

**بسم الله الرحمن الرحيم**

**Air Liquefaction and Cryogenic**

PROCESS CONTROL

SYSTEM

**Produced by: Nour Karim**

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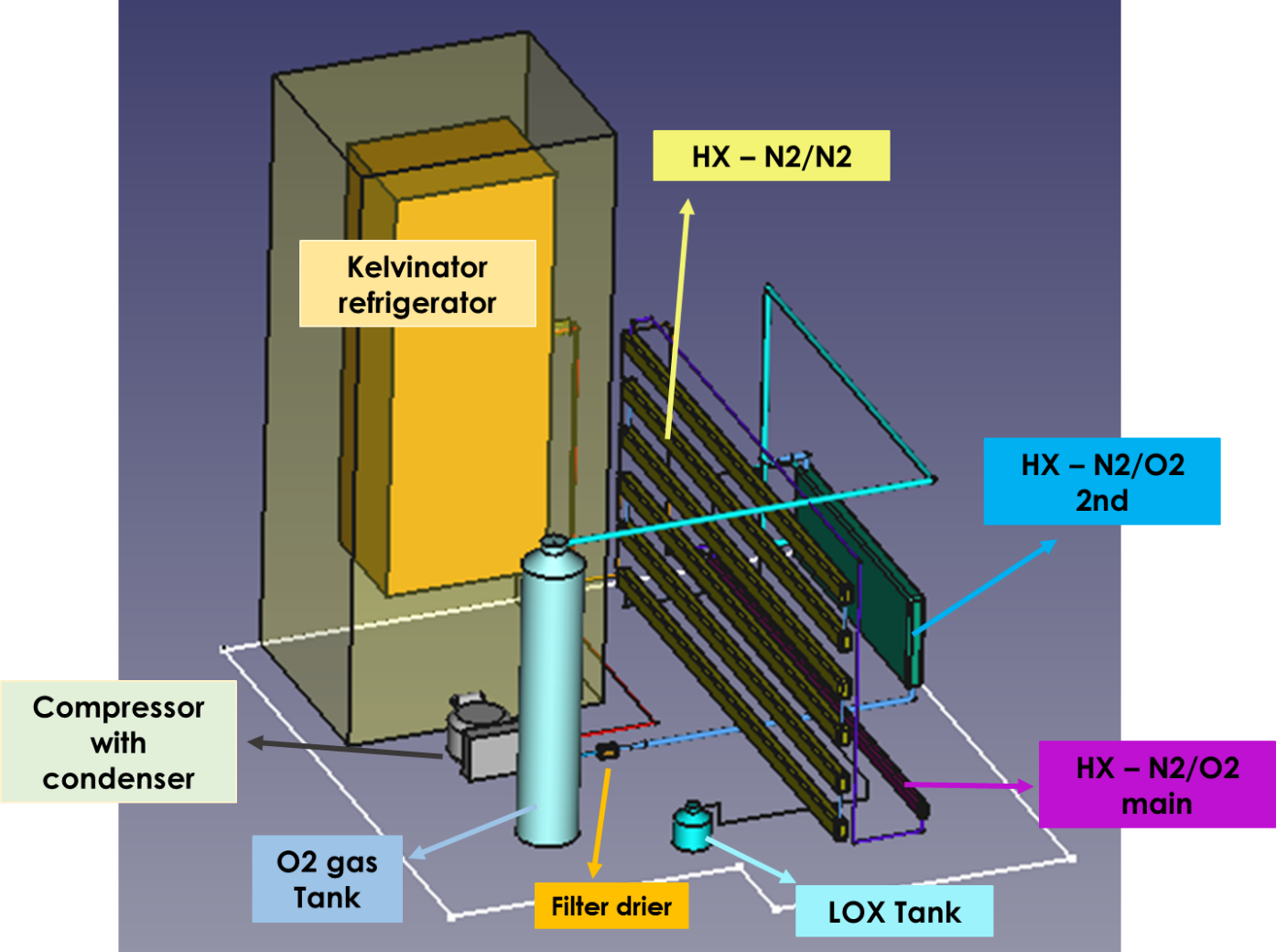


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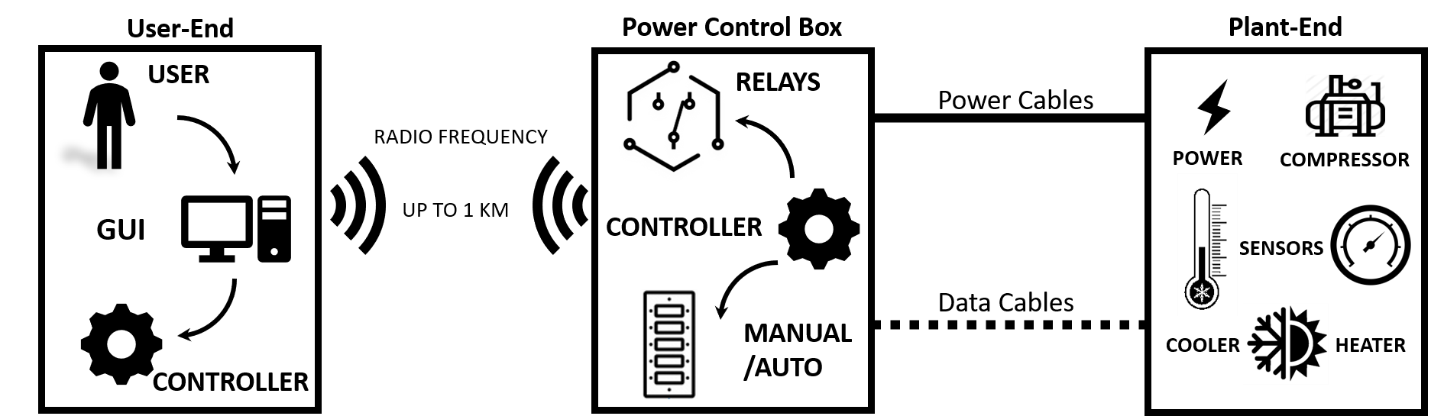
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# Requirements and Overview

