe full of water, so when the pump will be turned on again. This stagnated water immediately goes to the pump, refrigerating it and allowing it to work well. If this valve is damaged and allow that the water goes down, when the pump will be turned on, in the suction pipe there will be not water, causing the pump to work without being refrigerated. In less than a minute working like this, the impeller ceramic seals will be overheated, and the material will start to expand, making an irreparable damage on it.

Two actions are required to detect that this problem is happening. The first one is to set a timer that starts when the system is turned on counting until it signs 50 seconds, in order to keep the safety of the component. The other one is that the pump provides a water flow less than the expected. If it happens, a warning will be sent to the operator. If between 30 seconds the sensor signs an unexpected flow rate, but then works well, the code will send a warning showing that the foot valve is defective. Given that the operational point is around 2212 L/h, and when cavitation occurs it is reduced to 1140 L/h, set point value will be

defined in 1000 L/h. The next code explains this idea. The code in appendix C.6 shows this idea.

The third problem to be detected is cavitation in the pump. To do it, it is necessary to have another Arduino only for this fault. Due to the sampling frequency is different for this sensor since it is required to have more accurate measures over time. The sensor MPU 6050 is set with a sampling frequency of $F_s = 15 \text{ Hz}$. This sensor is programmed to send three different signals, one per axis, and another for linear acceleration component. When these signals are storage in independent arrays, the next step is to take data and storage it in an external document, to be treated later in a Python code.

For this case is necessary to implement another algorithm used in supervised machine learning named K-nearest neighbors (KNN). A supervised machine learning algorithm has labeled input data to learn, in this case the labeled data are cavitation or not cavitation, but there are expressed as 1 or 0 respectively. Moreover, the KNN method allows to make a prediction if the newly inputted data values are going to belong to which group (cavitation and non-cavitation). The other data points are the signals described before (MPU 6050). This algorithm uses the information of the nearest points and use it to assume that this point should belong to this classification, in other words, if a new point is printed between four of some specific classification, it means that this new point should belong to this group. The Appendix K.2 describes this definition using five nearest neighbors (Bhattacharya et al., 2012).

The code in appendix C.7 uses a data set with 1498 samples for each case, cavitation and not cavitation. This will be separated in four variables, two for training and two for testing, this is useful to know if the algorithm is working well because, when the train set is fully developed it starts to make predictions and compare with the test set, giving a score of correct answers. An important term is the number of neighbors to choose. To do it in a good

way the algorithm should be run several times changing this value and comparing with the previous score (Bhattacharya et al., 2012).

This code is useful for this case because it can compare each new point given by each sensor axis, starting a counter that will give the number of points that are cavitating or not in order to know what is happening with the pump. The code in appendix C.8 explains the idea of this fault detection algorithm.

The last two faults to be detected are the solenoid is stuck or disconnected and leaks in the water tank, both are related to each other, because the solenoid feeds the water tank. In order to detect the faults, several combinations of the three available sensors will be developed. To do it deeper, the algorithm will detect all the stages, it means, when the tank is filling, emptying, already full and empty. Knowing the stages is easier to detect when the solenoid is stuck and cannot be closed or when the solenoid is disconnected and cannot be opened.

A timer will be set to measure the filling and emptying time, assuming that in the beginning, the system does not have problems. In this learning period, the algorithm will collect data in order to have a statistic mean of filling/emptying time. To do it, the water level sensors will work as logical operators, sending 1 for close sensor and 0 for open sensor. The timer should start when in an array the status change from 0 to 1 or vice versa, depending on the case. The algorithm that describes all the combinations possible are in appendix C.9.

The appendix C.10 explains the detection of all stages and problems using if statements to detect them in a very simple way. If both sensors are close and the flow meter is close, then the tank should be full.

If both sensors are open or the low sensor is recently open, the tank is empty. When this situation happens, the Arduino sends the signal to activate the solenoid, if this does not

happen, the solenoid is burned or disconnected and cannot be opened. Like described in appendix C.11, if the flow sensor is printing values it is assumed that the solenoid is open and the tank is filling. This idea is developed in appendix C.12.

If the water is over the low sensor and it still continues filling after the high level sensor is close, it means that the solenoid is stuck and cannot be closed because the flow sensor print values even after the Arduino sends the signal to stop the flow. This can be found in appendix C.13. The last stage is to detect when the tank is emptying. To do it, it is necessary to detect when the flow is stopped, and the high-level sensor is open. Refers to appendix C.14.

The last problem to be detected is water tank leaks. When the tank is empty a timer should start and when this is full should stop and storage this data in order to have a mean of these values. It is needed to design a filter for choosing the max value of time in the vector. To do it, the vector should have only values different from zero, also it is needed to stay under the maximum number of data that can be stored. When the mean is obtained, the next step is to get the percentage error between the mean and the next value, if it is over 5% the fault is detected. The algorithm in appendix C.15 describes this idea.

3.2.3. Refrigeration.

In this system the fault that is going to be detected is the unexpected change in the temperature. The sensor of temperature will measure the cold room's temperature at the set point of -14°C . While the temperature is in this set point, the system will work normally, and it is not going to have any faults. The cold room has a door that opens and closes to put in or take out the product. This door is usually open maximum for 30 minutes, if the time estimated is higher, a warning will appear notifying that the door is open and it must be closed, this will happen because of the change of the temperature that it is not at the set point.

Due to the system is not built, the data is not given in real time, so the temperature that is used in this project was acquired from a paper that is performing a cold room with the purpose of freezing blocks of ice. The data was saved in an external program with all the temperatures given in the paper. Also, exists the unexpected changes that are going to be detected as faults.

In the same way that heating was analyzed, the refrigeration system will be too. It means that at first, the data that the system is giving changes with time until it arrives to a steady state. When the system reaches the set point it starts to storage the data in an array that is going to append all the data and start learning how the data behaves.

The components are going to be analyzed when the temperature is at the set point of -14°C and the system is in steady state. The temperature obtained is going to be appended in an array (DataLearn) where only the values lower than -14°C are going to be taken. Then, if the temperature is higher than -14°C it will appear a message saying, “The system is not stable”, and those values are not going to be taken. Refers to appendix C.16.

The data that is given by the sensor of temperature is going to be processed in order to detect the fault, and this happens when the temperature starts to increase. The data is giving each ten minutes, so the program detects when the temperature is increasing or decreasing. If the temperature increases once or twice there is no problem but if the temperature is higher from the set point for three times in a row or more, it sends a warning with a message saying, “The door is open”. This message appears until the door is close, and the system returns to the set point temperature. This code is in appendix C.17.

3.3. Engineering experiment for verification

In this section all the calculations are going to be tested in order to know real data to improve the algorithm.

3.3.1. Heating.

As previously mentioned, heating has two problems; both depend on temperature measurement. It was necessary to test the PID for the heater resistor selected and find the right values for the settle time and rise time. The temperature sampled signal is shown in Figure 10 and it is important to highlight that the first peak is inside the expected like the steady state error.

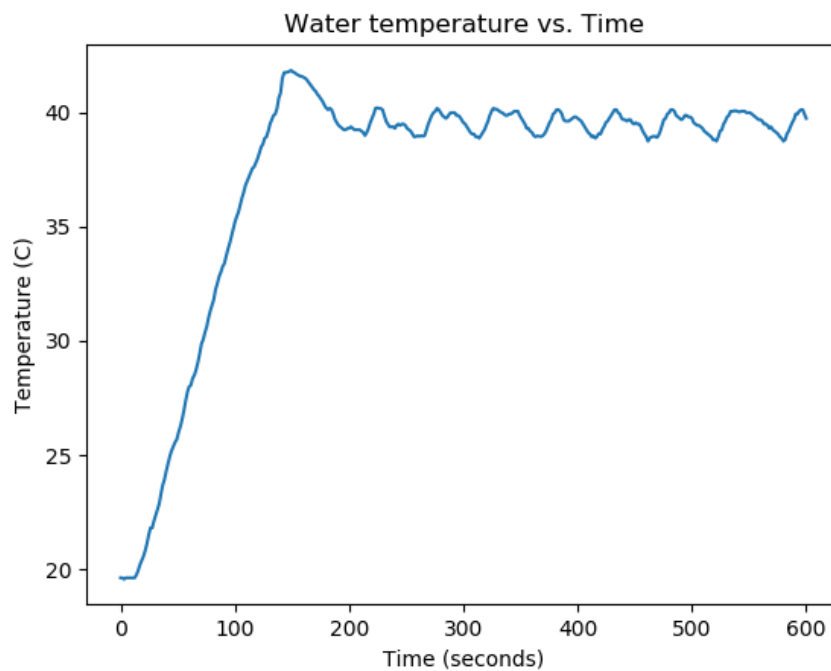


Figure 10: System's temperature change over time using PID real model.

The experimental PID has a similar behavior in its Y axis amplitude values with the theoretical one. However, values regarding time are uncertain and cannot be perfectly determined by any analytical method. Experimental data shows that the rising time (t_r) is of 2 min 10 s while the peak time (t_p) reaches 42.8 °C in 2min 22s. By observing Figure 19, it is

expected that the signal's behavior will stabilize right after reaching the first curve peak. Experimentally, the settling time was 3 min 02s, which is a value within a coherent range.

When the PID is stabilized, the minimum temperature reached is 38.1°C given an actual error in steady state of 4.75%, this value is inside the accepted range (2% - 5%), if it is not the PID is not working well showing a fault in the integrative constant (Ogata, 2013). This value is used to change the algorithm and modify the filter that detects if the system is stabilized or not. When the system reaches the number of samples for learning (NS), faults will be detected. The Figure 11 represents 200 samples and the linear regression produced.

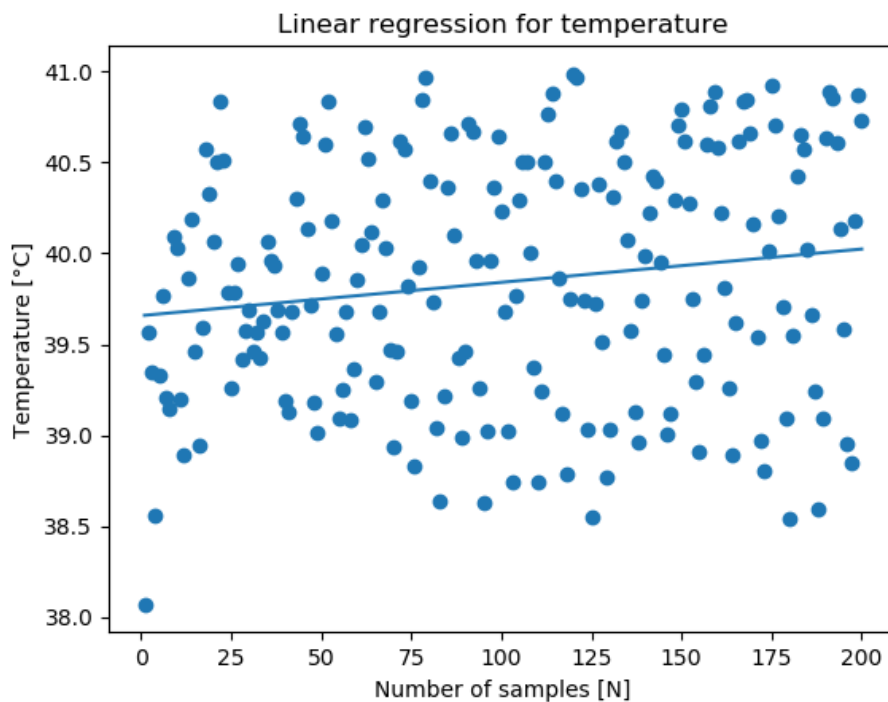


Figure 11: Linear regression model using temperature datapoints over number of samples.

This linear regression follows the increasing tendency of the growing temperature from the sampled data. Therefore, the model will represent the system's behavior within the allowed range of temperatures. Since the water is heated in the tank and then recirculated back into the main storage tank, it will reenter it with a higher temperature. Over time, all the system's water will be circulating at an almost constant temperature. Once the system starts

to stabilize, the regression model's increasing tendency will stop to represent the system's behavior.

In the following figures, two heating faults are shown:

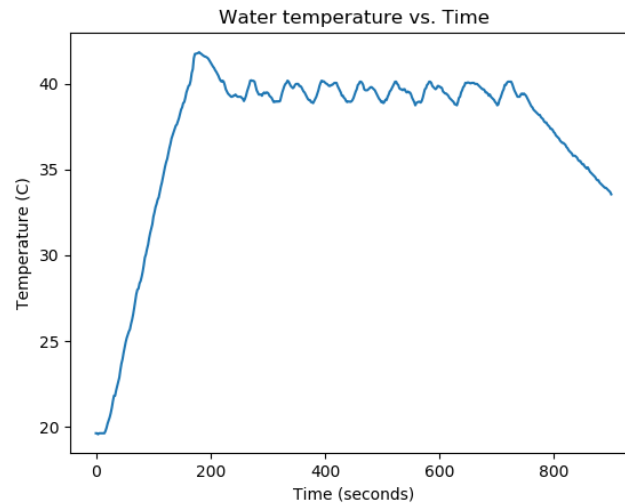


Figure 12: Temperature's behavior over time when resistor is disconnected.

For Figure 12, the electric resistor was disconnected, simulating a burned resistor. A 5.5 °C temperature drop over a 140 second time span is evidenced, showing a gradual temperature drop over time. Therefore, the PID control is sending a signal to turn on the heater. However, since the heater is disconnected the temperature decreases smoothly but progressively over time.

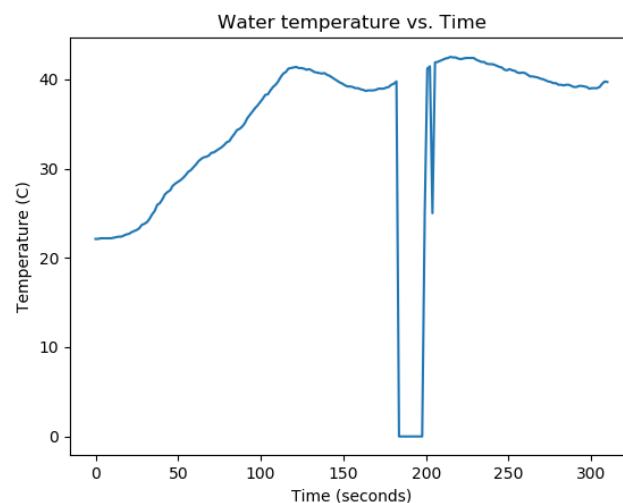


Figure 13: Sudden temperature drop over time when temperature sensor is disconnected.

The other fault happens when the thermocouple is disconnected at 170 seconds as shown in Figure 13. In this case the sensor gives a set value of 0°C , showing a drastic temperature drop whereas Figure 12 has a smooth and progressive one. Around 200 seconds, the thermocouple is connected again, and the curve returns to its expected behavior. This portrays the difference between these two faults.

3.3.2. Cavitation.

The next experiments show the data taken and processed by the sensor MPU 6050 for each system case. Figure 14.B shows the system's normal operation with its valves fully open. Figure 14.A shows the system's operation with its valves $\frac{2}{3}$ closed, generating cavitation. The sensor is sending data for two minutes. The X axis represents the total number of samples (1806 samples) and the Y axis shows the acceleration in their respective units $\frac{m}{s^2}$.

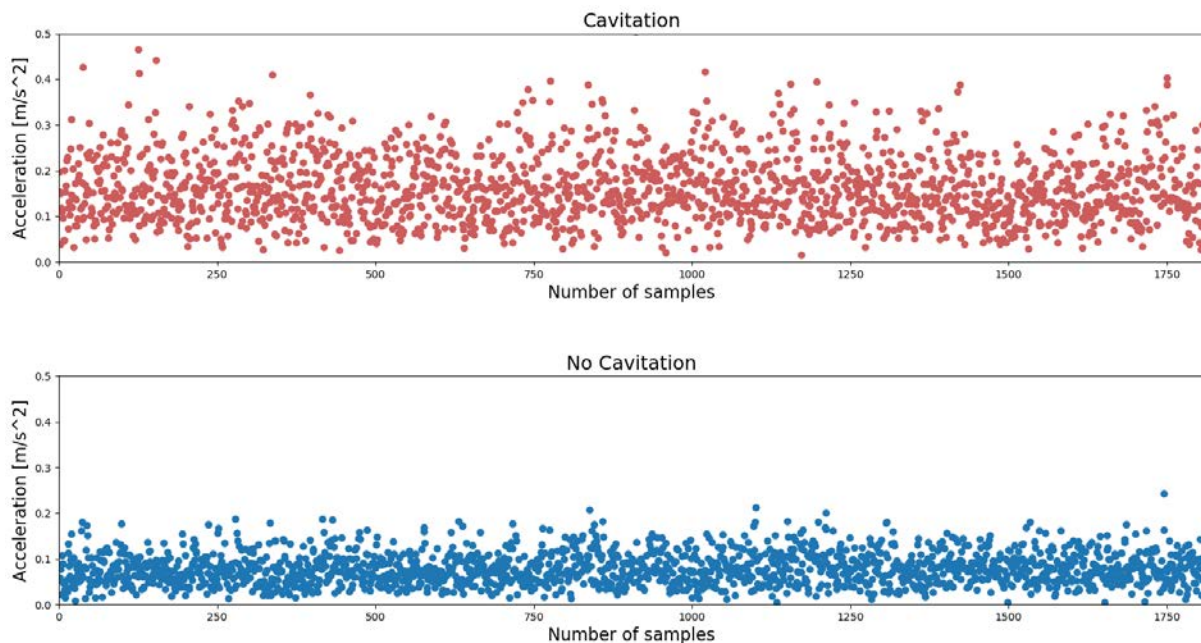


Figure 14: Linear acceleration data plotting for 1806 samples. A) Cavitation. B) No cavitation.

Figure 14 shows the difference in the system, when it is no cavitating the max value is around to $0.25 \text{ [m/s}^2\text{]}$ in the Y axis. On the other hand, when the pump is cavitating, the max

value is doubled and is around to $0.5[m/s^2]$. This shows that the data is different, and the algorithm can work well finding the nearest neighbors. However, it is important to give more data that feeds the code. To do this, the three axes are appended too. The Appendix L show the behavior of the data in each case.

The experiments show the change in data when the fault occurs; this helps to understand how the algorithm KNN works. To prove this data, it is useful to know the score of correct answers. Using the right code, it is found that with test variables the prediction accuracy is around 80%. This is a good enough achieved prediction accuracy because it is close to the percentage found in training set (86%) that is the maximum allowable for this data set. Showing that the algorithm is working well. The score value can change depending on the number of neighbors.

One common problem in machine learning is over fitting. It means that the algorithm does not learn from the data but just memorizes it and considers valid only data that is identical to the data train set. To know if the code has this problem it is necessary to test the score with train variables. If the score is 1.0, it means that the algorithm guessed right every time, showing that it only memorized the data train set. If not, it means that the algorithm learned well. For this case, the score is 0.86 (Bishop, 2006).

3.4. Prototype test plan

Table 6
Validation test per component.

Requirement	Test name	System	Check
Reach water temperature at 40°C	Heating system test	Heating	
Calibrate MPU-6050	Vibration test	Cavitation	
Water flow sensor	Flow-meter test	Water supply	

To validate the data given by the sensors it is essential to test it with an external equipment. For example, in the heating system the main objective is to reach the set point temperature, so results useful to take data with an digital multimeter with thermocouple and compare it with the given by the sensor used in the system. An allowable tolerance should be inside the error in steady state (2% – 5%). The next check list must be completed in order to validate the data taken by the sensor.

Table 7
Check list for heating system test.

Action to complete	Check
Connect the Arduino with the resistor and sensor	
Verify that the Arduino's port is the right one	
Run the Arduino's code together with Python's	
Wait until the message that the system is stabilized appears	
Turn on the digital multimeter with thermocouple	
Take data and compare with the shown in python code	
Verify if the temperature is around of the set point	

Another sensor that needs to be verified is the MPU 6050. To do it, it is going to be used science journal app from Google. It has an option to measure the same variables described before. To compare it is necessary to have data from both and using a computational software like Matlab compare each sample and get the maximum error, using a simple code line like:

```
error = max(abs(SciJournal - MPU6050))
```


This error must be less than 0.1. This percentage is big because this signal has several variables which influence over the data collection, even if both are in the same place. If this value is out of an acceptable error, the MPU could be wrong calibrated. The next check list should be filled to verify the good behavior of this sensor.

Table 8
Check vibration test.