The liquification of oxygen (LOX) process control system to be implemented should have the following technical requirements:

* The user most be able to switch between manual and automatic modes.
* The user must be able to control the Liquification of Oxygen plant remotely, with a distance range that’s up to 1 km.
* The user must be able to monitor different sensor data on a well-organized GUI
* The system must have a 2-way communication channel.

Therefore, Figure 1 below, presents a brief graphical illustration of LOX system functionality.



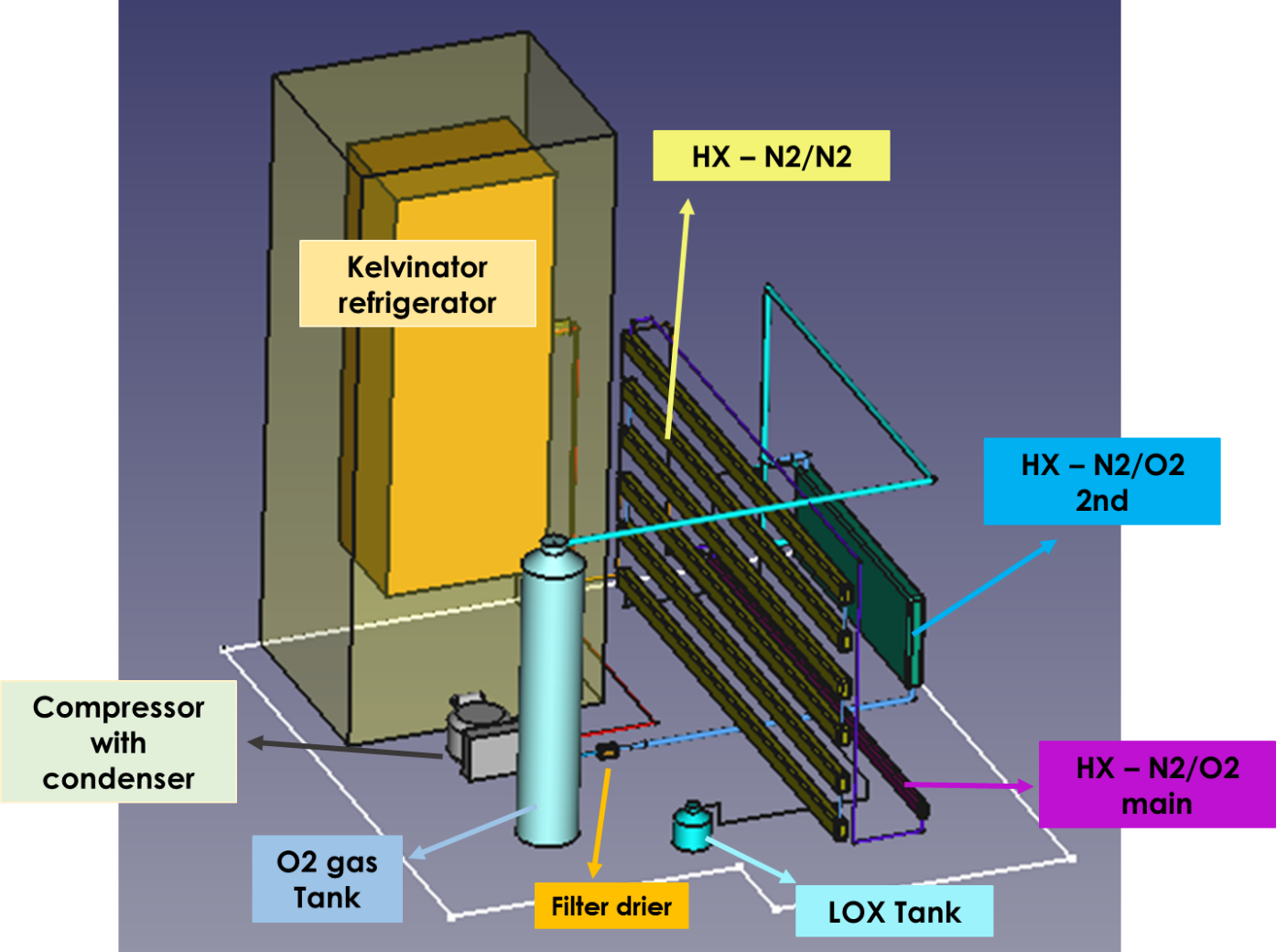
**Figure 1. LOX System functionality**

The system can be divided into 3 subcategories. First one is the plant where the liquification of oxygen setup is set, then, the power control unit that handles all the control procedure, and the user side where all the controls are set.