Action to complete	Check
Connect the sensor to the right Arduino's port	
Calibrate the MPU using the library given for this sensor	
Run the Science Journal app	
Run the Arduino's code together with Python's	
Save both data in an external software	
Import the data to Matlab	
Run the code line described before	
Verify if the error is inside the expected	

The experiments developed before describe a way to prove if the machine learning algorithms have the right input data. The next sensors are related to "if statement" code part.

The water flow sensors should be tested by making an experiment with a tank and a timer, measuring the amount of water that is delivered in time and calculating the volumetric flow in liters per hour and then compare it with the data given by the sensors.

The next check list should be completed. An acceptable error between the measures should not exceed 0.05.

Table 9
Check list for flow-meter test.

Action to complete	Check
Have a tank with measure line in liters	
Have an accurate timer	
Connect the flow meter with the right Arduino's port	
Run the Arduino's code together with Python's	
Take data with the timer and calculate the water flow	
Verify if the error is within the expected	

The last sensor to be tested is the water level. These sensors should activate the solenoid, so the only way to know if it is properly connected is proving that the solenoid is working. To test if the algorithm is working well, it is necessary to force all the faults described to validate the fault detection. Using the operational manual section, all the faults should be acted upon to test the algorithm.

3.5. Safety through design

The risks that can happen in the system are:

- A. Water tank cracks can cause water leakage problems.
 - a. *Impact:* Causes an error in the filling of the water reservoir.
 - b. *Management strategy:* Completely turn off the heating system to continue emptying the water reservoir to apply a sealer with the necessary properties.

- B.** Debris or dirt can cause clogging problems in the pipe or valves.
- a.** *Impact:* Causes the obstruction of the passage of the fluid by increasing the pressure, it can also obstruct the valve not allowing to open or close it.
 - b.** *Management strategy:* Turn off the heating equipment and proceed to check the damage.
- C.** A bad installation or a breakdown in the sensors causes data collection failure.
- a.** *Impact:* It causes a bad data collection allowing the solenoid valve to open or close the passage improperly.
 - b.** *Management strategy:* Proceed to calibrate the sensors or change the unit, depending on the cause of the failure.
- D.** Not having the right pump.
- a.** *Impact:* Excessive water flow for the system.
 - b.** *Management strategy:* Find a way to control the flow delivered by the pump.
- E.** The compressor is not new, and it has irreparable damage.
- a.** *Impact:* The system is not going to work, and we need to buy another compressor that works well.
 - b.** *Management plan:* Do the necessary tests to verify that the compressor available is going to work with zero problems.
- F.** Exceed the cost in the components.
- a.** *Impact:* It is not going to be possible to simulate the other systems or to have any failures in the path because we are not going to have money to solve the problems.

- b.** *Management plan:* Make a list with all the components that we will use and try to buy the cheapest or try to make ourselves using additive manufacturing, among others.

G. Flow sensors not available

- a.** *Impact:* Causes a problem in the main design because it is needed that change the geometry or equipment distribution to adapt a new way to sensing data.
- b.** *Management strategy:* Find the availability of sensors in external markets or try to design two options, one with a pressure sensor.

The Appendix M.1 represents the probability and the impact that the components can have if any of them fails or do not work correctly. In the horizontal part is the probability that a component has to be damaged or not worked well, whilst the vertical part shows the impact of how hard it will be if any of the components have any failure. This table is important because this data can be used in the next table.

The Appendix M.2 shows the priorities of the risks from the higher to the lower one that the components of the project have. These are the possible problems that can be found in the components while the system is installing. The importance of each one of them must be taken into account and likewise know which causes more damage if it stops working.

3.6. Results, discussion, and conclusions

After all the previously presented analysis, there are various important results to be highlighted and discussed.

The experimental trials carried out for the heating system show two main aspects from the design. Although the PID's development is independent of the heat input it receives, it is important to consider the resistor's power so the system can reach the desired temperature. The 5000 W electric resistance chosen allowed the system to reach the set point. Higher power resistances could have been selected under the same conditions, allowing the system to reach the set point temperature in a shorter time. However, for the project's purpose the resistor's performance was acceptable and therefore its selection correct.

The resulting constants for the developed PID gave good results. When the system is stabilized, the steady state error was within acceptable values, showing the integrative constant T_i was correct. The settling time had the desired behavior too since the temperature curve stabilized right after it reached its first peak, showing a properly developed derivative part. Additionally, the proportional part allowed that the rising time and over elongation to be within allowed values. This indicates that the computational methodology employed was accurate.

The inverse engineering procedure followed for the cold room's design ended up in a resulting 0.1 m^3 of required space based on the component's characteristics. The established dimensions for the room were 0.4, 0.5 and 0.6 meters, giving a total 0.12 m^3 in order to properly fit the components for the system in the building's room. This small increase in volume would not impact the design's performance.

The characteristics that allows cavitation to happen are a combination of the height at which the pump is located, its suction pressure, the temperature at which water enters it and

all the present accessories that regulate the water flow along the system. The operational point of 3.150 m is taken as a reference value for the NPSHr. This value is compared to both NPSHa scenarios. For the situation when the ball valves are fully open, a NPSHa of 11.334m is found. In this case, NPSHa is bigger than the reference NPSHr which indicates that the system works correctly and there is no undergoing cavitation. On the other hand, when the flow is restricted with partially opened valves, the new NPSHa is of 2.950m. Therefore, cavitation will occur and the design of the system to force cavitation is validated.

Two machine learning approaches are used: a linear regression model and KNN model. The heating system uses a linear regression model to diagnose at what number of samples the system starts to recirculate hot water. This method allows to understand and predict the system's behavior within the limiting temperature values of 38.1°C and 42.8°C. After the regression is established, whenever the heating system starts to run, it could help to evaluate the system's behavior. However, it does not work to obtain future predictions because it has a linear behavior that does not adapt to how the system starts to act after a certain amount of time. Therefore, it is not correct to use this algorithm to predict the number of samples in which the temperature will go out of range.

The chosen KNN algorithm for cavitation detection works correctly with the four input variables selected (a_x , a_y , a_z and relative linear acceleration). The algorithm works more precisely while more input variables are included for comparison. The method was appropriately chosen because there was a significant difference found between the cavitation and not cavitation samples as portrayed in Figure 14. In order to verify that the algorithm is properly designed, an overfitting test was performed to corroborate that the algorithm is not memorizing but in fact learning from the data. As a result, the KNN algorithm shows an 86% precision in its predictions.

It is important to highlight that the majority of faults to be detected are programmed with if statements. For these cases it was not necessary to apply any machine learning methods to them because the employed sensors act as simple logic operators that need no further intricate programming.

In order to confirm the algorithm's proper operation, five experimental tests were conducted to force every desired fault; they all validate the algorithm's expected performance. Therefore, all previously described and induced faults are properly addressed, and no further testing is required to corroborate the correct algorithm's functioning.

The project was a success because an algorithm capable of detecting all the initially proposed faults was developed. Being able to detect these faults at an early stage can prevent them to further progress and prevent Ecuadorian industries from falling into unnecessary extra costs. Likewise, it helps to identify what part of an energy system is undergoing a malfunction. It can also be scaled to larger energy systems since the algorithm is not dependent to specific mechanic and electronic components. Thus, the project has relevance under real life situations. Although the detected problems are relevant to the industry, more detectable faults exist, giving the project an opportunity to further develop.

3.7. Future work

The present project develops an FDD methodology for just a few problems related with energy systems. The next step should be increasing the number of problems to be detected. It is important to take into account the sampling frequency that will be selected when including the new problems in order to avoid aliasing effects (Ingle & Proakis, 2012).

Currently, only warning messages are being sent when faults are detected by the algorithm. However, if a Raspberry Pi is integrated into the control system, the opportunity of acting over faults could be possible. This would allow to integrate actuators into the energy

systems that could automatically correct faults and therefore avoid a cascade of failures to occur.

The algorithm may include transitory state of energy systems too. For example, the algorithm could be employed within the initial increasing temperature section of the heating system, learn from it and evaluate if its behavior is consistent over time.

Another way to continue with the development of the project is designing, building and automating another energy system. Air conditioning is a wide area to be explored where many faults can be found that would help to expand the algorithm's reach. One specific area is exhaust systems. The scale building model could be expanded into a fourth level that would simulate a parking lot that requires an air extraction system. Typical CO₂ levels found in this kind of places could be scaled down and produced by placing a piece of dry ice. Also, the extraction system could cover other building levels if desired. Some preliminary calculations and concept designs are going to be presented for a future exhaust system development.

There are two main considerations for an initial design phase. First, according to the *HVAC – How to Size and Design Ducts* handbook, ducting design for air extraction falls under a low velocity system category. These systems are characterized by air velocities up to 2,000 fpm (10 m/s). This parameter can be used as a starting point in the design and also as a limit of what air and CO₂ velocities are to be expected in each ducting line. Additionally, there may exist size limitations established by the scale model building if extraction ducts are desired to run through a false ceiling.

According to chapter 21 from the ASHRAE fundamentals Handbook, “round ductwork is preferable to rectangular or flat oval ductwork” (pg. 617). Round duct work has less mass than rectangular ductwork, less perimeter and excellent resistance to low-frequency

break out noise. These facts imply that round ductwork will be lighter, better for insulation (since less surface needs to be covered), better noise properties and therefore the preferred geometry.

The faults that could be evaluated for this energy system would differ from the ones that the developed algorithm can cover since it is not going to be centered around temperature control but rather on CO₂ concentration levels. Noise generation by high gas extraction velocities could be an important fault. As mentioned before, a maximum of 10 m/s is a criterion that helps with noise generation control. Therefore, the extraction system could be designed to go above this limit to induce unwanted noise into the process and generate a detectable fault. Additionally, the ducting could be designed with controlled leaked sections, removable filters, and damaged ventilation grills to induce more faults into the system.

The following figures show a concept design for a possible exhaust configuration consisting of two duct lines for two different floors that connect two one main line (section 3) where one common extraction fan is located.

As shown in Appendix O.2, the three main points of interest are A, B and C. Point A represents a particle of air anywhere in one room, point B represents a CO₂ particle anywhere in the parking lot room and point C represents particles of mixed air with CO₂ anywhere after being expelled from the building and ducting. The energy equation and a constant flow rate will be the guiding equations and are based in points A, B, C. Detailed calculations are shown in Appendix O.

$$\frac{P_B}{\gamma} + \frac{V_B^2}{2g} + z_B + h_{a_2} = \frac{P_C}{\gamma} + \frac{v_C^2}{2g} + z_C + h_{L_2}$$

Where ρ_a is the air density, ρ_{CO_2} is CO₂ density, $\left(\frac{\rho_a + \rho_{CO_2}}{2}\right)$ is an average density, v_1 is the average air velocity in duct line 1, v_2 is the average air velocity in duct line 2, v_3 is the average air velocity, h_{L_1} and h_{L_2} are the respective total losses for both lines and h_{a_1} and h_{a_2} are the head rise supplied by the fan to the air and CO₂, respectively.

3.8. References

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4. APPENDIX

Appendix – Detailed calculations

Appendix A – Engineering analysis

Before to start the assembly of all mechanical parts, it must be tested if the sensors are connected in a correct way and sending the right signal. To do this is fundamental to have the adequate Arduino code. For this case all data recorded will have a delay of 0.25 seconds, it means that each sensor will be sampled at frequency of $F_s = 4 \text{ Hz}$, taking four data per second.

Appendix A.1. Heating system

Problem description.

PID controllers work with three terms: proportional, integral and derivative control in order to manipulate and regulate process variables like pressure, flow or temperature. It maintains the output of the system around a desired set point within a close loop (Ogata, 2013).

The constant k_p stands for proportional controller that compares the set point with the actual value, increasing the speed of the response. The integrative part eliminates or minimizes as much as possible the steady state errors. It reduces the speed of response and affects the stability, but these problems are tackled by the derivative part improving the stability and compensating phase lag.

In order to maintain a stable temperature condition of 40°C, a PID is required to control a resistance of 5000 W by using computational methods to reach the most accurate values for K_p , T_i and T_d constants. The first step is to find the transfer function of the system; this will be the open loop function. Then, a PID section with a summative part will be included to obtain the closed loop function with the signal given by the temperature sensor.

The system has an inlet flow with an ambient temperature of water and a fluid flow given by the manufacturer of the fish pump and described before in material section as a reference data. To make things easier, it is defined the same flow for the outlet part. In order to obtain the transfer function, heat transfer equations need to be used. The heat transferred to the atmosphere by the system needs to be considered.

Sketch.

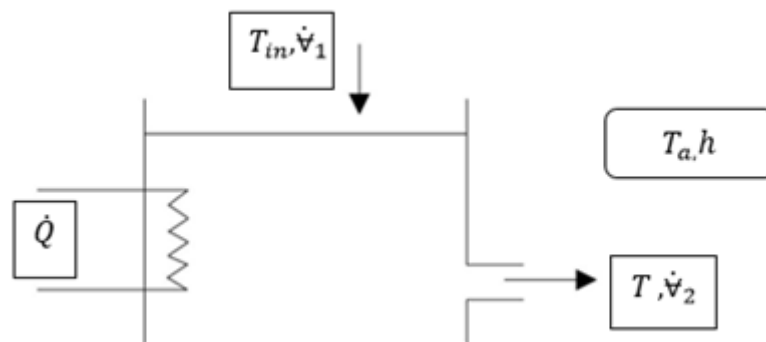


Figure 15: Initial conditions for heating system.

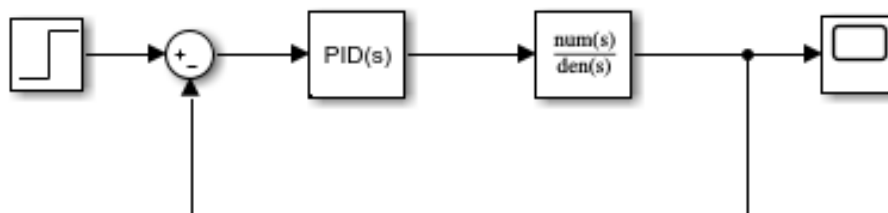


Figure 16: PID block diagram.

Calculations.

Data

$$T_a = 20^\circ\text{C}$$

$$d_2 = 26 \text{ cm}$$

$$d_1 = 25.4 \text{ cm}$$

$$L = 15 \text{ cm}$$

$$\dot{V} = 6.897 \times 10^{-6} \text{ m}^3/\text{s}$$

Assumptions

$$T_{in} = 20^\circ\text{C}$$

$$h = 25 \text{ W/m}^2\text{k}$$

$$k = 0.167 \text{ W/mk}$$

$$\rho = 998.2 \text{ kg/m}^3$$

$$C_p = 4179 \frac{\text{J}}{\text{kg K}}$$

Where T_a represents the ambient temperature, T_{in} the water inlet temperature, d_1 and d_2 the internal and external water heating container diameters respectively, L the container's

height, \dot{V} the water inlet's volumetric flow, ρ and C_p water's density and specific heat at 20 °C, h the convective coefficient and k the conductivity coefficient.

Solutions.

First, it should be started by making an energy balance:

$$\dot{E}_{in} - \dot{E}_{out} = \frac{dE}{dt}$$

$$\dot{Q}_{in} + \dot{m}_1 C_p T_{in} - \dot{m}_2 C_p T - U_o A [T - T_a] = \frac{d}{dt} (m C_p T)$$

$$\frac{d}{dt} (\rho \dot{V} C_p T) = \rho \dot{V} C_p T_{in} - \rho \dot{V} C_p T + \dot{Q} - U_o A [T - T_a]$$

$$\rho \dot{V} C_p \frac{dT}{dt} = \rho \dot{V} C_p (T_{in} - T) + \dot{Q} - U_o A T + U_o A T_a$$

$$\frac{dT}{dt} = (T_{in} - T) + \frac{\dot{Q}}{\rho \dot{V} C_p} - \frac{U_o A T}{\rho \dot{V} C_p} + \frac{U_o A T_a}{\rho \dot{V} C_p}$$

$$\frac{dT}{dt} + T + \frac{U_o A T}{\rho \dot{V} C_p} = T_{in} + \frac{\dot{Q}}{\rho \dot{V} C_p} + \frac{U_o A T_a}{\rho \dot{V} C_p}$$

In control system design it is useful to define deviation variables around the stabilization point

$$\bar{T} = T - T_s$$

$$\bar{Q} = \dot{Q} - \dot{Q}_s$$

This helps to eliminate terms like the inlet and ambient temperature, because it does not change in time.

$$\frac{d}{dt} (T - T_s) + (T - T_s) + \frac{U_o A}{\rho \dot{V} C_p} (T - T_s) = (T_{in} - T_{in,s}) + \frac{(\dot{Q} - \dot{Q}_s)}{\rho \dot{V} C_p} + \frac{U_o A (T_a - T_{a,s})}{\rho \dot{V} C_p}$$

Simplifying the equation

$$\frac{d\bar{T}}{dt} + \bar{T} + \frac{U_o A}{\rho \dot{V} C_p} \bar{T} = \frac{\bar{Q}}{\rho \dot{V} C_p}$$

$$\frac{d\bar{T}}{dt} + \bar{T} \left(1 + \frac{U_o A}{\rho \dot{V} C_p} \right) = \frac{\bar{Q}}{\rho \dot{V} C_p}$$

$$\frac{d\bar{T}}{dt} + \bar{T} \left(\frac{\rho \dot{V} C_p + U_o A}{\rho \dot{V} C_p} \right) = \frac{\bar{Q}}{\rho \dot{V} C_p}$$

$$\left(\frac{\rho \dot{V} C_p}{\rho \dot{V} C_p + U_o A} \right) \frac{d\bar{T}}{dt} + \bar{T} = \frac{\bar{Q}}{\rho \dot{V} C_p} \cdot \frac{\rho \dot{V} C_p}{\rho \dot{V} C_p + U_o A}$$

$$\left(\frac{\rho \dot{V} C_p}{\rho \dot{V} C_p + U_o A} \right) \frac{d\bar{T}}{dt} + \bar{T} = \frac{\bar{Q}}{\rho \dot{V} C_p + U_o A}$$

Applying Laplace transform

$$\tau \frac{d\bar{T}}{dt} + \bar{T} = k\bar{Q}$$

$$T(s) = \frac{k}{\tau s + 1} \cdot Q(s)$$

To have the terms of heat transfer is needed to make an analysis of convective and conductive parts in the system as shown in Figure 17, in order to calculate the overall heat transfer:

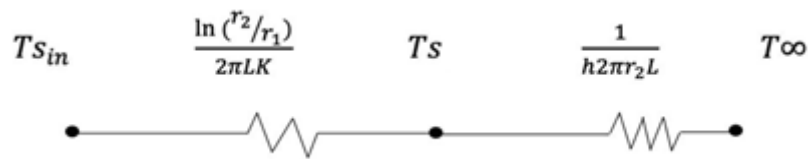


Figure 17: Heat resistance analysis.

Overall heat transfer calculations:

$$U_o A = \frac{1}{\frac{\ln(r_2/r_1)}{2\pi L k} + \frac{1}{2\pi r_2 L h}}$$

$$U_o A = \frac{1}{\frac{\ln(0.130m/0.127m)}{2\pi(0.150m)(0.167W/mK)} + \frac{1}{2\pi(0.130m)(0.150m)(25W/m^2K)}} = 2.106 \left[\frac{W}{K} \right]$$

$$\tau = \frac{\rho \dot{V} C_p}{\rho \dot{V} C_p + U_o A} = \frac{998.2 \text{ kg/m}^3 (6.897 \times 10^{-6} \text{ m}^3/\text{s})(4179 \frac{J}{\text{kg K}})}{998.2 \frac{\text{kg}}{\text{m}^3} (6.897 \times 10^{-6} \frac{\text{m}^3}{\text{s}}) 4179 \frac{J}{\text{kg K}} + 2.106 \frac{J}{\text{s K}}} = 0.932 \text{ [dim]}$$

$$k = \frac{1}{\rho \dot{V} C_p + U_o A} = \frac{1}{998.2 \frac{\text{kg}}{\text{m}^3} (6.897 \times 10^{-6} \frac{\text{m}^3}{\text{s}}) 4179 \frac{J}{\text{kg K}} + 2.106 \frac{J}{\text{s K}}} = 0.0324 \left[\frac{K}{W} \right]$$

Then the data is used in order to obtain the constants for the equation

$$\tau = 0.932 \text{ [dim]}$$

$$k = 0.0324 \left[\frac{K}{W} \right]$$

Using these constants

$$\frac{T(s)}{Q(s)} = \frac{0.0324}{0.932s + 1}$$

With the transfer function of the system obtained as shown in Figure 18, the next step is to define the PID part by using the equation.

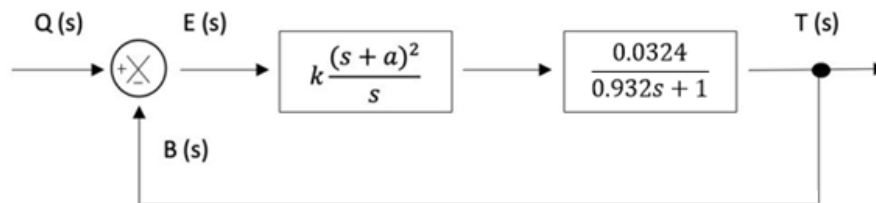


Figure 18: System response.

Block diagram transfer function:

$$T(s) = H(s) G(s) E(s)$$

$$E(s) = Q(s) - B(s)$$

$$E(s) = Q(s) - T(s)$$

$$T(s) = H(s) G(s) [Q(s) - T(s)]$$

$$T(s) = H(s) G(s) Q(s) - H(s) G(s) T(s)$$

$$T(s) + H(s) G(s) T(s) = H(s) G(s) Q(s)$$

$$T(s)[1 + H(s) G(s)] = H(s) G(s) Q(s)$$

First, the close loop function transfer must be defined

$$\frac{T(s)}{Q(s)} = \frac{H(s) G(s)}{1 + H(s) G(s)}$$

Now apply the equations found

$$\begin{aligned}
\frac{T(s)}{Q(s)} &= \frac{\frac{k(s+a)^2}{s} \left(\frac{0.0324}{0.932s+1} \right)}{1 + \frac{k(s+a)^2}{s} \left(\frac{0.0324}{0.932s+1} \right)} = \frac{\frac{k(s^2+2as+a^2)}{s} \left(\frac{0.0324}{0.932s+1} \right)}{1 + \frac{k(s^2+2as+a^2)}{s} \left(\frac{0.0324}{0.932s+1} \right)} \\
&= \frac{\frac{0.0324 ks^2 + 0.0648 kas + 0.0324 ka^2}{0.932s^2 + s}}{1 + \frac{0.0324 ks^2 + 0.0648 kas + 0.0324 ka^2}{0.932s^2 + s}} \\
&= \frac{0.0324 ks^2 + 0.0648 kas + 0.0324 ka^2}{0.932s^2 + s + 0.0324 ks^2 + 0.0648 kas + 0.0324 ka^2}
\end{aligned}$$

Now apply the equations found

$$\frac{T(s)}{Q(s)} = \frac{0.0324 ks^2 + 0.0648 kas + 0.0324 ka^2}{s^2(0.932 + 0.0324k) + s(1 + 0.0648ka) + 0.0324 ka^2}$$

Using this transfer function in Matlab and defining a maximum elongation of 10% with a settlement time of 30 seconds, and a permissible error in steady state of 2%, the code finds the most accurate constant for k and a. Figure 19 shows the step response. Detailed code is in appendix B.1.

$$k = 15.90, a = 8$$

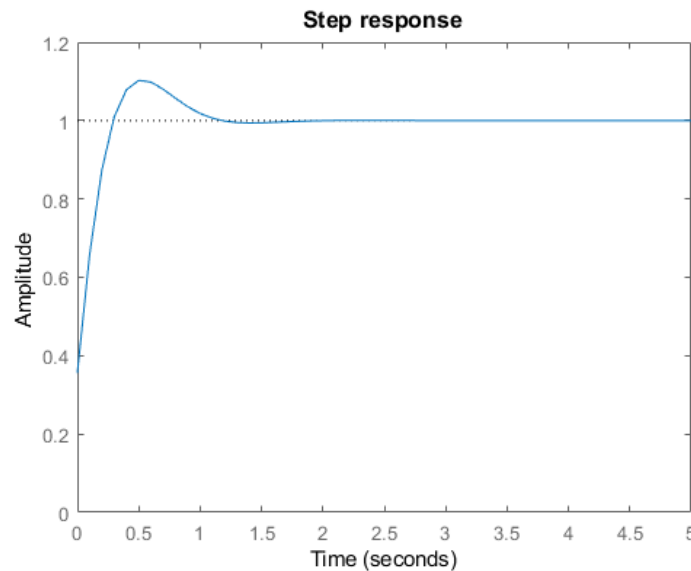


Figure 19: Time versus amplitude that shows the step response.

Redefining the equation for PID

$$2ak \left(1 + \frac{a}{2s} + \frac{s}{2a} \right) = k \frac{(s+a)^2}{s}$$

$$Kp = 2ak = 2 \cdot 8 \cdot 15.9 = 254.4$$

$$T_i = \frac{2}{a} = \frac{2}{8} = 0.25$$

$$T_d = \frac{1}{2a} = \frac{1}{2 \cdot 8} = 0.0625$$

The Matlab code is appended in annexes. The response of the system given by the constants has an ideal behavior like the Figure 19. However, this situation is far from real one because the stabilization time and rise time are very low. It means that is needed to find an electric resistance with enough power for heat water since 20°C to 40°C in less than a half of second, exactly 0.3 seconds. Assuming that the water is stagnant:

$$\dot{Q} = \dot{m}Cp\Delta T$$

Data

$$m = 1.996 \text{ kg}$$

$$t = 0.3 \text{ s}$$

$$\dot{Q} = \frac{1.996 \text{ kg}}{0.3 \text{ s}} \left(4179 \frac{\text{J}}{\text{kg K}} \right) (40 - 20) \text{ K} = 556085.6 \text{ W}$$

This power value is higher than the given for the scale model. To stay in real operations, the power of 5000 W will be kept, and the right rise time will be calculated with the same equation, obtaining:

$$t = \frac{mcp\Delta T}{\dot{Q}} = \frac{1.996 \text{ kg} \left(4179 \frac{\text{J}}{\text{kg K}} \right) (40 - 20) \text{ K}}{5000 \frac{\text{J}}{\text{s}}} = 33.4 \text{ s}$$

The actual rise time with real conditions and water flow will be found experimentally in following section, this time value is only reference to know if the power reach the temperature set point in an acceptable time.

Appendix A.2. Refrigeration

Problem description.

The refrigeration system has several applications in daily life as industrial freezers, air conditioning, heat pumps and domestic refrigerators. The most common use for a refrigeration cycle is in refrigerators. Household refrigerators are used to chill beverages, food, legumes, and meat, among others. It is necessary to keep all this food in a certain temperature in order to maintain them, so they do not get damaged.

Also, another use for the refrigeration system is for cold rooms, these rooms keep inside them food such as meat, chicken, seafood, or in other cases certain pharmaceutical products, among others. These products also need to maintain a temperature so that the products continue fresh. These cold rooms are installed in restaurants, supermarkets, etc.

So, keeping this in mind it was decided to build a cold room having the following components extracted from a refrigerator like a compressor of ¼ HP, evaporator of ¼ HP, condenser of ¼ HP and capillary.

In this case, inverse engineering will be carried out because the components for the refrigeration cycle are already selected. In the case of the capillary it has to be selected given the data of the temperature and the heat load of the chosen compressor.

Calculations.

Data

$$C_{p_{water@20^{\circ}C}} = 4.182 \frac{kJ}{kg \cdot K}$$

$$\dot{Q}_{evaporation@-10^{\circ}C} = 0.313 \frac{kJ}{s}$$

$$C_{p_{ice@0^{\circ}C}} = 1.960 \frac{kJ}{kg \cdot K}$$

$$\Delta T_{water} = 20^{\circ}C - 0^{\circ}C = 20^{\circ}C$$

$$\Delta T_{ice} = 0^{\circ}C - (-5^{\circ}C) = 5^{\circ}C$$

$$l_{freezing} = 333.55 \frac{kJ}{kg}$$

$$F_1 = 1.15$$

$$\rho_{water@20^{\circ}C} = 998.29 \frac{kg}{m^3}$$

$$F_2 = 0.67$$

Where $C_{p_{water@20^{\circ}C}}$ is water's specific heat at $20^{\circ}C$, $C_{p_{ice@0^{\circ}C}}$ is ice specific heat at $0^{\circ}C$, $l_{freezing}$ is the ice latent heat, $\rho_{water@20^{\circ}C}$ is water's specific heat at $20^{\circ}C$, $\dot{Q}_{evaporation@-10^{\circ}C}$ is the rate at which heat will be absorbed by the evaporator, ΔT_{water} is the water temperature difference and ΔT_{ice} the ice temperature difference. The correction factors are defined as F_1 and F_2 , explained above.

Sketch.

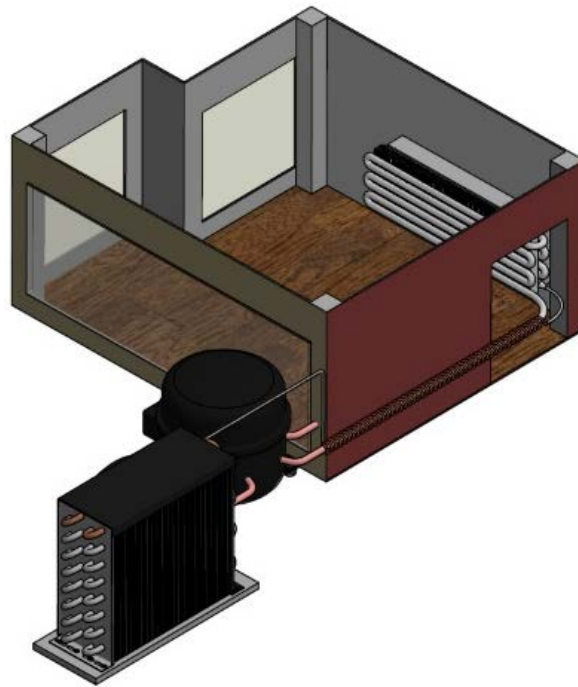


Figure 20: Refrigeration system's actual distribution on building floor.

Solution.

Heat Capacity in the liquid state (water)

$$Q_1 = m \cdot C_{p_{water@20^{\circ}C}} \cdot \Delta T_{water}$$

Latent Heat

$$Q_2 = m \cdot l_{freezing}$$

Heat Capacity in the solid state (ice)

$$Q_3 = m \cdot C_{p_{ice@0^{\circ}C}} \cdot \Delta T_{ice}$$

Then, in order to get $\dot{Q}_{evaporation}$ it must be done the sum of $Q_1 + Q_2 + Q_3$ and m is the same from the three cases, the value that is going to be found is m . This is obtained in a day, so it is going to be changed into seconds instead of being in hours.

Also, the numerator will be multiplied by F_1 because this factor is the one that represents the heat provided by the walls and floor (Ajav & Mankinde, 2015). The three equations are going to be mixed, having as common factor m :

$$\dot{Q}_{evaporation} = \frac{m \cdot \left[(C_{p_{water@20^\circ C}} \cdot \Delta T_{water}) + l_{freezing} + (C_{p_{ice@0^\circ C}} \cdot \Delta T_{ice}) \right] \cdot F_1}{day}$$

Clearing m , it is obtained this equation:

$$m = \frac{\dot{Q}_{evaporation} \cdot day}{\left[(C_{p_{water@20^\circ C}} \cdot \Delta T_{water}) + l_{freezing} + (C_{p_{ice@0^\circ C}} \cdot \Delta T_{ice}) \right] \cdot F_1}$$

Replacing with the values, it is obtained:

$$m = \frac{0.313 \frac{kJ}{s} \cdot 24h \cdot \frac{3600s}{1h}}{\left[\left(4.182 \frac{kJ}{kg \cdot ^\circ C} \cdot 20^\circ C \right) + 333.55 \frac{kJ}{kg} + \left(1.960 \frac{kJ}{kg \cdot ^\circ C} \cdot 5^\circ C \right) \right] \cdot 1.15}$$

Replacing with the values, it is obtained:

$$m = 55.07 \text{ kg}$$

This value of m is the mass of water that it is going to be frozen. To obtain the volume of this product, the density equation will be used:

$$\rho_{water@20^\circ C} = \frac{m_{water}}{V_{water}}$$

Obtaining V_{water} :

$$V_{water} = \frac{m_{water}}{\rho_{water@20^\circ C}}$$

Replacing the corresponding values:

$$V_{water} = \frac{55.07 \text{ kg}}{998.29 \frac{kg}{m^3}}$$

Obtaining a product volume of:

$$V_{water} = 0.06 \text{ m}^3$$

Finally, this volume will be divided by the F_2 , that is the air circulation space and the evaporator space (Ajav & Mankinde, 2015). To obtain the volume of the cold room.

$$V_{cold\ room} = \frac{V_{water}}{0.67} = \frac{0.06 \text{ m}^3}{0.67} = 0.09 \text{ m}^3 \sim 0.1 \text{ m}^3$$

The volume of the cold room is approximately 0.1 m^3 , with this value the measures of the room are going to be proposed, having in Table 6 the results.

Table 10
Dimensions for the cold room.

Dimensions	[m]
Long	0.6 m
Depth	0.5 m
High	0.4 m

For the selection of the capillary, the parameters that must be considered depends on the compressor that is going to be used. For example, with the compressor characteristics the heat load is obtained given the value of $1068 \frac{BTU}{h}$. The evaporating and the condensing temperature are -10°C and 45°C , respectively. Finally, the return has temperature is 5°C and the refrigerant is R-134a. With these values, the length and inner diameter are 1.51m and 0.044 in , respectively. These results are the more appropriate to use and is detailed in Appendix J.1.

Appendix A.3. Water delivery

Problem description.

Water supply system consists of transporting water from a main storage tank to another one located on the top floor of the building. It will be filled by a pump for fish tank. The water flow that is connected to the main tank will be calibrated by a ball valve. The required amount of water will be observed by a flow meter that will notify if the flow rate is the desired one, among other uses like fault detection.

Water will pass to the tank once the solenoid valve is activated. This solenoid valve will allow the passage of liquid once the level sensors indicate if the tank requires water (whether it is full or not).

In the water tank there will be two level float sensors that will indicate when the tank needs to be filled because it is empty. The tank will be filled in a specific time because in this way it will be possible to know if there is any damage or fault in the components prior to the tank.

The next calculations are going to find the best diameter to supply the necessities for the system in order to force faults and have a right filling time.

Calculations.

Data

Obtained from NEC-11-Cap16-14

$$\dot{V}_1 = 0.20 \frac{L}{s}$$

$$P_{g1} = 7 \text{ mca (gage)}$$

$$\phi_{nozzle} = 16 \text{ mm}$$

Assumptions

Obtained from Munson at 20°C

$$\rho_{H2O} = 998.2 \frac{kg}{m^3}$$

$$\mu_{H2O} = 1.002 \times 10^{-3} \frac{N \cdot s}{m^2}$$

$$\gamma_{H2O} = 9.789 \frac{kN}{m^3}$$

Where \dot{V}_1 is the water transport system's inlet volumetric flow, P_{g1} is the gage pressure at the output of the faucet, ϕ_{nozzle} is the exit nozzle's diameter, ρ_{H_2O} is the water's density, μ_{H_2O} is dynamic viscosity and γ_{H_2O} is specific weight.

Sketch.



Figure 21: Water supply system.

Solution.

Obtaining the water flow

$$\dot{V}_1 = 0.20 \frac{L}{s} \cdot \frac{1 \text{ m}^3}{1000 L} = 2 \times 10^{-4} \frac{\text{m}^3}{s}$$

$$\dot{V}_1 = v_1 A_1 \Rightarrow v_1 = \frac{2 \times 10^{-4} \frac{\text{m}^3}{s}}{\frac{\pi}{4} \cdot (0.016 \text{ m})^2} = 0.995 \frac{\text{m}}{s}$$

Determine the diameter of the pipe, using type III

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 + h_L \quad \Rightarrow \quad P_2 = P_{atm}, P_1 = P_{atm} + P_{gage}$$

$$h_L = \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + (z_1 - z_2)$$

$$\frac{f \ell v^2}{2gD} + (\kappa_T + 2\kappa_v + 5\kappa_{vr} + \kappa_c + \kappa_s) \frac{v^2}{2g} = \frac{P_1}{\gamma} + \frac{v_1^2}{2g} + (z_1 - z_2)$$

$\Rightarrow v = \text{velocity inside the pipe}$

$$v = \frac{\dot{V}_2}{\frac{\pi}{4}D^2} \Rightarrow v = \frac{2 \times 10^{-4} \frac{m^3}{s}}{\frac{\pi}{4}(D)^2} = \frac{0.000255}{D^2}$$

$$\frac{70000Pa}{9789 \frac{N}{m^3}} + \frac{\left(0.995 \frac{m}{s}\right)^2}{2 \cdot \left(9.81 \frac{m}{s^2}\right)} + 0.14m$$

$$= \left(\frac{\left(\frac{2.55 \times 10^{-4}}{D^2}\right)^2}{2 \left(9.81 \frac{m}{s^2}\right)} \right) \cdot \left(\frac{f\ell}{D} + \kappa_T + 2\kappa_v + 5\kappa_{vr} + \kappa_c + \kappa_s \right)$$

$$7.15 + 0.05 + 0.14 = \left(\frac{3.31422 \times 10^{-9}}{D^4} \right) \left(\frac{f(0.84)}{D} + 0.9 + 2 \cdot 10 + 5 \cdot 0.08 + 1.5 + 1 \right)$$

$$7.34 = \left(\frac{3.31422 \times 10^{-9}}{D^4} \right) \left(\frac{f}{D}(0.84) + 23.8 \right)$$

$$7.34 = \left(\frac{3.31422 \times 10^{-9}}{D^5} \right) (f(0.84) + 23.8D)$$

$$7.34D^5 = 2.78394 \times 10^{-9}f + 7.88784 \times 10^{-8}D$$

$$7.34D^5 - 7.88784 \times 10^{-8}D = 2.78394 \times 10^{-9}f$$

Obtaining the friction factor in function of diameter

$$f = 2.63655 \times 10^9 D^5 - 28.33D$$

$$Re = \left(\frac{\rho v D}{\mu} \right) = \left(\frac{\left(998.2 \frac{kg}{m^3}\right) \left(\frac{2.55 \times 10^{-4}}{D^2}\right) D}{1.002 \times 10^{-3} \frac{N \cdot s}{m^2}} \right) = \frac{254.03}{D}$$

With Matlab code described in appendix B.2, it is obtained next results:

$$\varepsilon = 0$$

$$Re = 244425.96$$

$$f = 0.267$$

For ½ inch pipe diameter the outlet velocity is:

$$v_{outlet} = \frac{\dot{V}_2}{A_2} \Rightarrow v_{outlet} = \frac{2 \times 10^{-4} \frac{m^3}{s}}{\frac{\pi}{4} (0.0127m)^2} = 1.579 \frac{m}{s}$$

Having a diameter given by Matlab in appendix B.3:

$$D_{intern} = 0.0104m$$

The existing commercial diameter closest to the one found is $\left(\frac{1}{2}\right)$ " or 0.0127m

$$Re = 20002.4$$

$$f = 0.0259$$

To obtain water supply time

$$\sum \dot{m}_{in} - \sum \dot{m}_{out} = (\dot{m}_2 - \dot{m}_1)_{sys}$$

$$\dot{m}_{in} = (\dot{m}_2 - \dot{m}_1)_{sys}$$

$$\rho A_1 v_{outlet} = \rho \dot{V}$$

$$t = \frac{0.02m^3}{\frac{\pi}{4} (0.0127m)^2 \cdot 1.579 \frac{m}{s}} = 99.9s \approx 100s$$

Appendix A.4. System curve calculations

Problem description.

Before to know if the pump with the components selected can produce cavitation, it is important to know the operational point of the system. In order to know the flow rate and the power that will be supplied by the pump, the system curve will be calculated and then used to compare it with the curve provided in the pump's datasheet.

When this point is reached, the total head found will be a reference to compare the NPSHa because for this pump the NPSHr curves do not exist.

Calculations.*Data*

$$l_a = \text{longitud de } 1'' = 2.32 \text{ m}$$

$$l_b = \text{longitud de } 3/4'' = 0.055 \text{ m}$$

$$D_a = 0.0254 \text{ m}$$

$$D_b = 0.0191 \text{ m}$$

Assumptions obtained from Munson

$$\mu = 1.002 \times 10^{-3} \text{ kg m/s}^2$$

Where l_a and l_b are 1'' and 3/4'' pipe lines lengths respectively, D_a and D_b their respective and μ is the water's dynamic viscosity.