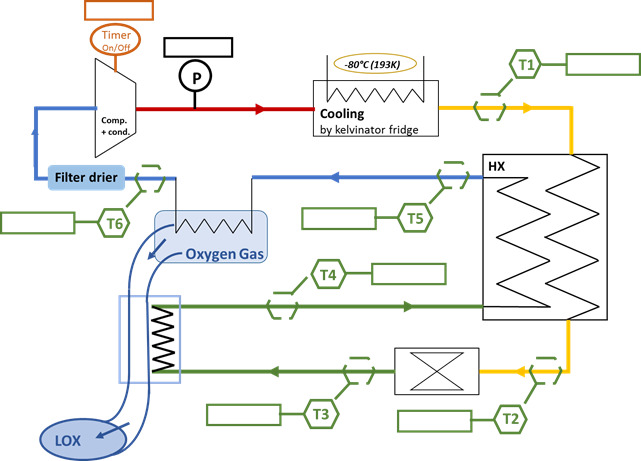
Note: photos about the three subcategories are needed.

# Plant-End

## Description

****The following **Figure *2*** presents the real layout of prototype in AECENAR Facility. While ***Figure 3***, illustrates the circuit design that Gaz must flow according to it. In addition, the places of temperature (mentioned by **T1~6**) and Pressure (mentioned by **P**) sensors are presented below.

**Figure 2. Real Layout of LOX with Heat Exchanger**



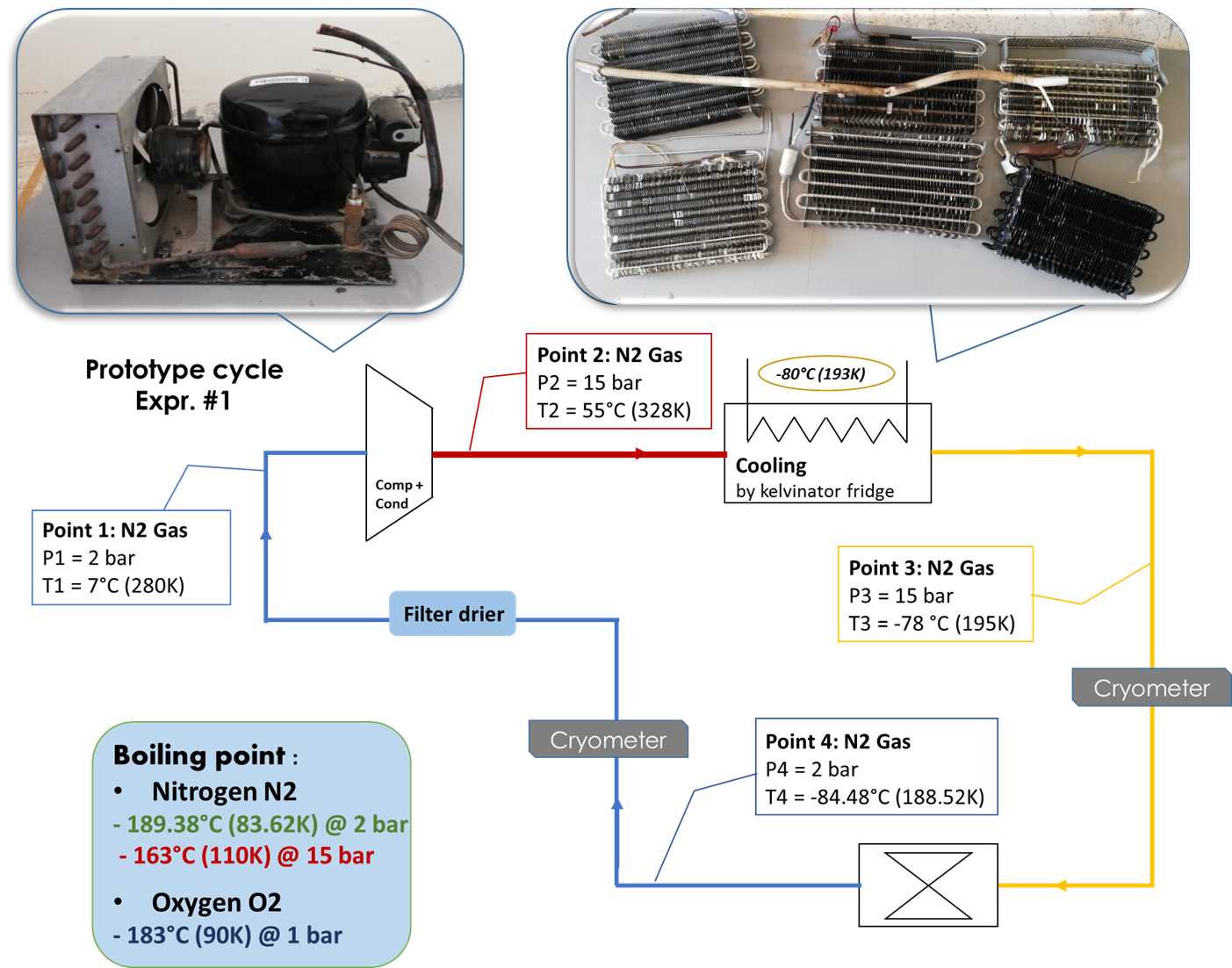
**Figure 3. LOX Circuit with Heat Exchanger**

## Electrical Equipment

The following electrical devices had been chosen for LOX Prototype.