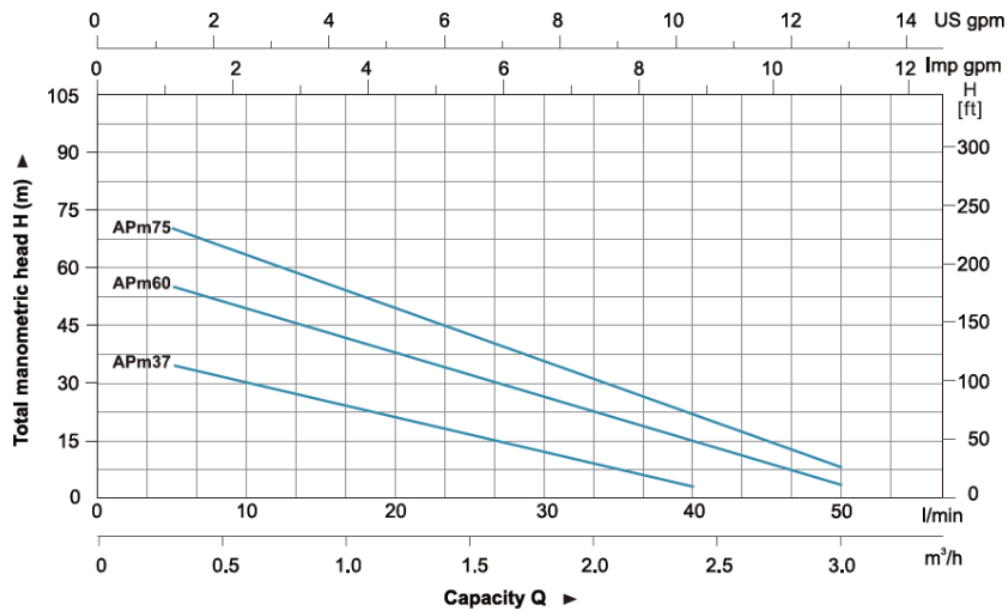
Sketch.

Figure 22: Hydraulic performance curves.
Obtained from: Leo Group, 2015

Solution.

Assuming that the max flow rate is 1140 L/h $\left(3.167 \times 10^{-4} \frac{\text{m}^3}{\text{s}}\right)$. This data was obtained

by using the flow sensor and put the system to work in normal conditions.

$$\frac{P_1}{\gamma} + \frac{V_1^2}{2g} + z_1 + h_a = \frac{P_2}{\gamma} + \frac{V_2^2}{2g} + z_2 + \frac{V^2}{2g} \left(\frac{fl}{D} + \Sigma K_L \right)$$

$$h_a = (z_2 - z_1) + \frac{v_a^2}{2g} \left(\frac{f_a l_a}{D_a} + \Sigma K_{La} \right) + \frac{v_b^2}{2g} \left(\frac{f_b l_b}{D_b} + \Sigma K_{Lb} \right)$$

Defining

$$v_a = \frac{\dot{V}}{A_a} = \frac{\dot{V}}{\frac{\pi}{4} (0.0254)^2} = 1973.53 \dot{V}$$

Knowing \dot{V}

$$\dot{V} = 3.167 \times 10^{-4} \frac{\text{m}^3}{\text{s}}$$

Therefore,

$$v_a = 0.625 \frac{\text{m}}{\text{s}}$$

$$Re_a = \frac{\rho v_a D_a}{\mu} = \frac{998.2(0.625)(0.0254)}{1.002 \times 10^{-3}} = 15814.80$$

Similarly,

$$v_b = \frac{\dot{V}}{A_b} = \frac{\dot{V}}{\frac{\pi}{4} (0.0191)^2} = 3508.49 \dot{V}$$

$$v_b = 1.111 \frac{\text{m}}{\text{s}}$$

$$Re_b = \frac{\rho v_b D_b}{\mu} = \frac{998.2(1.111)(0.0191)}{1.002 \times 10^{-3}} = 21139.60$$

Using Matlab code in appendix B.2 for smooth pipe

$$f_a = 0.0274$$

$$f_b = 0.0255$$

Finding the pressure loss coefficient for the reduction since 1 inch to $\frac{3}{4}$ inch

$$\kappa_R = \left(1 - \frac{A_1}{A_2}\right)^2 = \left(1 - \frac{\frac{\pi}{4} (0.0254)^2}{\frac{\pi}{4} (0.01905)^2}\right)^2 = 0.605$$

Having the necessary data, it returns to the Bernoulli equation

$$h_a = 2.03 + \frac{(1973.53 \dot{V})^2}{2 \cdot 9.81} \left(\frac{0.0274 \cdot 2.32}{0.0254} + \kappa_{vp} + \kappa_c + \kappa_{vb} + 2 \cdot \kappa_T + \kappa_{vr} + \kappa_c \right) \\ + \frac{(3508.49 \dot{V})^2}{2 \cdot 9.81} \left(\frac{0.0255 \cdot 0.055}{0.01905} + \kappa_{vb} + \kappa_s + \kappa_R \right)$$

$$h_a = 2.03 + 198513 \dot{V}^2 (2.503 + 2 + 1.5 + 0.05 + 2 \cdot 0.9 + 0.08 + 1.5) \\ + 627396 \dot{V}^2 (0.0736 + 0.05 + 1 + 0.605)$$

$$h_a = 2.03 + 1872573.129 \dot{V}^2 + 1084516.726 \dot{V}^2 \left[\frac{m^3}{s} \right]$$

$$h_a = 2.03 + 2.957 \cdot 10^6 \dot{V}^2$$

In the same way it is proceeded to perform the same calculation but with units $\left[\frac{m^3}{h} \right]$

$$h_a = 2.03 + \frac{(1973.53 \dot{V})^2}{2 * 1.271x10^8} (9.433) + \frac{(3508.49 \dot{V})^2}{2 * 1.271x10^8} (1.729)$$

$$h_a = 2.03 + 0.145 \dot{V}^2 + 0.0837 \dot{V}^2$$

Then the head rise is found with units $\left[\frac{m^3}{h} \right]$

$$h_a = 2.03 + 0.229 \dot{V}^2$$

Equation of the Total Head vs Flow line, given by the manufacturer

$$y_2 = 40 \quad x_2 = 0$$

$$y_1 = 5 \quad x_1 = 2.1$$

$$m = \frac{40 - 5}{0 - 2.1} = -16.667$$

$$y - y_1 = m(x - x_1)$$

$$y - 5 = -16.667 (x - 2.1)$$

$$y = 5 + 35 - 16.667x$$

Equation of the Total Head vs Flow line, given by the manufacturer

$$y = 40 - 16.667x$$

Graphing this first equation of h_a against the given by the manufacturer y . It is obtained the operational point where the system will work. It gives that the volumetric flow rate should be $2.212 \left[\frac{m^3}{h} \right]$ and the pressure head at this flow of water is $3.15[m]$, these two values will help to detect if the system produces cavitation or not. The figure below represents the operational point.

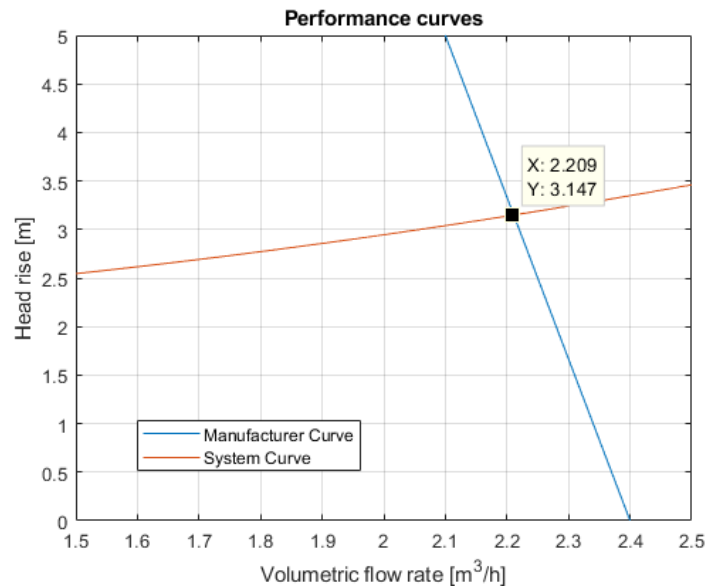


Figure 23: Operational point between manufacturer and calculated system curve.

In order to have an expanded view for the system curve, the next figure shows only this equation.

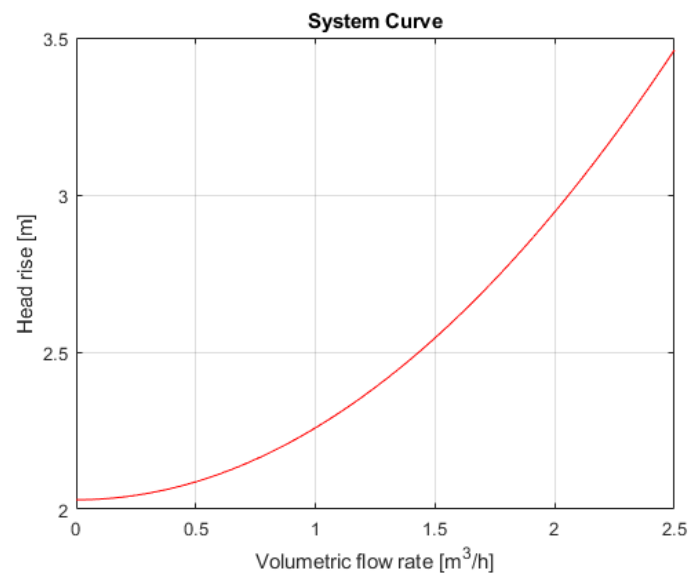


Figure 24: System's curve showing water's head rise gain over volumetric flow rate.

Appendix A.5. Cavitation

Problem description.

When the fluid passed through the pump and it reaches the last floor of the building, cavitation needs to be forced. Using the materials described in the previous sections, the calculations need to represent the pressure in the suction part, to reduce it under the required. Two ball valves are going to be closed until 2/3 of its normal conditions, so the calculations use the loss coefficients for pipe components with these conditions.

Calculations.

Data

$$D = 1 \text{ in}$$

$$Max_{suction} = 8 \text{ m}$$

$$l = 1.69 \text{ m}$$

Assumptions obtained from Munson at 20

$$\rho_{H_2O} = 998.2 \frac{\text{kg}}{\text{m}^3}$$

$$\mu_{H_2O} = 1.002 \times 10^{-3} \frac{\text{N}\cdot\text{s}}{\text{m}^2}$$

$$\gamma_{H_2O} = 9.789 \frac{\text{kN}}{\text{m}^3}$$

$$P_v = 2.34 \text{ kPa}$$

Sketch.

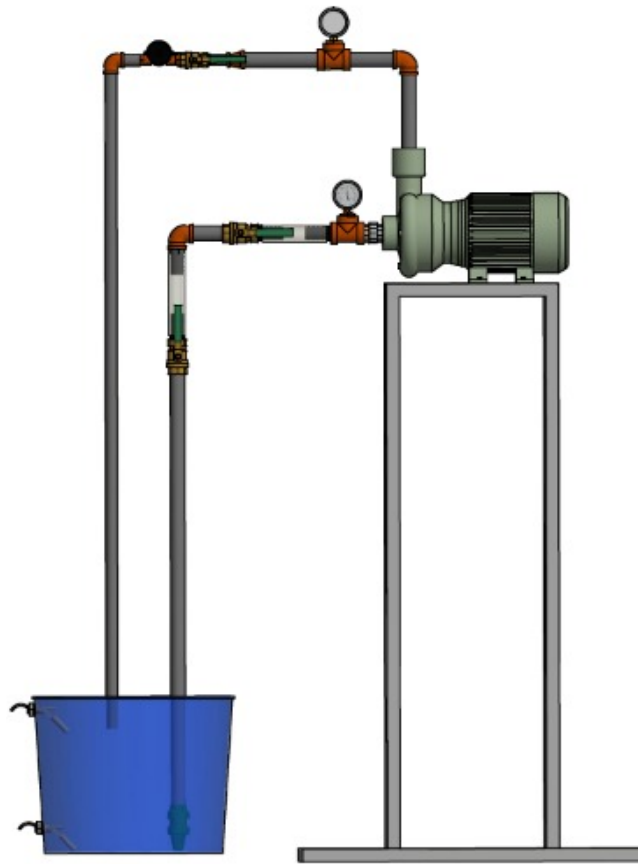


Figure 25: Cavitation system.

Solution.

Assuming that the max flow rate is the found in the previous section for operational point $2.212 \left[\frac{m^3}{h} \right] \left(0.000614 \frac{m^3}{s} \right)$, this value is assuming that the two ball valves are fully open.

However, for this case are 2/3 closed, so the flow rate decreases to $0.000317 \frac{m^3}{s}$.

First, the friction factor is obtained by using appendix B.2:

$$v = \frac{\dot{V}_1}{\frac{\pi}{4} D^2} \Rightarrow v = \frac{3.167 \times 10^{-4} \frac{m^3}{s}}{\frac{\pi}{4} * (0.0254 m)^2} = 0.625 \frac{m}{s}$$

$$Re = \left(\frac{\rho v D}{\mu} \right) = \left(\frac{\left(998.2 \frac{kg}{m^3} \right) \left(0.625 \frac{m}{s} \right) (0.0254 m)}{1.002 \times 10^{-3} \frac{N \cdot s}{m^2}} \right) = 15814.80$$

$$f = 0.0274$$

The cavitation of the system is going to be forced

$$NPSH_a \leq NPSH_r$$

$$NPSH_a = \frac{P_1}{\gamma} + z_1 - \sum \kappa_L - \frac{P_v}{\gamma} = \frac{101325 \text{ Pa}}{9789 \frac{\text{N}}{\text{m}^3}} + 1.35 \text{ m} - (h_m + h_M) - \frac{2340 \text{ Pa}}{9789 \frac{\text{N}}{\text{m}^3}}$$

$$NPSH_a = 10.351 + 1.35 - \left(\kappa_{vp} + \kappa_c + 2 \cdot \kappa_{vb} + \kappa_T + \kappa_{vr} + \kappa_s + \frac{f\ell}{D} \right) \frac{v^2}{2g} - 0.239$$

$$NPSH_a = 11.462 - \frac{0.625^2}{2 \cdot 9.81} \left(\frac{(0.0281)(1.69)}{0.0254} + 2 + 1.5 + 2 \cdot 210 + 0.9 + 0.08 + 1 \right)$$

$$NPSH_a = 2.95 \text{ m}$$

$$2.95 \leq 3.15 \text{ [m]} \Rightarrow \text{It should produce cavitation}$$

In normal conditions the $\kappa_{vb} = 0.05$

$$NPSH_a = 11.462 - \frac{0.625^2}{2 \cdot 9.81} \left(\frac{(0.0281)(1.69)}{0.0254} + 2 + 1.5 + 2 \cdot 0.05 + 0.9 + 0.08 \right)$$

$$NPSH_a = 11.334 \text{ m}$$

$$11.334 \geq 3.15 \text{ [m]}$$

$NPSH_a > NPSH_r \Rightarrow \text{It works in appropriate conditions}$

Appendix – Algorithms

Appendix B – Matlab Code

Appendix B.1. Code for PID constants selections

```

close all, clear all, clc
t = 0:0.1:100;
k = 0;
for K = 3:0.1:20 %range to find K
    for a = 1:0.1:10 %range to find a
        num = [0.000719.*K 0.001438.*K.*a 0.000718.*K.*a^2]; %
        den = [0.9987+0.000719.*K 1+0.001438.*K.*a 0.000719.*(a^2).*K];
        y=step(num,den,t);
        s = 800;
        while y(s)>0.98 && y(s)<1.02 % error in steady state
            s = s-1;
        end
        ts = (s-1)*0.01; % ts = setting time;
        m = max(y);
        if m<1.10 && m>1.05 % elongation permitted
            if ts<30 % settlement time
                k = k+1;
                solution(k,:)=[K a m ts]
            end
        end
    end
end

solution;
sortsolution=sortrows(solution,3);
K=sortsolution(1,1)
a=sortsolution(1,2)
num = [0.0324.*K 0.0648.*K.*a 0.0324.*K.*a^2];
den = [0.932+0.0324.*K 1+0.0648.*K.*a 0.0324.*(a.^2).*K];
step(num,den,t)
axis([0,5,0,1.2])

```

Appendix B.2. Code for friction factor

```

function [f, rough] = FrictionFactor(Re, ed) %Re = Reynolds Number, ed =
% eps/ relative roughness
colebrook = @(f, ed) 1/sqrt(f)+2*log10((ed/3.7)+(2.51)/(Re*sqrt(f)));
if Re > 4000 %Turbulent flow
    f = fzero(@(f) colebrook(f, ed), [0.008, 0.1]);
elseif Re < 2000 %Laminar
    f = 64/Re;
else %Transition
    f = (((Re-2000)/(4000-2000))*(0.1-0.008))+0.008;
end
array = linspace(0.00001, 0.05, 18);
narray = length(array);
rough = zeros(1, narray);
for K = 1 : narray
    i = array(K);
    rough(K) = colebrook(f, i);
end
end

```

Appendix B.3. Code for finding the optimal diameter

```
D=0.00005;  
FF=2.63655*10^9*(D^5)-28.33*D;  
Re=254.03/D;  
ff=frictionFactor(Re,0);  
a=FF-ff;  
  
while a<0.00001  
    FF=2.63655*10^9*(D^5)-28.33*D;  
    Re=254.03/D;  
    ff=frictionFactor(Re,0);  
    a=FF-ff;  
    D=D+0.00005;  
D  
End
```

Appendix C – Python algorithm for fault detection

Appendix C.1. Data filter and statistic mean

```
import statistics as stats
Temp_mean = stats.mean(Temperature)
NS = 100 # NS is number of training points
if Temp_mean < 38 or Temp_mean > 41: # Range of stabilization
    print("System is not stabilized")
elif 38 < Temp_mean < 41 and sd < NS: # sd is data set of temperature each 12.5s
    print("System is stabilized")
    sd += 1
    DataSample.append(sd)
    DataTemp.append(Temp_mean)
```

Appendix C.2. Linear Regression

```
import numpy as np
from sklearn import linear_model
from sklearn.metrics import mean_squared_error, r2_score

if sd == NS:
    # Create variables to train
    dataX = DataSample # X axes is number of samples
    dataY = DataTemp
    X_train = np.array(dataX).reshape(-1, 1)
    Y_train = dataY # Y axes is Temperature
    # Create object for linear regression
    reg = linear_model.LinearRegression()
    # Train the model
    reg.fit(X_train, Y_train)
    y_p = reg.predict(X_train)
    print(" Mean squared error: %2f" % mean_squared_error(Y_train, y_p))
    print(' Variance score: %2f' % r2_score(Y_train, y_p))
```

Appendix C.3. Number of samples out of the range

```
y_predicted = 0
count = NS
while y_predicted < 40 * 1.03:
    y_predicted = reg.predict(count)
    count += 1
print('Number of samples to go out of range')
print(count)
```

Appendix C.4. Heating system fault detection

```
if sd >= NS:
    y_expected = 40
```

```

exact = Temp_mean
# print(exact)
err = abs(y_expected - exact)/exact
# print(err)
sd += 1
if err < 0.03:
    print("Heating system is working well")
elif 0.03 < err < 0.1:
    # this range values were found experimentally
    print("Problem in electrical resistor")
elif err > 0.1:
    print("Problem in temperature sensor")

```

Appendix C.5. Pump is not working

```

s2 = 0
for PNW in Sensor_2:
    # PNW is the variable for Pump Not Working
    if PNW == 0:
        s2 += 1
if s2 >= 3:
    print("Pump is not working")
else:
    print("Pump is working")

```

Appendix C.6. Fault detection in the foot check valve

```

startTimeFCV = time.time()
# Start time Foot Check Valve.
# This line is at the beginning of the code
fcv = 0
# Foot check valve counter
Sen2_mean = stats.mean(Sensor_2)
if Sen2_mean < 1000:
    fcv += 1
elif 2500 > Sen2_mean > 1000:
    stopTimeFCV = time.time()
    TimeFCV = stopTimeFCV - startTimeFCV
if fcv == 4:
    # Each data set is taken each 12.5 seconds
    print('Stop the pump')
elif 2 <= fcv < 4:
    print('Foot Check Valve is damaged')
    print(TimeFCV)
    # Show the time needed to start working
elif fcv < 2:
    continue

```

Appendix C.7. Train and test arrays

```

"Define a dictionary with keys and values"
Detection = {'Data': KNN, 'Target': CNC}
"Define train set and test set, in order to probe if the algorithm works well"
X_train,X_test,y_train,y_test =
train_test_split(Detection['Data'],Detection['Target'])
"Import the library"
from sklearn.neighbors import KNeighborsClassifier
"Define the number of nearest neighbors"
knn = KNeighborsClassifier(n_neighbors=7)
"Fit the data"
knn.fit(X_train, y_train.values.ravel())

```

```

"Print correct percentage"
print(knn.score(X_test,y_test))
# print(knn.score(X_train, y_train)) Test overfitting

```

Appendix C.8. Cavitation fault detection

```

YC = 0          # Counter to know if the system has cavitation
NoC = 0        # Counter to know if the system has cavitation
"1 is for cavitation and 0 is for no cavitation"
for i in range(len(AccXSC)):
    YP = knn.predict([[AccXNoC[i],AccYNoC[i],AccZNoC[i],AcelLinealNoC[i]])]
    if YP == 1:
        YC += 1
    elif YP == 0:
        NoC += 1
    PredY.append(YP)

if YC > NoC:
    print("The pump has cavitation")
    print(YC)
if NoC > YC:
    print("The pump does not have cavitation")
    print(NoC)

```

Appendix C.9. Sensor combinations for stuck solenoid and tank leaks

```

c50_0 = 0          # counter of sensor level 5 that start in 0 and append 0
c50_1 = 0          # counter of sensor level 5 that start in 0 and append 1
c40_1 = 0          # counter of sensor level 4 that start in 0 and append 1
c40_0 = 0          # counter of sensor level 4 that start in 0 and append 0
c51_0 = 0          # counter of sensor level 5 that start in 1 and append 0
c51_1 = 0          # counter of sensor level 5 that start in 1 and append 1
c41_1 = 0          # counter of sensor level 4 that start in 1 and append 1
c41_0 = 0          # counter of sensor level 4 that start in 1 and append 0
csf_oc = 0        # counter for sensor flow when is open and then close
csf_oo = 0        # counter for sensor flow is open
csf_co = 0        # counter for sensor flow when is close and then open
csf_cc = 0        # counter for sensor flow is close

# Global variables defined in 10
C05 = 10
C04 = 10
SF10C = 10
SF1C0 = 10
O05 = 10
O04 = 10
CC5 = 10
CC4 = 10
SF100 = 10
SF1CC = 10

# Case 7.- S_LevelHigh is always open
# [0 0 0 0 0 0 0 0 0 0 0 0]
# Name: "O05"
# Case 4.- S_LevelHigh is open and then close
# [0 0 0 0 0 1 1 1 1 1 1 1]
# Name: "OC5"

```

```

if S_LevelHigh[0] == 0:
    for float50 in S_LevelHigh:
        if float50 == 1:
            c50_1 += 1
        elif float50 == 0:
            c50_0 += 1

    if c50_1 >= 1:
        OC5 = 11 # 11 means that the case happen
        O05 = 10 # 10 means that the case does not happen
    elif c50_0 == 10:
        O05 = 11
        OC5 = 10

# Case 9.- S_LevelLow is always open
# [0 0 0 0 0 0 0 0 0 0 0 0]
# Name: "004"
# Case 3.- S_LevelLow is open and then close# [0 0 0 0 0 0 1 1 1 1 1 1]
# Name: "0C4"
if S_LevelLow[0] == 0:
    for float40 in S_LevelLow:
        if float40 == 1:
            c40_1 += 1
        elif float40 == 0:
            c40_0 += 1

    if c40_1 >= 1:
        OC4 = 11 # 11 means that the case happen
        O04 = 10 # 10 means that the case does not happen
    elif c40_0 == 10:
        O04 = 11
        OC4 = 10

# Case 8.- S_LevelHigh is always closed
# [1 1 1 1 1 1 1 1 1 1 1 1]
# Name: "CC5"
# Case 1.- S_LevelHigh is closed and then open
# [1 1 1 1 1 1 1 0 0 0 0 0]
# Name: "C05"
if S_LevelHigh[0] == 1:
    for float51 in S_LevelHigh:
        if float51 == 0:
            c51_0 += 1
        elif float51 == 1:
            c51_1 += 1

    if c51_0 >= 1:
        C05 = 11 # 11 means that the case happen
        CC5 = 10 # 10 means that the case does not happen
    elif c51_1 == 10:
        CC5 = 11
        C05 = 10

# Case 10.- S_LevelLow is always closed
# [1 1 1 1 1 1 1 1 1 1 1 1]
# Name: "CC4"
# Case 2.- S_LevelLow is close and then open
# [1 1 1 1 1 1 1 0 0 0 0 0]
# Name: "C04"
if S_LevelLow[0] == 1:

```



```

for float41 in S_LevelLow:
    if float41 == 0:
        c41_0 += 1
    elif float41 == 1:
        c41_1 += 1

if c41_0 >= 1:
    C04 = 11 # 11 means that the case happen
    CC4 = 10 # 10 means that the case does not happen
elif c41_1 == 10:
    CC4 = 11
    C04 = 10

# Case 5.- Sensor flow 1 is open and then close
# [a a a a a a a a 0 0 0 0 0] "0 is no flow"
# Name: "SF10C"
# Case 11.- Sensor flow 1 is always open
# [a a a a a a a a a a a a]
# Name: "SF100"
if Sensor_1[0] != 0:
    for SF1 in Sensor_1:
        if SF1 == 0:
            csf_oc += 1
        elif SF1 != 0:
            csf_oo += 1

    if csf_oc >= 1:
        SF10C = 11
        SF100 = 10
    elif csf_oo == 10:
        SF100 = 11
        SF10C = 10

# Case 6.- Sensor flow is close and then open
# [0 0 0 0 0 a a a a a a a]
# Name: "SF1C0"
# Case 12.- Sensor flow is always close
# [0 0 0 0 0 0 0 0 0 0 0 0]
# Name: "SF1CC"
if Sensor_1[0] == 0:
    for SF1_0 in Sensor_1:
        if SF1_0 != 0:
            csf_co += 1
        elif SF1_0 == 0:
            csf_cc += 1

    if csf_co >= 1:
        SF1C0 = 11
        SF1CC = 10
    elif csf_cc == 10:
        SF1CC = 11
        SF1C0 = 10

```

Appendix C.10. Tank is full

```

if CC5 == 11 and CC4 == 11 and SF10C == 11:
    print("The tank is already full")

```

Appendix C.11. Solenoid is stuck

```

if 005 == 11 and (004 == 11 or C04 == 11):
    print("The tank is empty")
    if SF1CC == 11:
        print("The solenoid is stuck or disconnected and cannot be open")

```

Appendix C.12. Tank is filling

```

if SF100 == 11 or SF1CO == 11:
    print("The tank is filling")

```

Appendix C.13. Solenoid cannot be close

```

if (SF100 == 11 or SF1CO == 11) and (OC4 == 11 or CC4 == 11):
    print("The tank is filling over low sensor")
    if CC5 == 11:
        print("The solenoid is stuck and cannot be close")

```

Appendix C.14. Tank is emptying

```

if (C05 == 11 or 005 == 11) and SF1CC == 11 and CC4 == 11:
    print("The tank is emptying")

```

Appendix C.15. Leaks in the tank

```

cce = 0 # Counter for emptying
cc = 0 # Counter for filling
NSF = 20 # Max data to append
maxFilling = max(F_time)
maxEmptying = max(E_time)
LearnFilling = []
LearnEmptying = []
if maxFilling != 0 and ft_l < NSF:
    LearnFilling.append(maxFilling)
    DataSampleF.append(ft_l)
    ft_l += 1
if maxEmptying != 0 and fe_l < NSF:
    LearnEmptying.append(maxEmptying)
    DataSampleE.append(fe_l)
    fe_l += 1
if ft_l == NSF and cc == 0:
    FT_mean = stats.mean(LearnFilling)
    cc += 1
if fe_l == NSF and cce == 0:
    ET_mean = stats.mean(LearnEmptying)
    cce += 1
if cc == 1:
    FT_test = max(F_time)
if cce == 1:
    ET_test = max(E_time)
ErrorFT = abs(FT_mean - FT_test)/(FT_mean) # Defining percentage error for
filling
ErrorET = abs(ET_mean - ET_test) / (ET_mean)

```

```
if ErrorFT > 0.05 or ErrorET > 0.05:
    print("The tank has leaks")
```

Appendix C.16. Refrigeration data filter

```
# Data storage
T1 = df.Temperatura           # Temperature data
Sample = range(len(DataLearn)) # Data taken
# Filters
i = 0
j = 0
DataLearn = []
length = len(T1)
print(length)
for x in T1:
    if j < length:
        if T1[i] > -14:
            print("The system is not stable")
            i += 1
        elif T1[i] <= -14:
            DataLearn.append(T1[i])
            i += 1
j += 1
print(DataLearn)
```

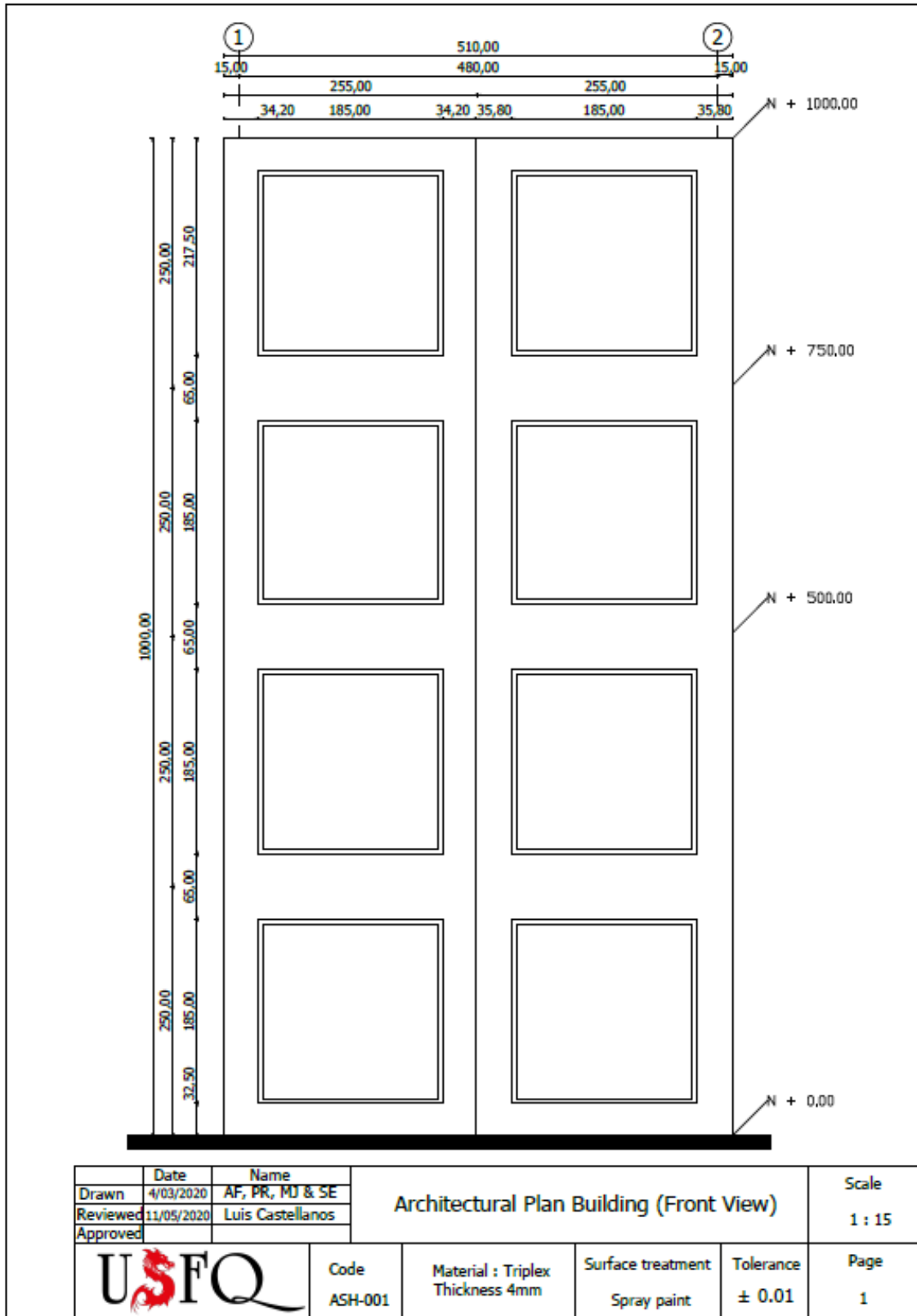
Appendix C.17. The door is open

```
temporal = 0
TSP = 3
for i in range(len(temp)):
    print(temp[i])
    if temp[i] > -14 and i >= 2 and temp[i - 1] > -14 and temp[i - 2] > -14:
        print("The door is open")
```

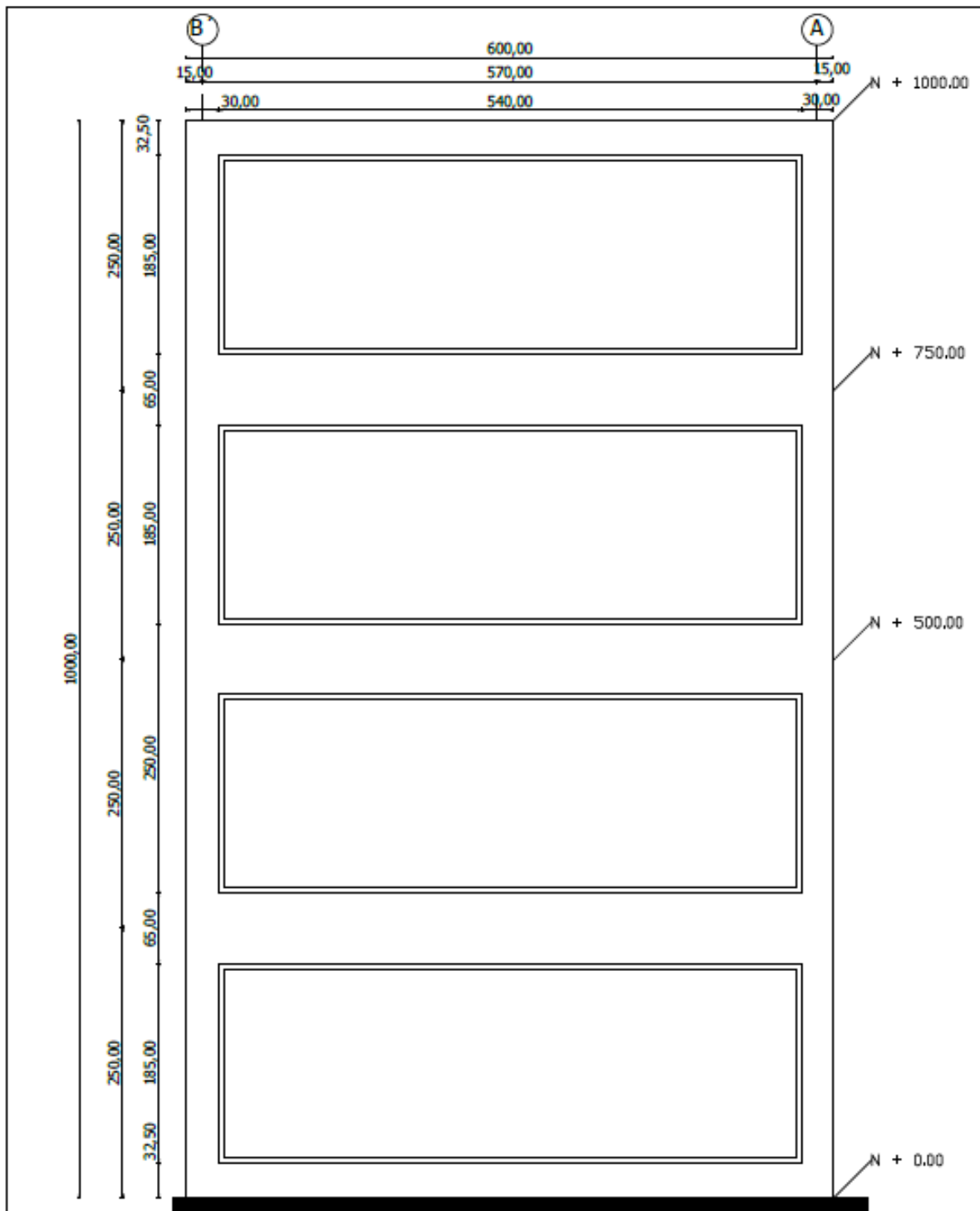
Appendix – Engineering drawing


Appendix D – Architectural Plans

Appendix D.1. Building front view

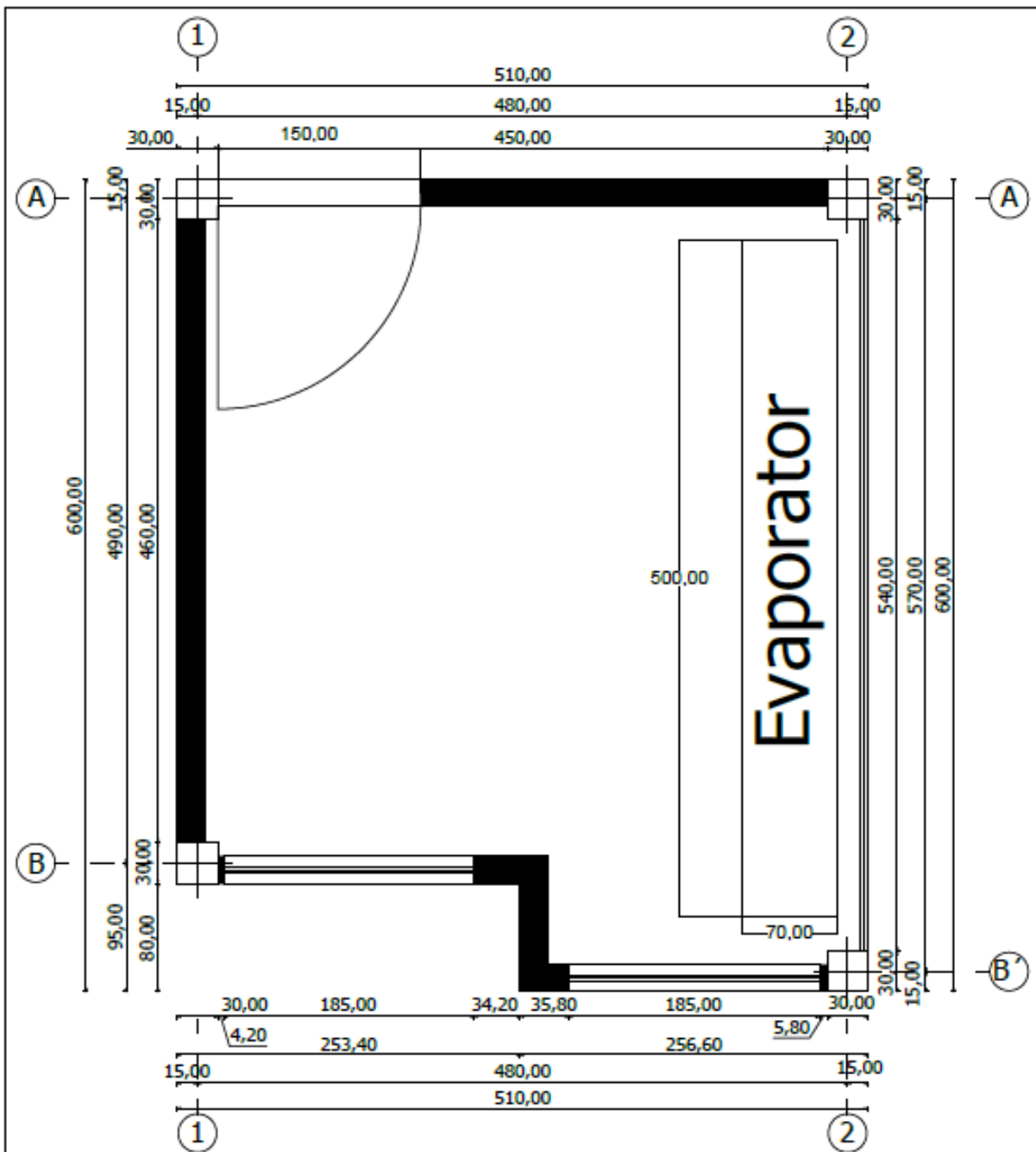


Appendix D.2. Building right side view




	Date	Name	Architectural Plan Building (Rigth side view)			Scale
Drawn	4/03/2020	AF, PR, MJ & SE				1 : 15
Reviewed	11/05/2020	Luis Castellanos				
Approved						
		Code ASH-002	Material : Triplex Thickness 4mm	Surface treatment Spray paint	Tolerance ± 0.01	Page 2