### Compressor

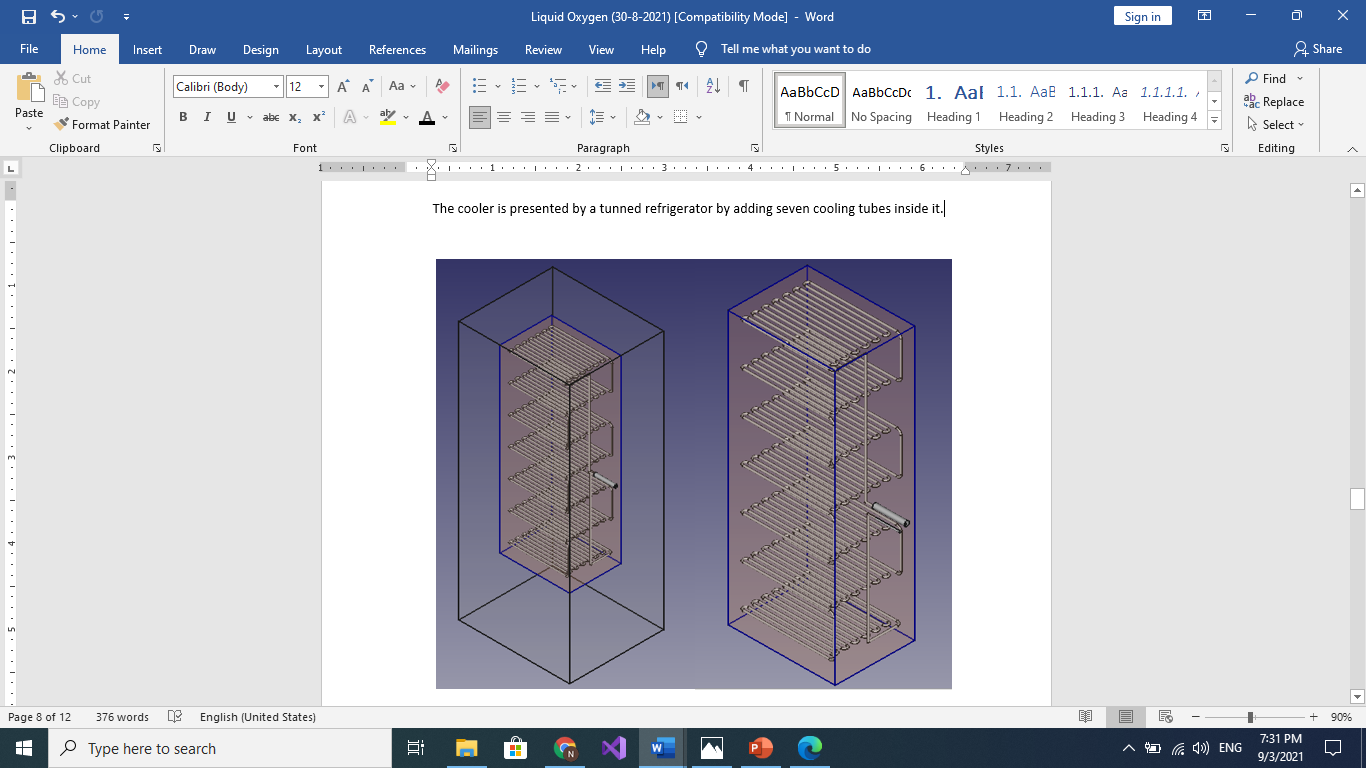
LR25B Laboratory refrigerator compressor, shown in ***Figure 4***., was selected.



**Figure 4. LR25B Compressor**

### Cooler

The cooler is presented by a tunned refrigerator by adding seven cooling tubes inside it.