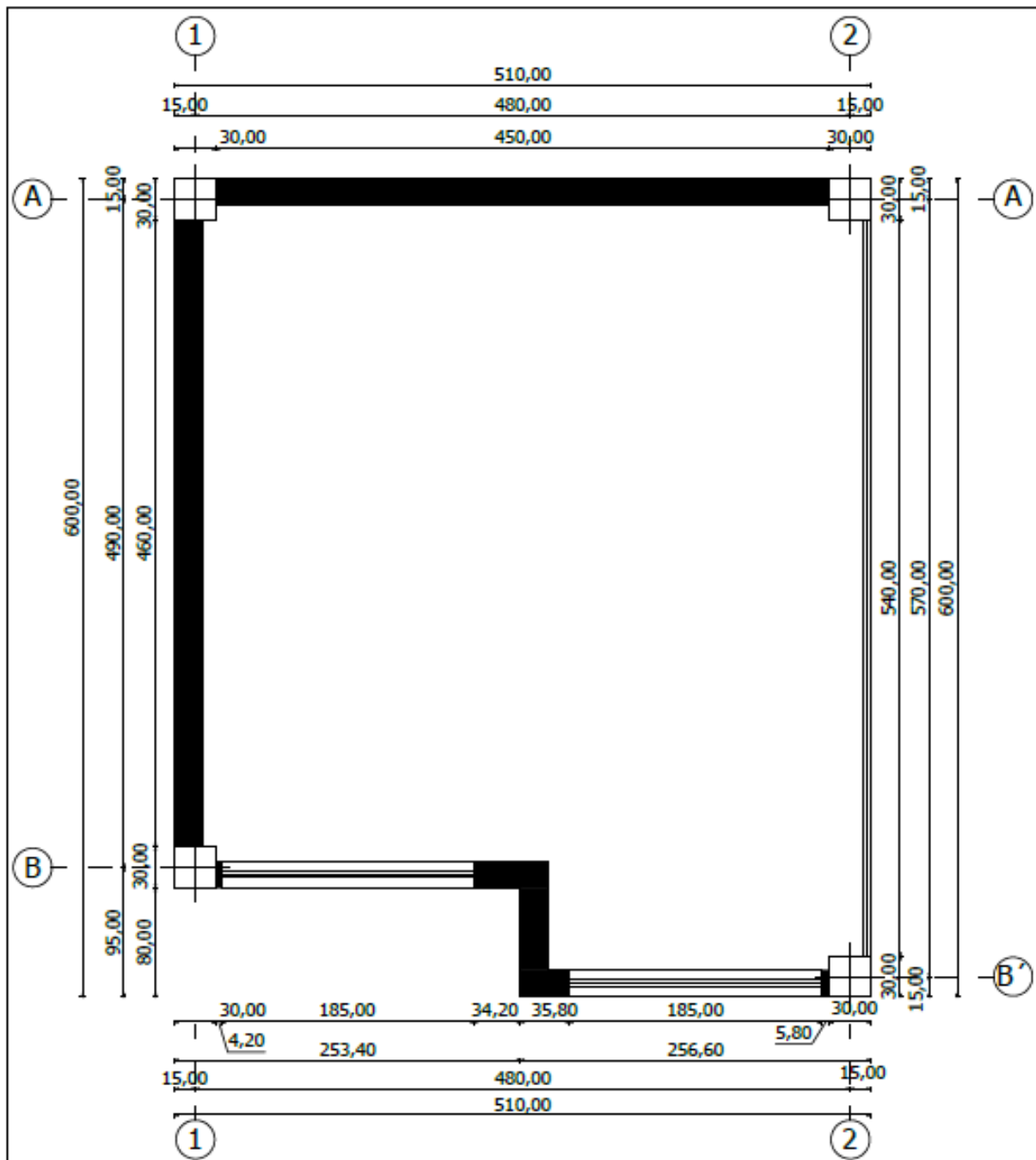
Appendix D.3. First floor top view




PLANT N: + 500.00

Drawn	Date	Name	First floor plan with top view			Scale
4/03/2020	AF, PR, MJ & SE					1 : 4
Reviewed	11/05/2020	Luis Castellanos				
Approved						
		Code	Material : Triplex	Surface treatment	Tolerance	Page
		ASH-003	Thickness 4mm	Spray paint	± 0.01	3

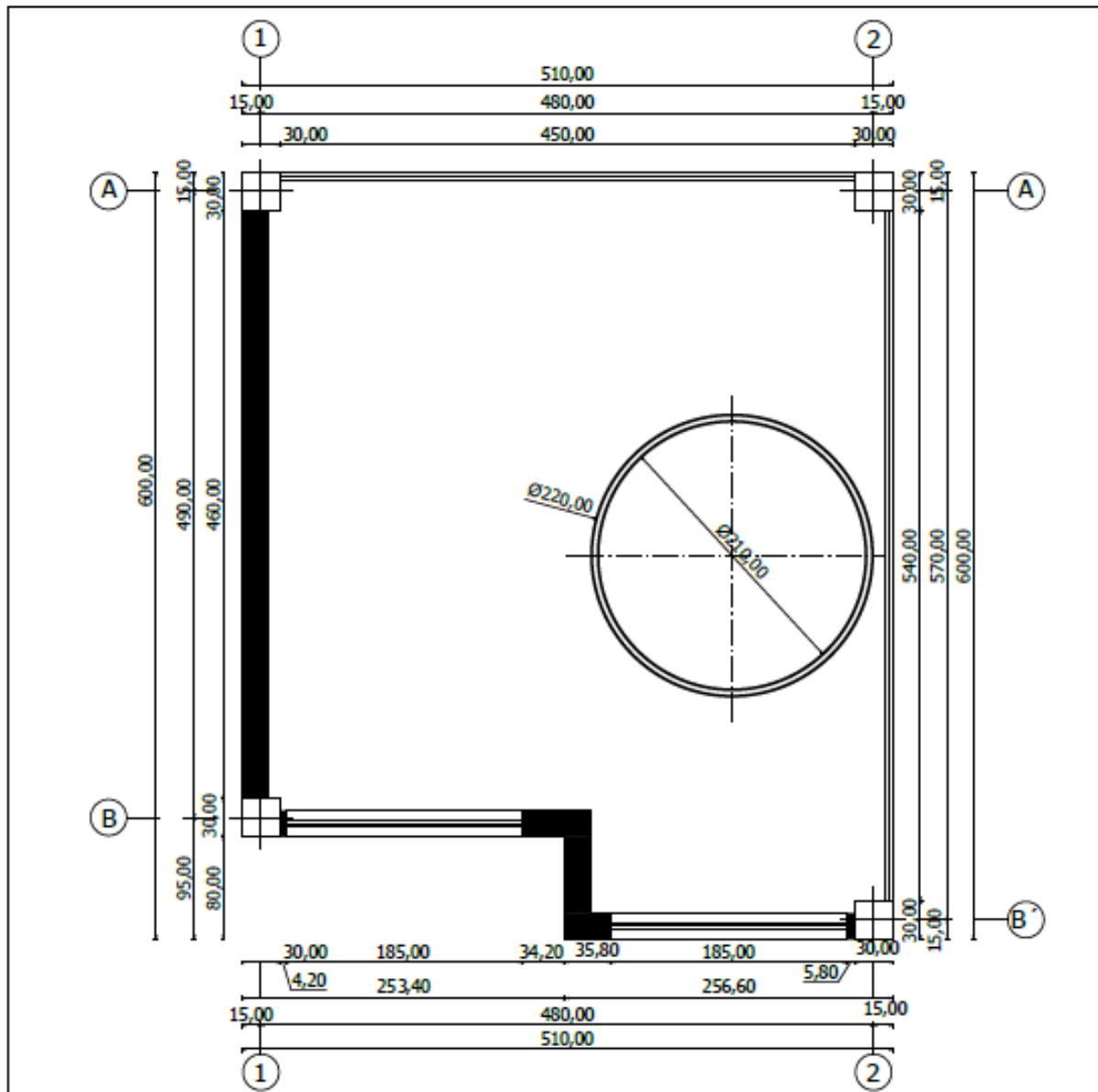
Appendix D.4. Third floor top view




PLANT N: +750.00

Drawn	Date	Name	Third floor plan with top view			Scale
4/03/2020	AF, PR, MJ & SE					1 : 4
Reviewed	11/05/2020	Luis Castellanos				
Approved						
		Code	Material : Triplex	Surface treatment	Tolerance	Page
		ASH-004	Thickness 4mm	Spray paint	± 0.01	4

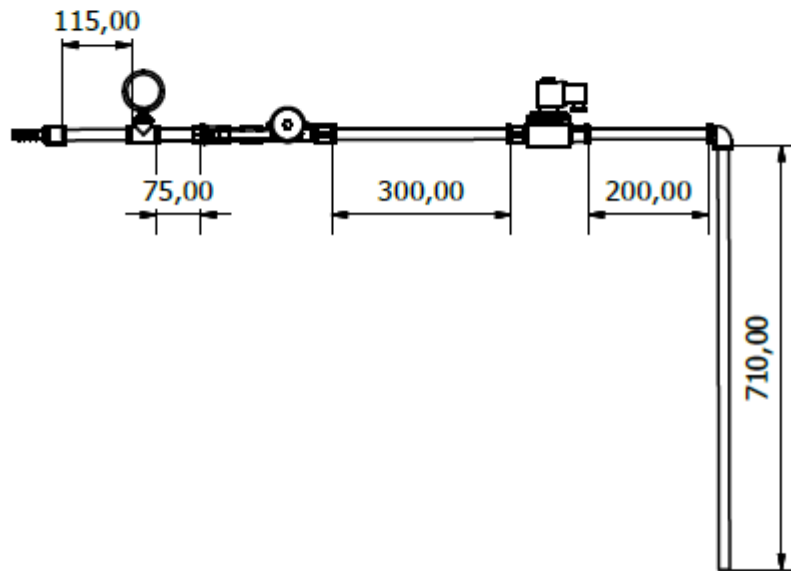
Appendix D.5. Fourth floor top view




PLANT N:+1000.00

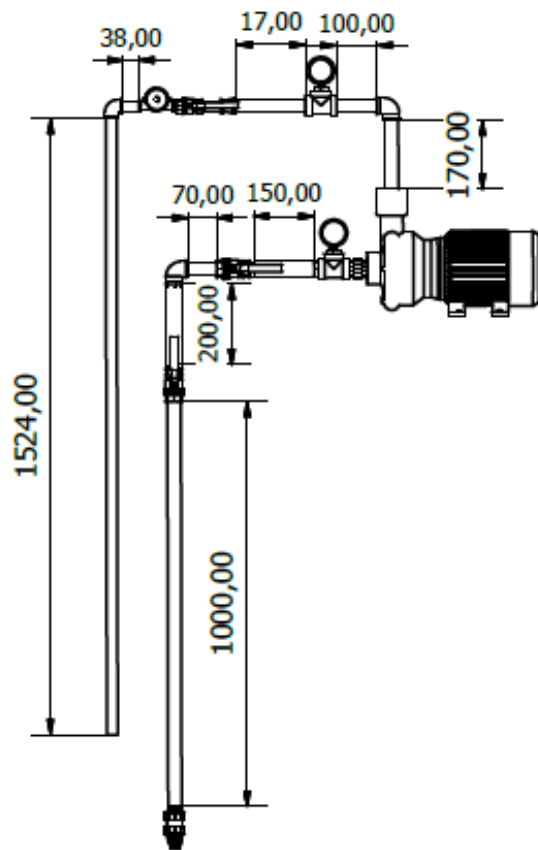
Drawn	4/03/2020	AF, PR, MD & SE	Fourth floor plan with top view			Scale
Reviewed	11/05/2020	Luis Castellanos				1 : 4
Approved						
		Code ASH-005	Material : Triplex Thickness 4mm	Surface treatment Spray paint	Tolerance ± 0.01	Page 5

Appendix D.6. Water supply



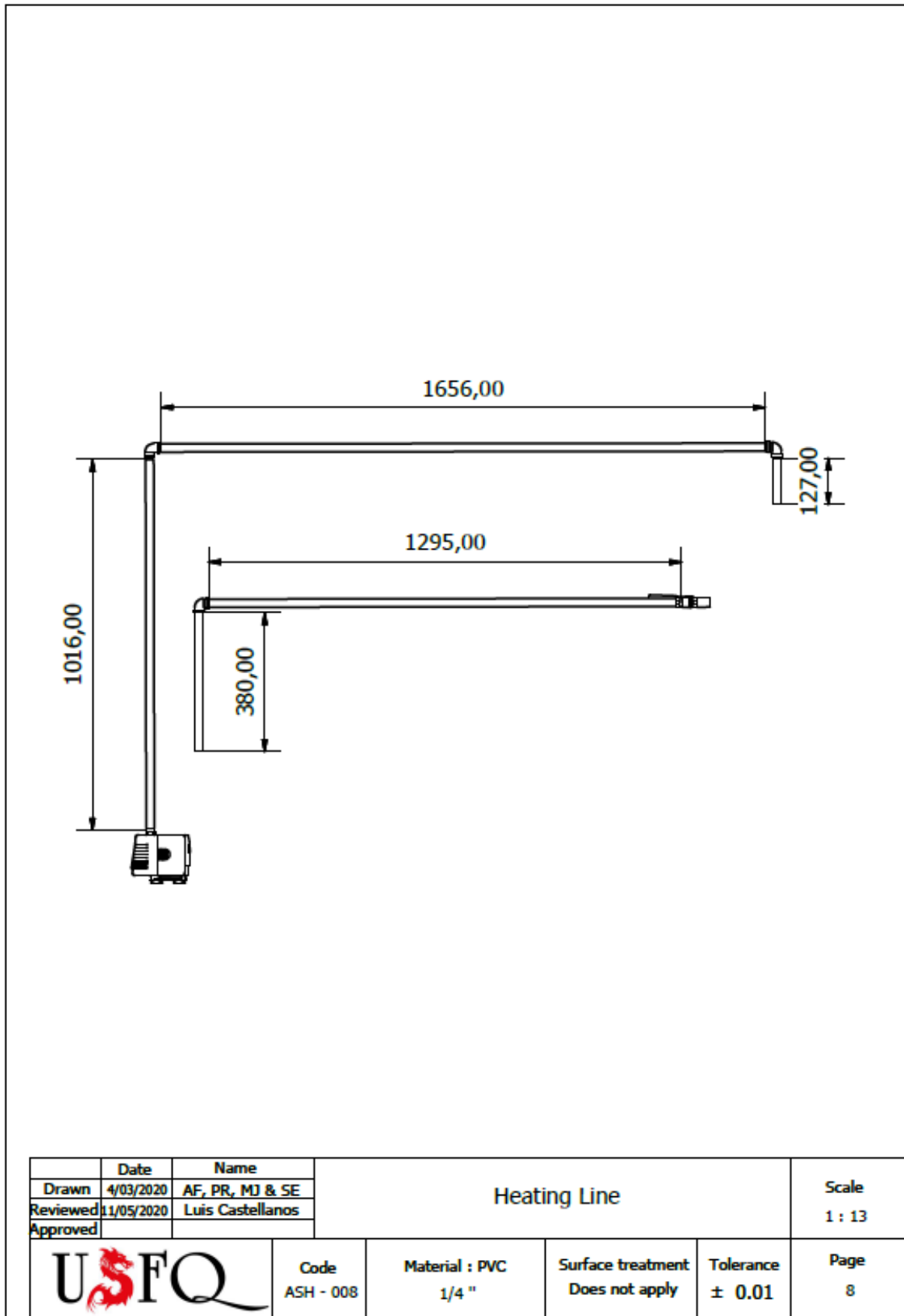
	Date	Name	Water supply line			Scale
Drawn	4/03/2020	AF, PR, M1 & SE				1 : 10
Reviewed	11/05/2020	Luis Castellanos				
Approved						
		Code ASH - 006	Material : PVC ½"	Surface treatment Does not apply	Tolerance ± 0.01	Page 6


Appendix D.7. Cavitation line



	Date	Name	Cavitation Line			Scale
Drawn	4/03/2020	AF, PR, MJ & SE				1 : 15
Reviewed	11/05/2020	Luis Castellanos				
Approved						
USFQ		Code ASH - 007	Material : PVC 1 " to 3/4 "	Surface treatment Does not apply	Tolerance ± 0.01	Page 7

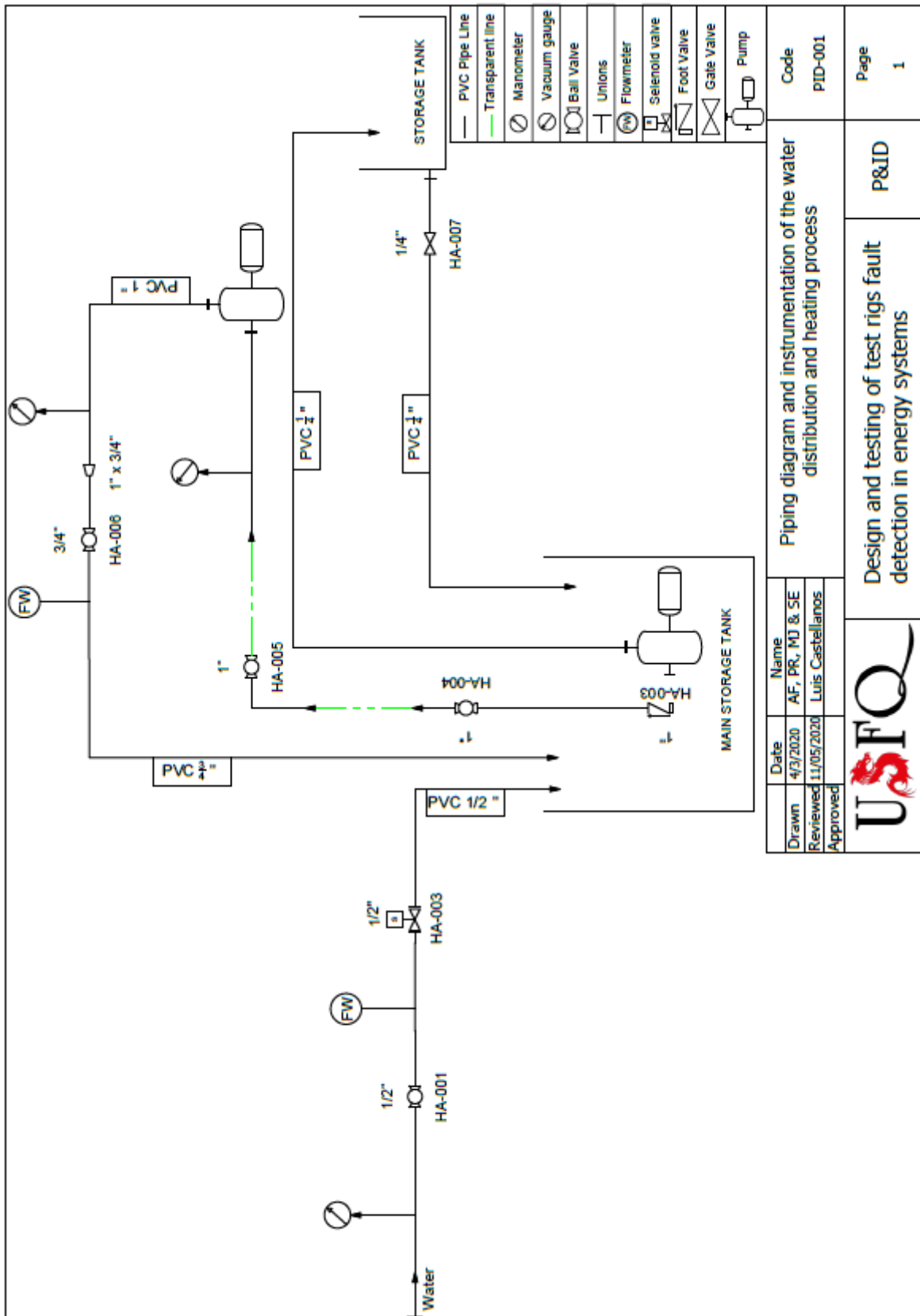
Appendix D.8. Heating line



	Date	Name	Heating Line			Scale
Drawn	4/03/2020	AF, PR, MJ & SE				1 : 13
Reviewed	11/05/2020	Luis Castellanos				
Approved						
		Code ASH - 008	Material : PVC 1/4 "	Surface treatment Does not apply	Tolerance ± 0.01	Page 8

Appendix E – P&ID plans

Appendix E.1. Heating and water supply system



Appendix – Project Management

Appendix F – Expenses and budget report

Item	System	Cost [\$]
Triplex	Building	25.00
Triplex cutting	Building	7.50
Glasses	Building	14.50
Paint for building	Building	6.72
Screws and screwdriver	Building	5.50
Glue for glass	Building	10.74
Electronic components	Heating	61.30
Elbows and accessories	Heating	61.10
Solenoid valve, electronic components, pipes	Water supply	30.00
Materials for pump support	Water supply	22.81
Condenser and evaporator	Refrigeration	45.00
Electronic components	Refrigeration	11.30
Total		301.47

Item	System	Cost [\$]
Wood, glass sheets, paint, additional materials	Building	50.00
Electronic components	Heating	70.00
Piping, accessories	Heating	50.00
Materials for pump support	Water supply	20.00
System main components	Refrigeration	50.00
Electronic components	Refrigeration	60.00
Total		300.00

Appendix – Materials and Methods

Appendix H – Materials and component selections

Appendix H.1. Ordinal method corrected by weighted criteria for heating

BY CRITERIAS					
Price > Energy > Efficiency					
Criteria	Price	Energy	Efficiency	$\Sigma+1$	Weighting
Price		1	1	3	0.5000
Energy	0		1	2	0.3333
Efficiency	0	0		1	0.1667
			Average	6	1.0000

BY CONSTRUCTION PRICE						
Solution 1 > Solution 2 > Solution 3 > Solution 4						
Criteria	Solution 1	Solution 2	Solution 3	Solution 4	$\Sigma+1$	Weighting
Solution 1		1	1	1	4	0.40
Solution 2	0		1	1	3	0.30
Solution 3	0	0		1	2	0.20
Solution 4	0	0	0		1	0.10
				Average	10	1.00

BY ENERGY CONSUMPTION						
Solution 1 > Solution 2 > Solution 3 > Solution 4						
Criteria	Solution 1	Solution 2	Solution 3	Solution 4	$\Sigma+1$	Weighting
Solution 1		1	1	1	4	0.40
Solution 2	0		1	1	3	0.30
Solution 3	0	0		1	2	0.20
Solution 4	0	0	0		1	0.10
				Average	10	1.00

BY THERMAL EFFICIENCY						
Solution 4 > Solution 2 > Solution 1 > Solution 3						
Criteria	Solution 1	Solution 2	Solution 3	Solution 4	$\Sigma+1$	Weighting
Solution 1		0	1	0	2	0.20
Solution 2	1		1	0	3	0.30
Solution 3	0	0		0	1	0.10
Solution 4	1	1	1		4	0.40
				Average	10	1,00

Appendix H.2 Ordinal method corrected by weighted criteria for refrigeration

BY CRITERIAS					
Pression drop > Size > Price					
Criteria	Price	Size	Pression Drop	$\Sigma+1$	Weighting
Price		0	0	1	0.1667
Size	1		0	2	0.3333
Pression Drop	1	1		3	0.5000
			Average	6	1.0000

BY EQUIPMENT PRICE				
Solution 2 > Solution 1				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		0	1	0.33
Solution 2	1		2	0.67
			3	1.00

BY THE SIZE THAT THE SYSTEM CAN HANDDLE				
Solution 2 > Solution 1				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		0	1	0.33
Solution 2	1		2	0.67
		Average	3	1.00

BY PRESSION DROP THAT CAN SUPPORT				
Solution 2 > Solution 1				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		0	1	0.33
Solution 2	1		2	0.67
		Average	3	1.00

Appendix H.3 Ordinal method corrected by weighted criteria for water supply

BY CRITERIAS					
Availability > Price > Accuracy					
Criteria	Availability	Price	Accuracy	$\Sigma+1$	Weighting
Availability		1	1	3	0.5000
Price	0		1	2	0.3333
Accurate	0	0		1	0.1667
			Average	6	1.0000

BY COMPONENTES AVAILABILITY				
Solution 1 > Solution 2				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		1	2	0.67
Solution 2	0		1	0.33
		Average	3	1.00

BY PRICE				
Solution 1 > Solution 2				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		1	2	0.67
Solution 2	0		1	0.33
		Average	3	1.00

BY PROXIMITY TO THE RESULTS				
Solution 1 > Solution 2				
Criteria	Solution 1	Solution 2	$\Sigma+1$	Weighting
Solution 1		1	2	0.67
Solution 2	0		1	0.33
		Average	3	1.00

Appendix I.2. Detailed materials list


BUILDING	HEATING SYSTEM (PIPELINE)	HEATING SYSTEM (ACCESORIES)
<p>(16) wooden columns, 30 mm x 30 mm cross section and 325 mm long</p>	<p>1" PVC pipe (total of 2.2 m) divided into the following segments</p> <ul style="list-style-type: none"> • (1) 134 cm • (1) 20 cm • (2) 17 mm • (1) 15 cm • (1) 10 cm • (1) 7 cm 	<p>1" PVC pipeline</p> <ul style="list-style-type: none"> • (1) foot valve • (2) ball valve • (4) nozzles • (2) elbows • (2) reduction sections from 1" to 1/2" • (2) tees • (1) universal pipe unión • (1) reduction section from 1" to 3/4"
<p>Wood sheets (3mm thick)</p> <p>(5) 510 mm x 600 mm</p> <ul style="list-style-type: none"> • (4) 460 mm x 250 mm • (2) 450 mm x 250 mm • (1) 540 mm x 250 mm • (1) 300 mm x 250 mm • (4) 34,2 mm x 250 mm • (4) 35,8 mm x 250 mm • (4) 80 mm x 250mm 	<p>3/4" PVC pipe (total of 1.6 m) divided into the following segments</p> <ul style="list-style-type: none"> • (1) 152.4 cm • (2) 3.8 cm 	<p>3/4" PVC pipeline</p> <ul style="list-style-type: none"> • (1) ball valve • (2) reduction sections from 3/4" to 1/2" • (1) elbow
<p>Glass sheets (3mm thick)</p> <ul style="list-style-type: none"> • (8) 185 mm x 185 mm • (3) 540 mm x 185 mm • (1) 150 mm x 185 mm • (1) 150 mm x 185 mm 	<p>1/2" PV PVC pipe (total of 1.4 m) divided into the following segments</p> <ul style="list-style-type: none"> • (1) 70 cm • (1) 29 cm • (1) 20 cm • (1) 11.5 cm • (1) 7.5 cm • (1) 2 cm 	<p>1/2" PVC pipeline</p> <ul style="list-style-type: none"> • (5) joints • (1) tee • (1) ball valve • (1) reduction section from 1/2" to 1/4" • (1) elbow • (1) nozzle
	<p>1/4" PVC pipe (total of 1.68 m) divided into the following segments</p> <ul style="list-style-type: none"> • (1) 130 cm • (1) 38 cm 	<p>1/4" PVC pipeline</p> <ul style="list-style-type: none"> • (3) elbows • (1) ball valve • (1) PVC reducing bushing
	<p>1/4" transparent flexible pipe (total of 2.8 m) dividend into the following segments</p> <ul style="list-style-type: none"> • (1) 165.7 cm • (1) 101.6 cm • (1) 12.7 cm 	

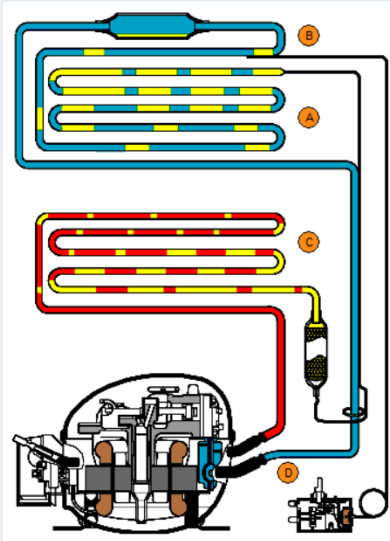
Appendix – Results and discussions

Appendix J – Engineering Analysis

Appendix J.1. Capillary selection obtained Danfoss, n.d.

Danfoss Capillary Tube Selector

DanCap™ Version 1.0 Database 1.0 



Input Data

Refrigerant	R134a
A Heat load of the system	1068,00i Btu/hr
B Evaporating temperature	-10 °C
C Condensing temperature	45 °C
D Return gas temperature	5 °C

Capillary Tube Recommendation

Flow Rate: 1.04 CFM (N₂ at delta p 145 psi)

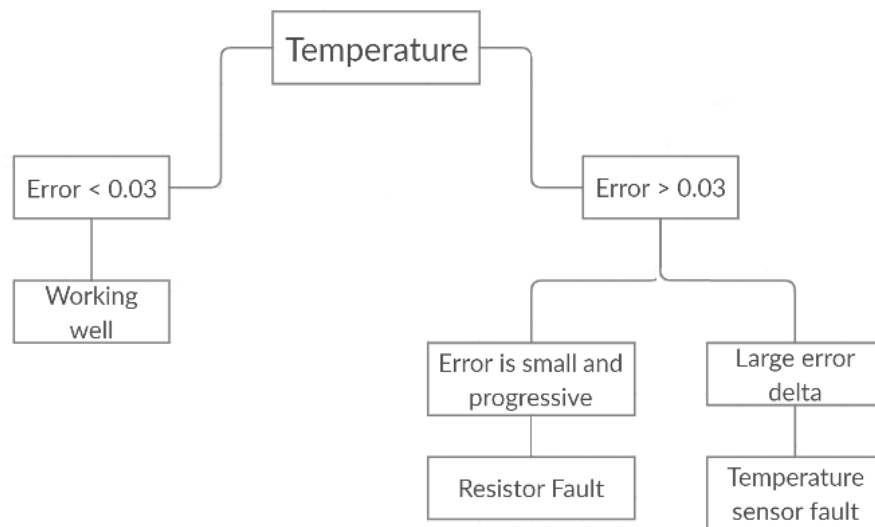
Length	Inner Diameter
0.11 m	0.026 in.
0.26 m	0.031 in.
0.56 m	0.036 in.
1.20 m	0.042 in.
1.51 m	0.044 in.
2.59 m	0.049 in.
2.87 m	0.050 in.
4.22 m	0.054 in.
4.62 m	0.055 in.

Optimal selection is highlighted in green.

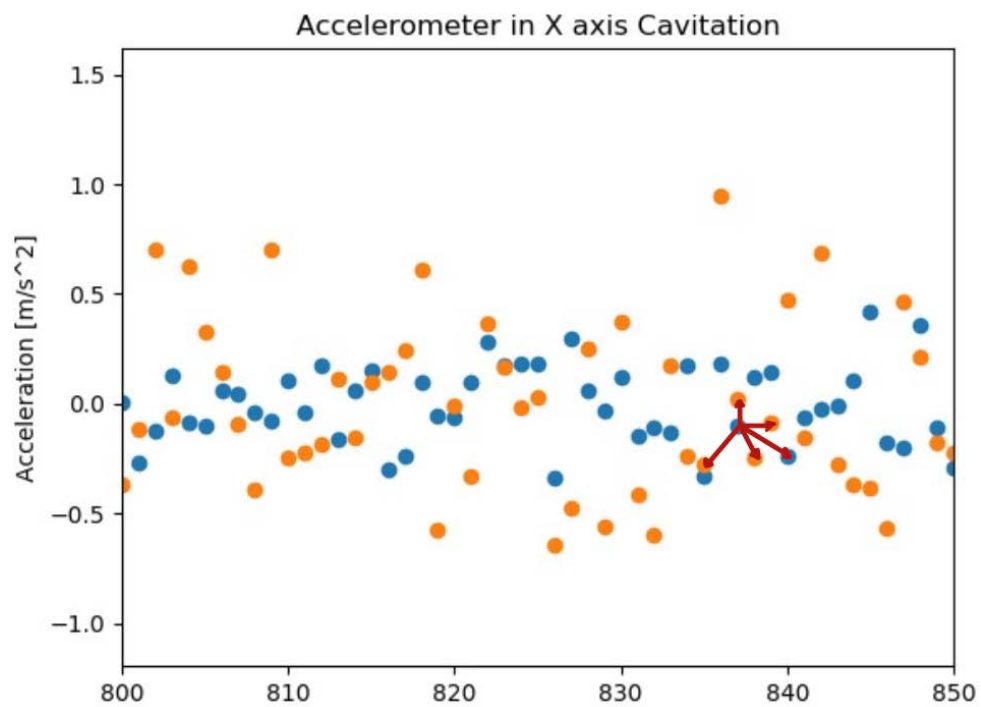
Homepage: compressors.danfoss.com Help Print Settings

Appendix K – Fault detection

Appendix K.1. Decision tree for heating faults

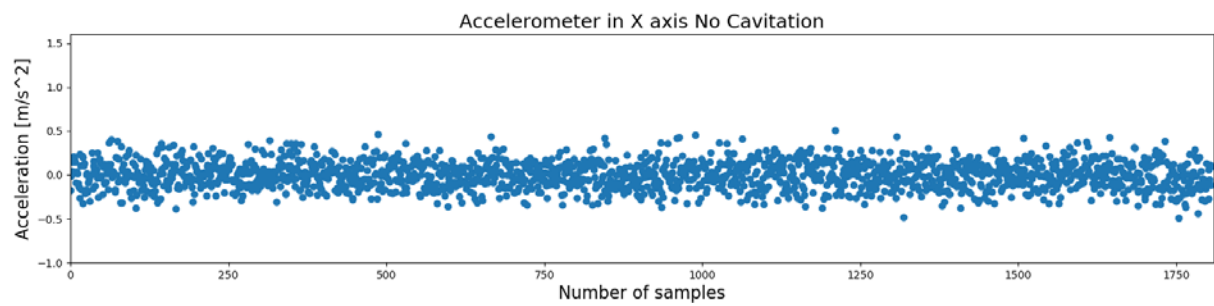
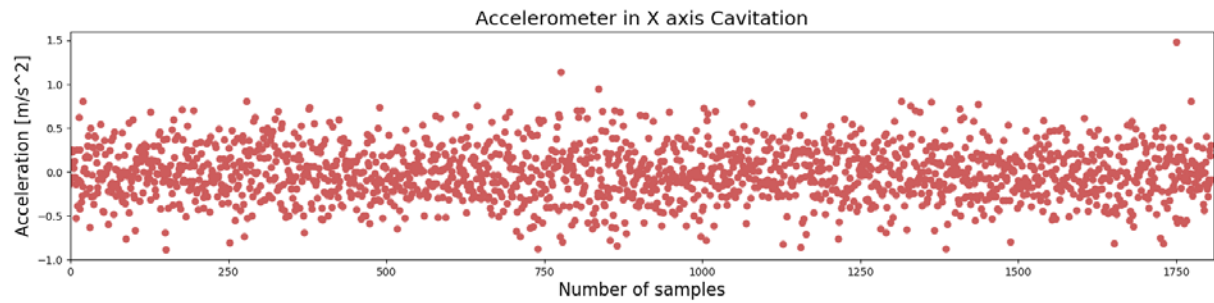


Appendix K.2. K- nearest neighbors

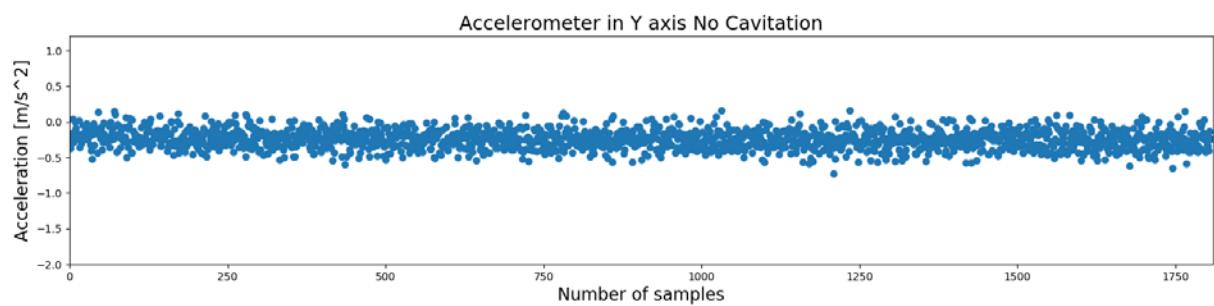
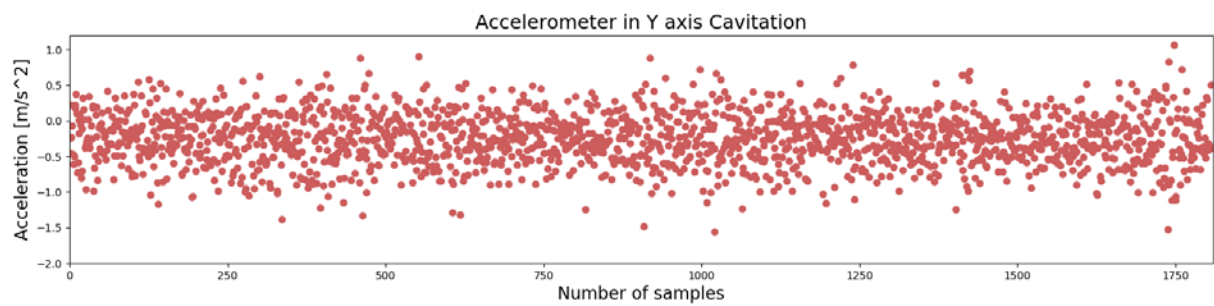


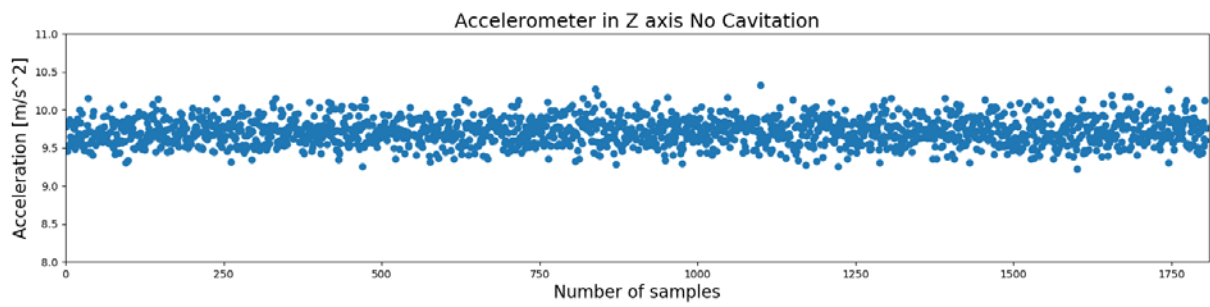
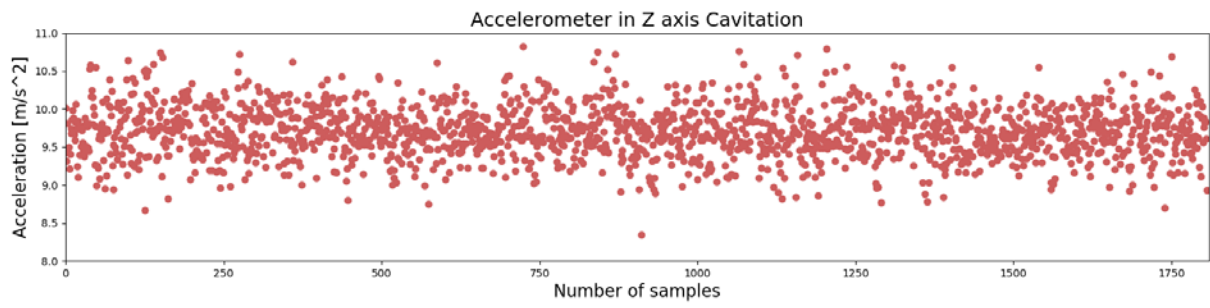
Appendix L – Engineering experiments for verification (Cavitation)

Appendix L.1. Accelerometer in X axis



Appendix L.2. Accelerometer in Y axis



Appendix L.3. Accelerometer in Z axis

Appendix M – Safety through design

Appendix M.1. Probability vs impact

Impact	5	D, E				
	4				F	
	3		C	B		
	2		A		G	
	1					
		1	2	3	4	5
		Probability				

Appendix M.2. Priority analysis

Code	Description	Priority = Impact x Probability
F	Exceed the cost in the components.	$4 \cdot 4 = 16$
B	Debris or dirt can cause clogging problems in the pipe or valves.	$3 \cdot 3 = 9$
G	Flow sensors not available.	$2 \cdot 4 = 8$
C	A bad installation or a breakdown in the sensors causes data collection failure.	$3 \cdot 2 = 6$
D	Not having the right pump.	$5 \cdot 1 = 5$
E	The compressor is not new, and it has irreparable damage.	$5 \cdot 1 = 5$
A	Water tank cracks can cause water leakage problems.	$2 \cdot 2 = 4$

Appendix N – Operational Manual

This part shows how make faults happen in the test rigs. To have good results is necessary to validate that the sensors are working well with Prototype Test Plan section before to continue with the next steps. The whole project sketch is in Appendix N.1.