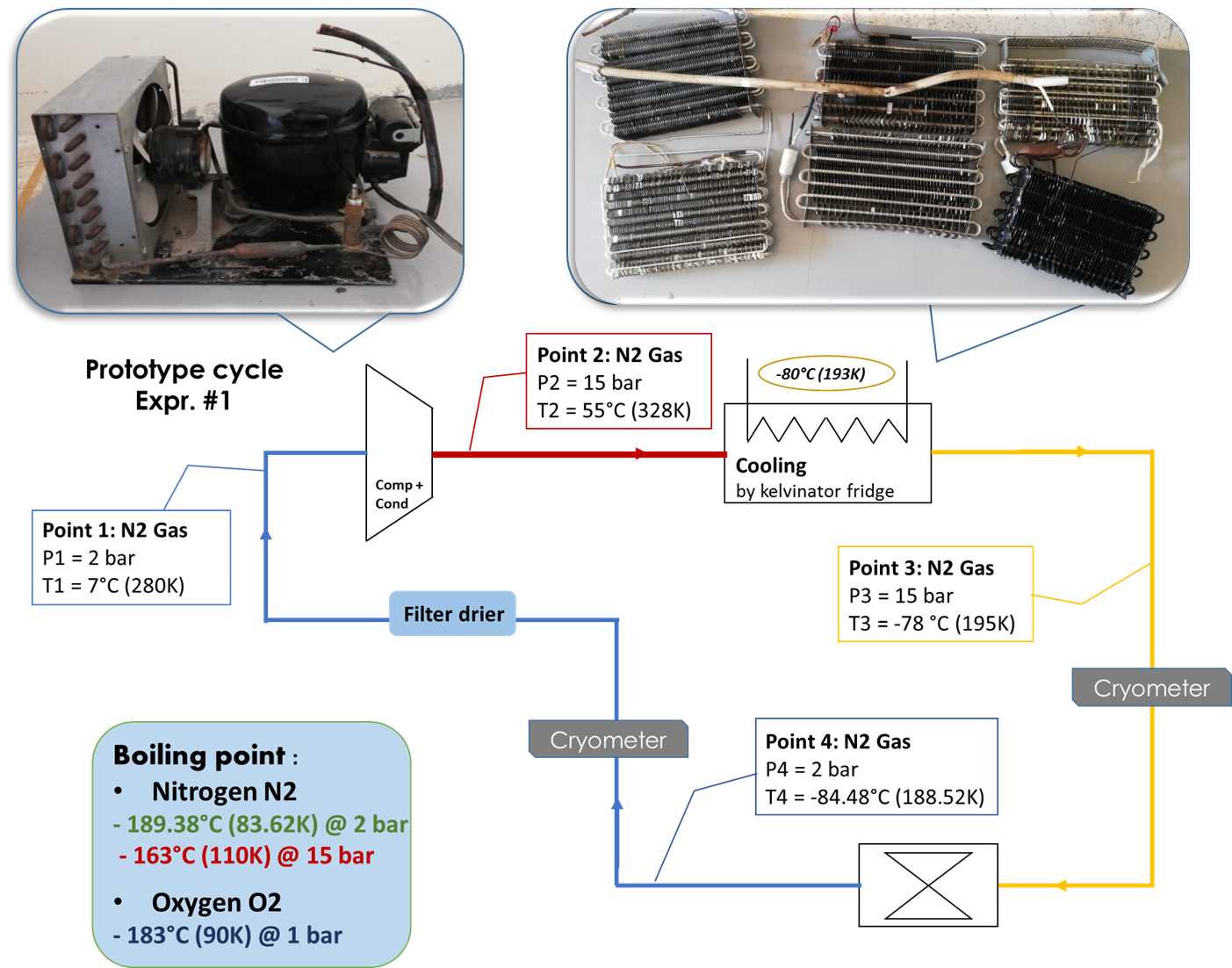
**Figure 5. Cooling Tube Design**



**Figure 6. Cooler Tube Implementation**

### Evaporator

The evaporator or Heater, shown in ***Figure 7*** below, is used to elevate temperature from -85 to 7 .

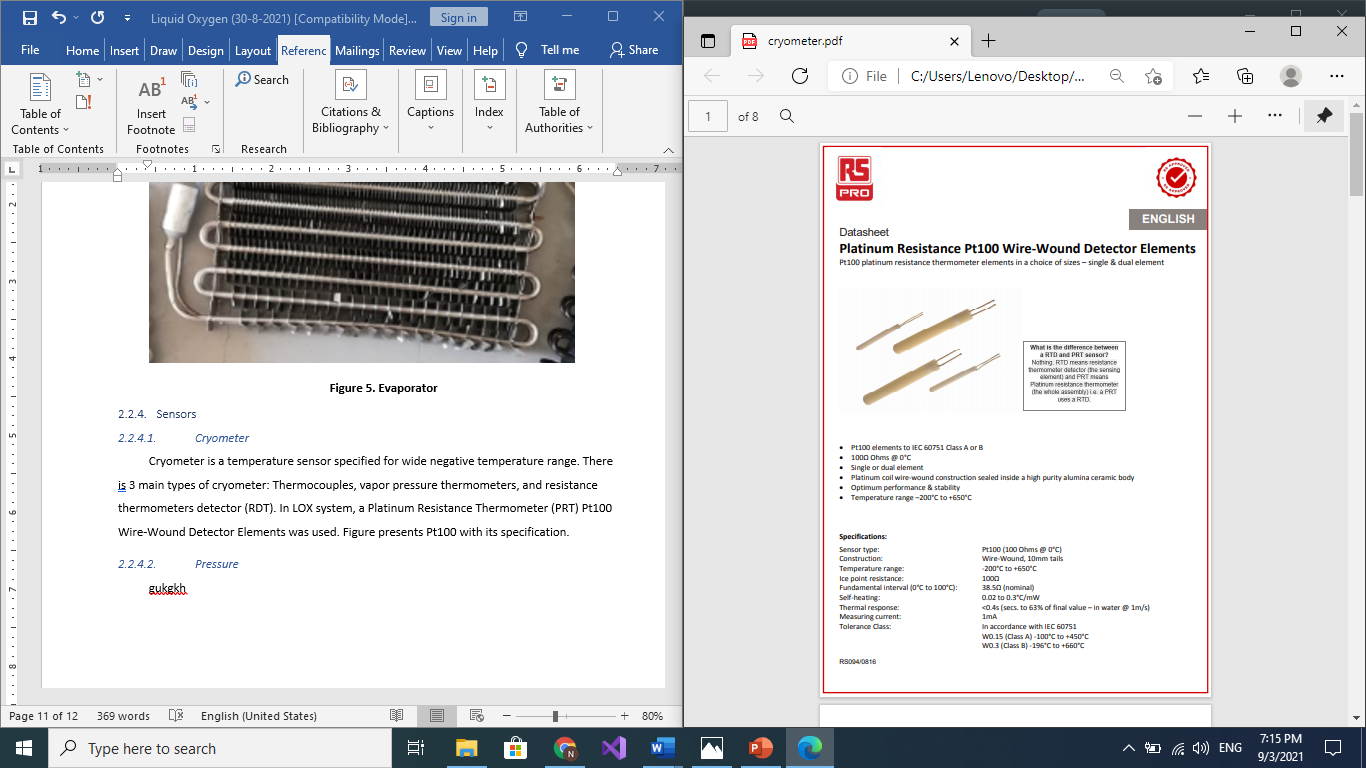


**Figure 7. Evaporator**

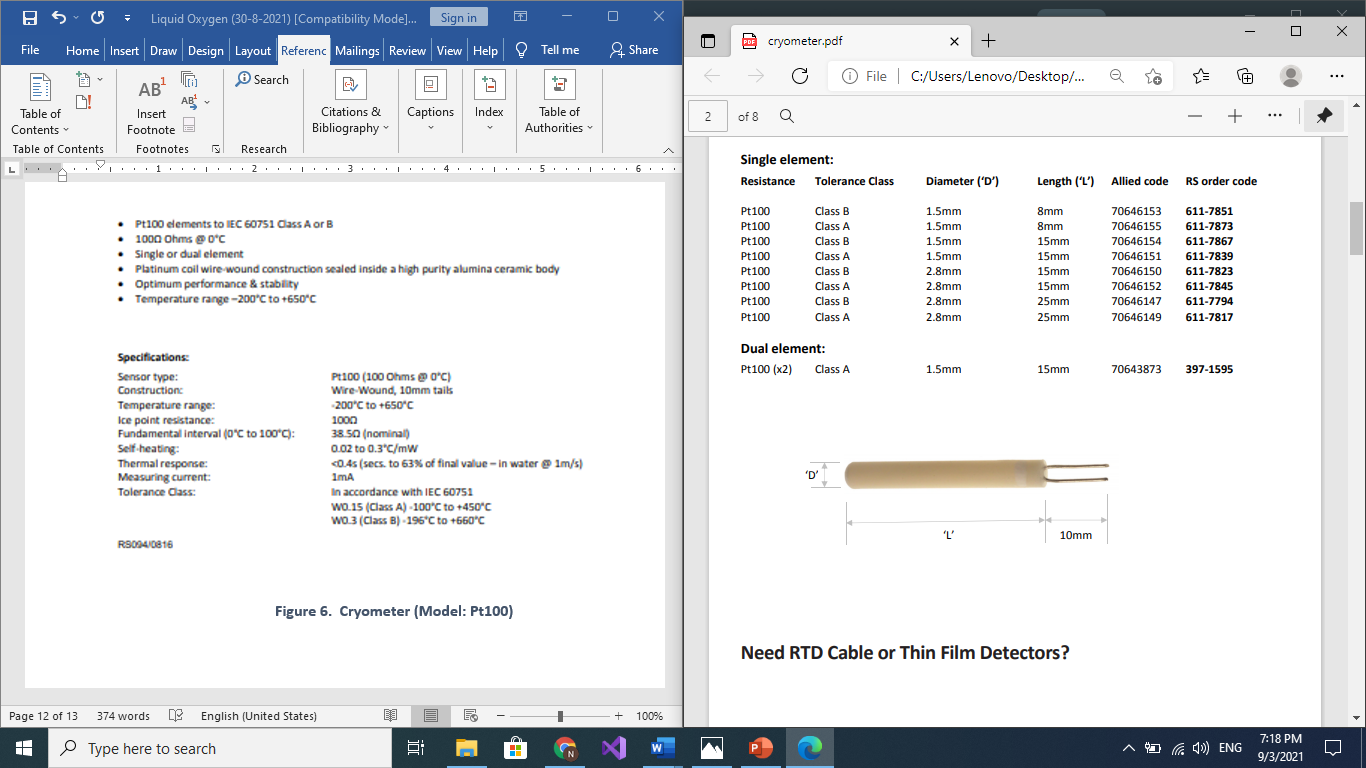
### Sensors

#### Cryometer

Cryometer is a temperature sensor specified for wide negative temperature range. There are 3 main types of cryometer: Thermocouples, vapor pressure thermometers, and resistance thermometers detector (RTD). In LOX system, a Platinum Resistance Thermometer (PRT) Pt100 Wire-Wound Detector Elements was used. ***Figure 8*** presents Pt100 with its specification.



**Figure 8. Cryometer (Model: Pt100)**



**Figure 9. Pt100 Class A**

#### Pressure Sensor

Collect data and pic...

The pressure sensor is used to control the functionality of the compressor, and for pressure monitoring. The pressure sensor needed, should have the capability to measure pressure up to 16 BAR.

### Arduino

Arduino is an open-source electronics platform based on easy-to-use hardware and software. Arduino Nano RF V3 is used in this project since it has a built-in RF24L01 radio frequency module.