- **Fault considerations.**

Using the Design Report section, it is easy to assemble the physical system. This project does not require advanced manufacturing, only joining components, pipe sections or electronic connections. Given that the sensors are far from the Arduino and breadboard, it is necessary to use Ethernet wires to reach the sensor and keep safe all electronic components. These connections are soldered with tin (Sn) and it needs to be checked constantly and handled carefully if the system gets disassembled. It is important to point out that the water flow sensors are in liters per hour, the temperature sensor in Celsius and the MPU signals are in meters over square second. Before starting the pump, it is very important to fill the pipeline with water. If there is no water stored in the pipeline, the algorithm detects a fault in the foot check valve.

With all components well located the next step is to connect the Arduino and run the program. It is necessary to check if the port (COM) is properly selected. Once the program is uploaded, the Python code can be run. Some values will appear in the print window that correspond to the sensor signals and 12.5 seconds later this will be repeated. During these 12.5 seconds time lapse, the first array is stored, processed and if all goes right, there should not appear any warning messages and the next array should continue. In this case, messages like “the system is not stabilized” will appear, meaning that the water in the heating part is not at the set point temperature. Also, another message is “the tank is filling” given that the initial state of the tank is empty. For the refrigeration fault detection there are no physically assembled components. However, the FDD methodology will still be applied. The Appendix

N.2 shows all the messages available where “Y” means that a fault happened and “N” for no problems detected.

Knowing these messages, the operator should act over the system when a fault is detected. When this happens, it is not necessary to stop running the code because it will continue to evaluate the situation every 12.5 seconds. If the fault is fixed, in the next evaluated array the message will change to another that indicates a normal condition.

To force those problems to happen, the state of the components must be changed. To detect a burned resistor, it is needed to disconnect one wire of the SSR that is connected to the breadboard. The PID sends the signal but the resistor does not work, in the same way for the thermocouple. In order to return to the normal state, the wires that were disconnected should return to their original port.

For refrigeration cycle, there is a data set that simulates the temperature in the cold room and measures are recorded every 10 minutes. Given that this system does not have physical components, the fault should be forced to happen in the set which has already the fault included.

In the water supply there are more problems than in the other systems. The first one is simulating that the pump is not working by disconnecting it. Then the algorithm should detect this fault. Another problem is located in the foot check valve. To simulate this problem, before turning on the pump the pipe should be emptied, having no water in the inlet and no water in the outlet.

One of the most important problems to be detected is cavitation. To make it happen, this system has two ball valves that have to be closed. When the problem is forced, the pump will start to vibrate depending on the allowed water flow by the valves. It is important to highlight that if the valves are closed more than 2/3 of their original state, the system does not cavitate because the suction is not adequate to allow enough water to reach the pump

inlet, detecting that it is not working. To detect water leaks in the tank it is necessary to perforate it and keep it covered until it is required to remove it and allow the water leakage.

The last fault to be detected is a burned solenoid. One wire should be disconnected to simulate the fault. The next table describes all faults related to each component.

Table 11
Fault list which is related components.

Component	Fault	System	Probability
Resistor	Burned/disconnected	Heating	High
Thermocouple	Burned/disconnected	Heating	Low
Temperature sensor	Unexpected change	Refrigeration	Low
Pump	Stop working	Water supply	Low
Foot check valve	Water go down	Suction part	High
Pump	Cavitation	Suction part	Low
Water tank	Leaks	Water supply	High
Solenoid	Stuck/burned	Water supply	High

- **Safety and operational parameters.**

Since the purpose of this project is to detect faults by making them happen, some components can suffer irreparable damage and should be replaced. To avoid this to happen early is necessary to handle it within the right safety norms and parameters.

The ball valves in figure 26 should be closed no more than 2/3 of their capacity. If they do, the pump's maximum suction could not be enough to carry water, making the pump work without water. If this happens the pump needs to be disconnected and the pipe refilled. Also, the temperature should stay under 40°C which is a limitation given by the manufacturer.

When the pump starts to cavitate the impeller and other components may be damaged. To prevent further harm the pump must stay cavitating within 1 or 2 minutes. This is enough time to provide data for analysis and fault detection. After the data is taken, the valves must be returned to their normal state (fully open).

Another fault that can generate damage in pumps is a malfunctioning foot check valve. As already said, the water acts like refrigerant for the pump so it cannot stay working without water for more than 50 seconds. It is essential to be alert when the fault is detected so the pump can be promptly disconnected. It is also advised to not touch the pump because its surface may be hot after the experiment is carried out.

In the heating section, the resistor should be submerged in water before it is turned on. It is important to make sure that the Arduino is disconnected until the resistor is well located. Do not touch the water or the resistor while the system is working. It could cause burns to the skin and affect the sensor's measurements.

All electric components should be connected and well located in the breadboard, making sure they are far from the water supply system.

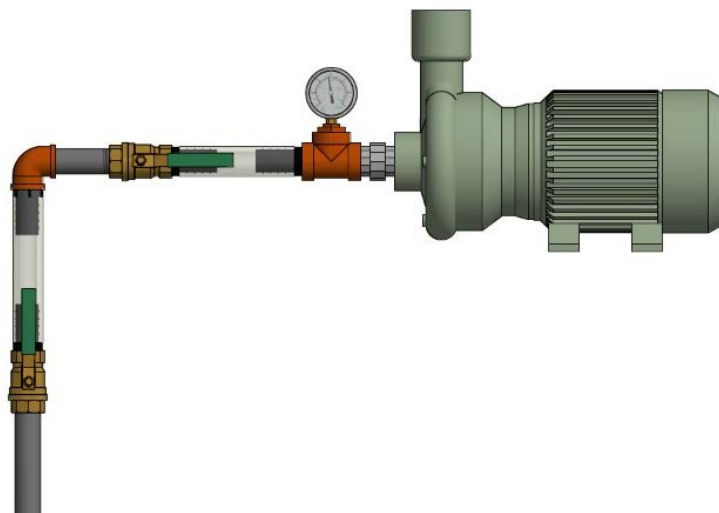
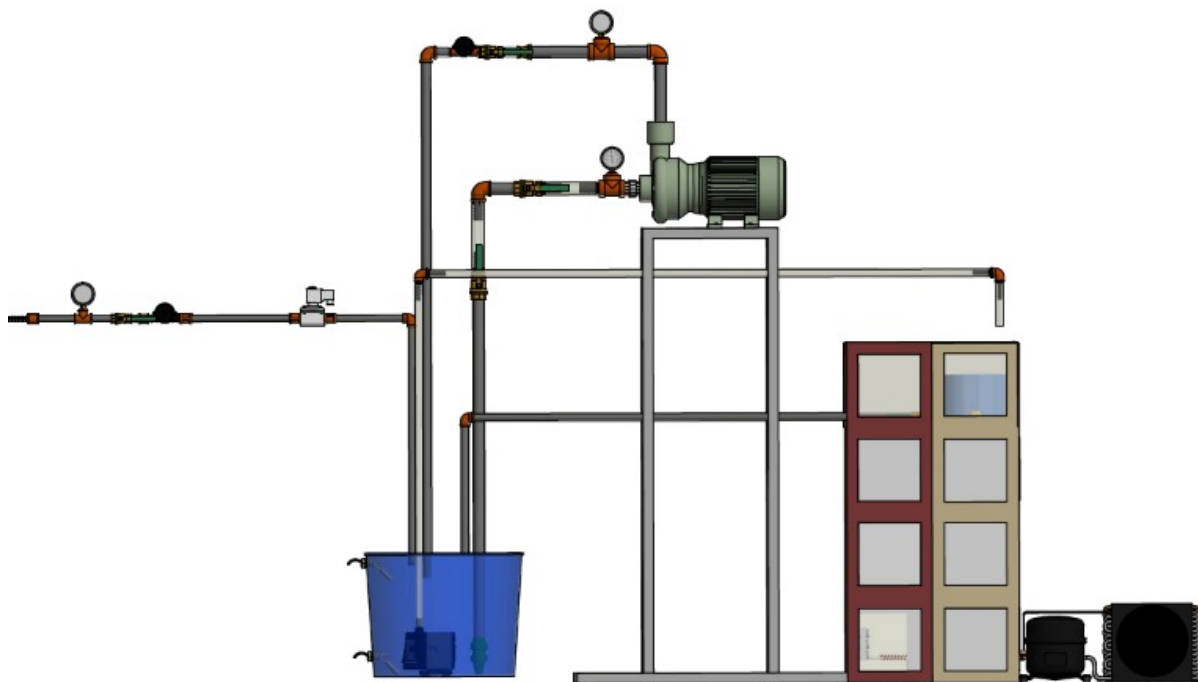


Figure 26: Ball valves in suction part.

Appendix N.1. Project sketch

Appendix N.2. Messages available in the code

System	Message	Fault
Water supply	Pump is not working	Y
Water supply	Pump is working	N
Heating	System is not stabilized	N
Heating	System is stabilized	N
Heating	Heating system is working well	N
Heating	Problem in electrical resistor	Y
Heating	Problem in temperature sensor	Y
Heating	Number of samples to go out of range	N
Water supply	The tank has leaks	Y
Water supply	The tank is already full	N
Water supply	The tank is empty	N
Water supply	The solenoid is stuck or disconnected and cannot be open	Y
Water supply	The tank is filling	N
Water supply	The tank is filling over low sensor	N
Water supply	The solenoid is stuck and cannot be close	Y
Water supply	The tank is emptying	N
Water supply	Stop the pump	Y
Water supply	Foot check valve is damaged	Y
Water supply	The pump has cavitation	Y
Water supply	The pump does not have cavitation	N
Refrigeration	The door is open	Y
Refrigeration	The refrigeration cycle is not stabilized	N

Appendix O – Future work

Appendix O.1. Detailed calculations

$$\dot{V}_1 + \dot{V}_2 = \dot{V}_3$$

$$\rho_a v_1 A_1 + \rho_{CO_2} v_2 A_2 = \left(\frac{\rho_a + \rho_{CO_2}}{2} \right) v_3 A_3$$

$$\frac{P_A}{\gamma} + \frac{v_A^2}{2g} + z_A + h_{a_1} = \frac{P_C}{\gamma} + \frac{v_C^2}{2g} + z_C + h_{L_1}$$

$$\frac{P_B}{\gamma} + \frac{v_B^2}{2g} + z_B + h_{a_2} = \frac{P_C}{\gamma} + \frac{v_C^2}{2g} + z_C + h_{L_2}$$

Points A, B and C are assumed to be sufficiently away from the entrance and the exit of the plumbing so that:

$$P_A = P_B = P_C = 0$$

$$v_A = v_B = v_C = 0$$

$$z_C = 0$$

Thus, equations before are reduced to:

$$h_{a_1} = f_1 \frac{L_1}{D} \frac{V_1^2}{2g} + f_3 \frac{L_3}{D_{h_3}} \frac{V_3^2}{2g} + \Sigma K_{L1} \frac{(v_1^2 + v_3^2)}{2g} + z_A$$

$$h_{a_2} = f_2 \frac{L_2}{D} \frac{v_2^2}{2g} + f_3 \frac{L_3}{D_{h_3}} \frac{v_3^2}{2g} + \Sigma K_{L2} \frac{(v_2^2 + v_3^2)}{2g} + z_B$$

In order to find values for the three different friction factors, Reynolds number values and relative roughness will be calculated and inputted into Colebrook's equation.

$$Re_1 = \frac{\rho_a v_1 D}{\mu_{air}}$$

$$Re_2 = \frac{\rho_{CO_2} v_2 D}{\mu_{CO_2}}$$

$$Re_3 = \frac{\left(\frac{\rho_a + \rho_{CO_2}}{2} \right) v_3 D_{h_3}}{\left(\frac{\mu_{air} + \mu_{CO_2}}{2} \right)}$$

$$\frac{\varepsilon_1}{D} \text{ relative roughness for section 1}$$

$$\frac{\varepsilon_2}{D} \text{ relative roughness for section 2}$$

$\frac{\varepsilon_3}{D_{h_3}}$ relative roughness for section 3

Where Re_1 , Re_2 and Re_3 are The Reynolds numbers. The above equations are the relative roughness values that will be employed, to find the friction factors. The following equations shows this.

$$\frac{1}{\sqrt{f_1}} = -2.0 \log \left(\frac{\frac{\varepsilon_1}{D}}{3.7} + \frac{2.51}{Re_1 \sqrt{f_1}} \right)$$

$$\frac{1}{\sqrt{f_2}} = -2.0 \log \left(\frac{\frac{\varepsilon_2}{D}}{3.7} + \frac{2.51}{Re_2 \sqrt{f_2}} \right)$$

$$\frac{1}{\sqrt{f_3}} = -2.0 \log \left(\frac{\frac{\varepsilon_3}{D_{h_3}}}{3.7} + \frac{2.51}{Re_3 \sqrt{f_3}} \right)$$

Notes:

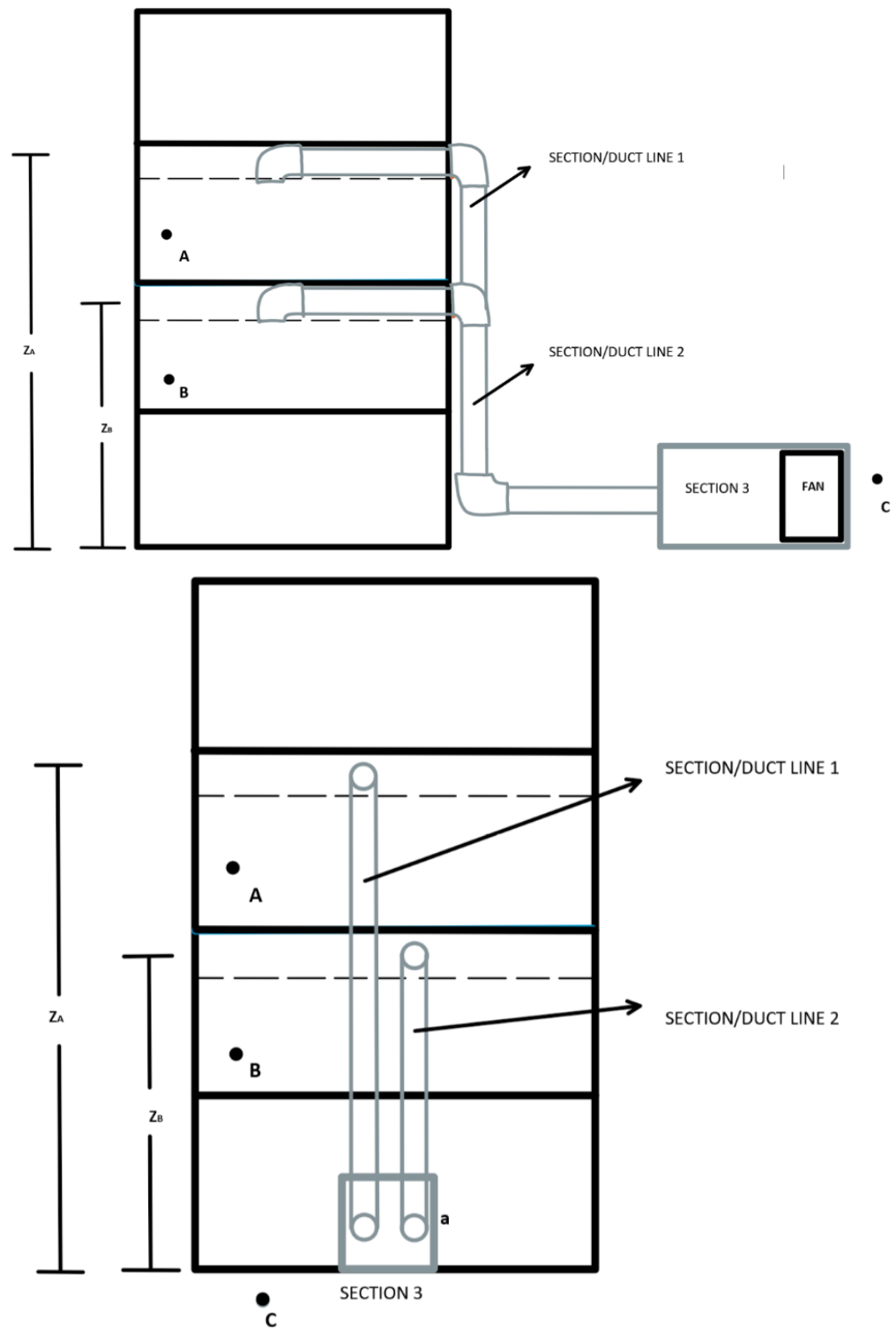
It is important to highlight that every time section three's geometry is involved, its hydraulic diameter will be employed. As shown in Appendix O.2 geometry is assumed a square with a side length a . The hydraulic diameter is defined as:

$$D_{h_3} = \frac{4A}{P} = \frac{4a^2}{4a} = a$$

Where A is the cross-sectional area for section 3 and P its perimeter.

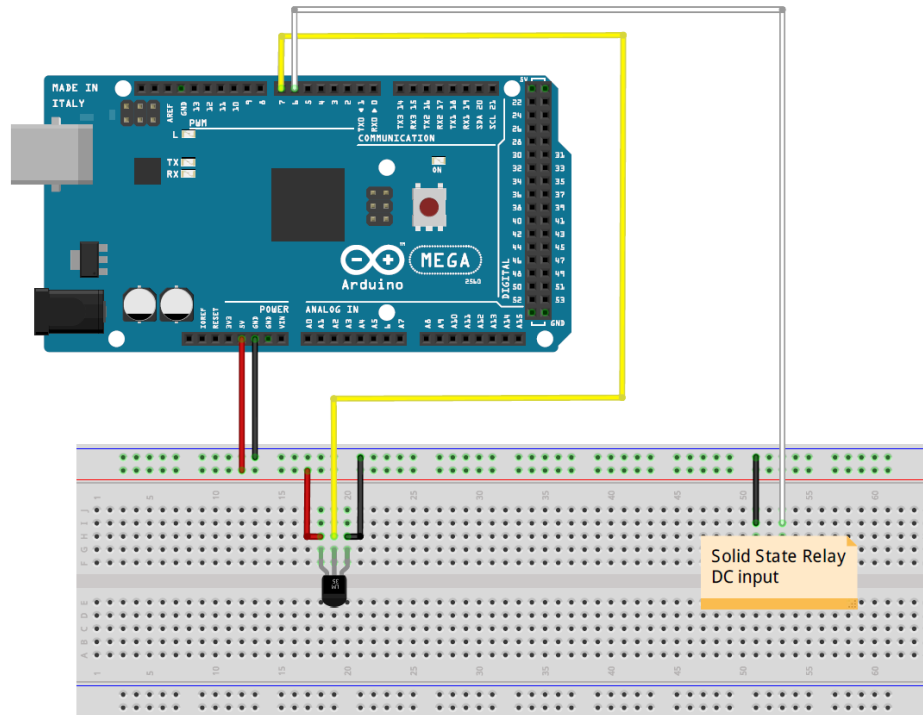
After both head rises are calculated, the actual power that would need to be supplied to the air can be calculated by

$$P_a = \gamma Q h_p = \left(\frac{\rho_a + \rho_{CO_2}}{2} \right) g \cdot v_3 \cdot A_3 \cdot (h_{a_1} + h_{a_2})$$

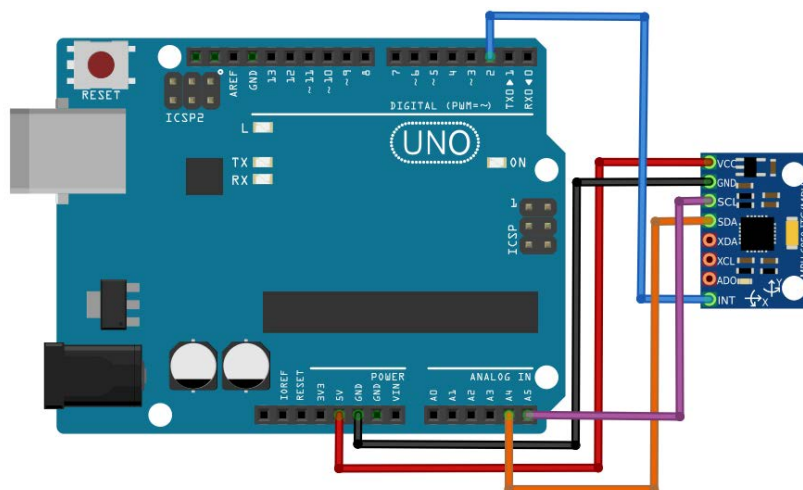
Appendix O.2. Ducting configuration

Appendix P – Electric components and connections

Appendix P.1. Heating connections



Appendix P.2. Cavitation (MPU 6050)



Appendix P.3. Heating and water supply connections