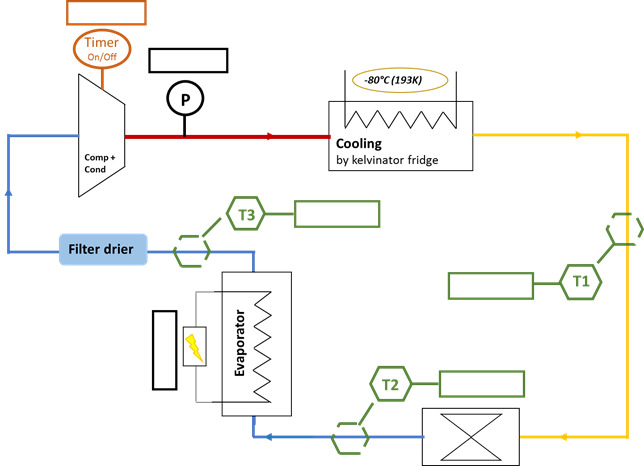
# Process Control System

**Figure 10. Arduino Nano RF**

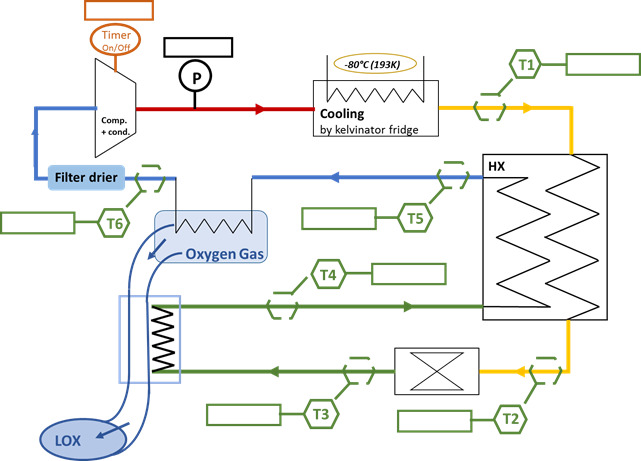
Note: the process control system is the same for LOX system with/without heat exchanger (HX)

LOX system will be controlled via Arduino

For better understanding, ***Figure 11*** and ***Figure 12*** presents LOX System with/without HX



**Figure 11. LOX without Heat Exchanger**



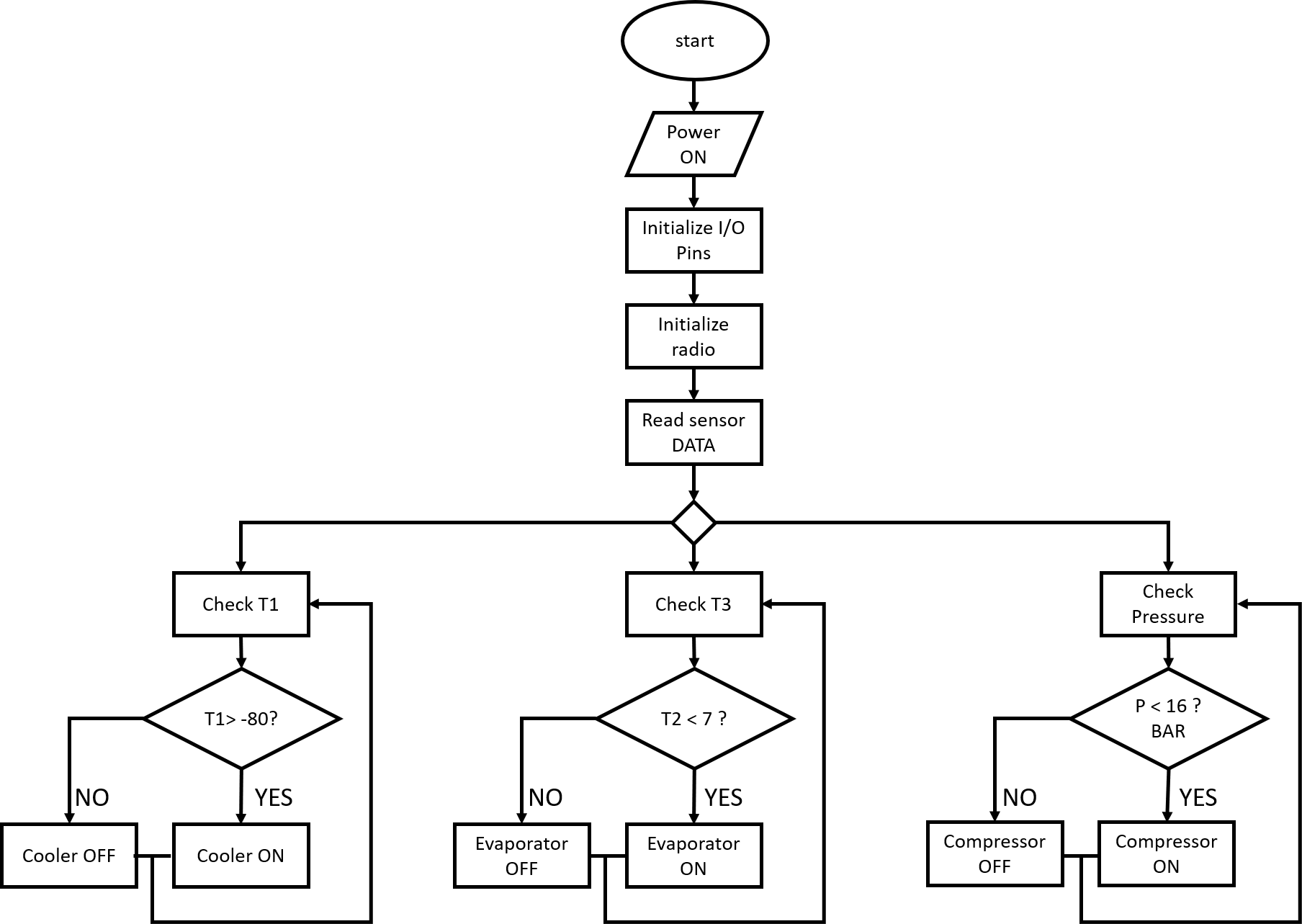
**Figure 12. LOX with Heat Exchanger**

Referring to aforementioned circuit diagram, **Table 1. Sensors ID with Role** highlights sensors that’s have the same role with mentioning their IDs in each system.

**Table 1. Sensors ID with Role**

|  |  |  |
| --- | --- | --- |
| ID | | ROLE |
| LOX With Heat Exchanger | LOX Without Heat Exchanger |
| T1 | T1 | Cooler control + Temperature monitoring |
| T2 |  | Temperature monitoring |
| T3 | T2 | Temperature monitoring |
| T4 |  | Temperature monitoring |
| T5 |  | Temperature monitoring |
| T6 | T3 | Evaporator control + Temperature monitoring |
| P | P | Compressor control + pressure monitoring |

As can be seen, these two systems have the same basic components needed for fully system control. Therefore, all extra temperature sensors are for better temperature monitoring.

The flow chart below, gives more information about how sensors above will control its accountable device.

**Figure 13. flow chart**

## The System

DC Power Supply

Controller Circuit

Compressor Breaker

Controller Breaker

Compressor Contactor

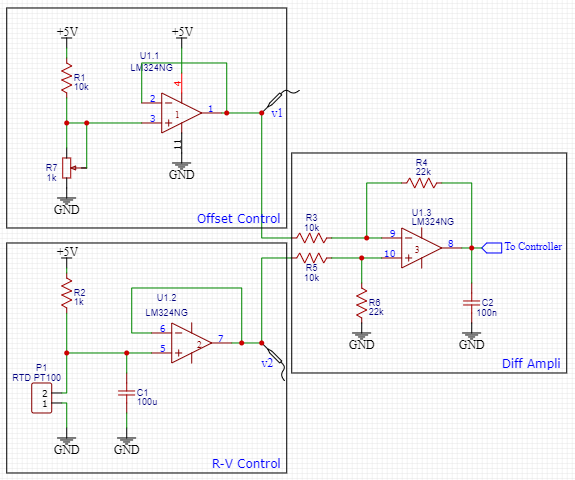
Relay Box

## Temperature Sensor (PT100) Measurement Circuit

The cryometer used, as mentioned before, measures a wide range of temperatures (-200 to 400 degrees C). In this project, the desired temperatures to be measured are between -200o to 100o C.

The Platinum cryometer (PT100) changes its resistance with the change of temperature in a known rhythm. To measure the change of the PT100, a Wheatstone bridge is used. The control circuit is composed of 3 parts as shown in **Figure 14** below.

**Figure 14. PT100 Control Circuit**



In the above circuit, when the resistance of the RTD (PT100) changes, the output voltage Vout (To controller) also changes. It is noteworthy that the PT100 RTD comes in different wiring connections: 2 wires, 3 wires, or 4 wires. All wiring connections have only single input and single output. For 4-wire wiring diagram, one can connect both connected terminals together (can be tested by continuity test via a multimeter).



### R-V Control

The first part of the circuit is the R-V Control shown in **Figure 14** above which converts the resistance change of the RTD into voltage change at the voltage terminal v2. The voltage across the PT100 can be expressed using voltage divider formula:

|  |  |  |
| --- | --- | --- |
|  |  | () |

When choosing the value of R1, one must respect the following restrictions:

1. Value of resistor (R1) must be great enough in order to avoid the self-heating problem. If we use low value resistance, more voltage drops across PT100 as a result more self-heating. This increase errors.
2. Value of R1 must be low enough in order to avoid the problem of lower signal to noise ratio. If we increase the value of R1, change in magnitude per degree decreases as a result lower signal to noise ratio. Large value of R also increases noise which is also responsible for lower signal to noise ratio.

For selecting the best value of R1, a trade-off between self-heating and better signal to noise ration should be taken. In this application, R1 is chosen to be 1 K Ohms.

In order to design the proper amplifier, the range of temperature measurement (which is the desired temperatures to measure) should be known. In this application, it is desired to measure temperatures between -200o and +100o C. From the data table shown below in **Figure 15** given by the manufacturers of the PT100, the voltage range between these 2 temperatures can be calculated:

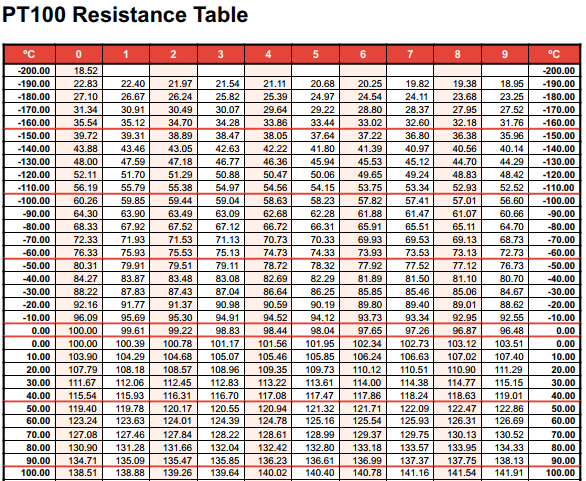
The resistance at -200o C is 18.52 Ω which gives (from equation (1)):

|  |  |  |
| --- | --- | --- |
|  |  | () |

And the resistance at +100o is 138.51 Ω which gives:

|  |  |  |
| --- | --- | --- |
|  |  | () |

From equations (2) and (3), it is desired to measure voltages between 0.0909 V and 0.6082 V.



**Figure 15. PT100 Resistance Table**

The length of RTD leads may be long and might act as an antenna which starts to pick up noises from the surrounding environment. In order to avoid this problem, a high-value capacitor is used in parallel with the RTD which acts as a low-pass filter and removes all noises.

Finally, a voltage-follower circuit is used (using op amp LM324) which gives the advantages of avoiding the loading effect (voltage drop when a load is connected across the voltage divider network) and delivering a high input resistance. The output voltage measured across the PT100 is fed into the voltage-follower circuit which is basically a unity-gain non-inverting amplifier (gain = 1). It is called voltage-follower circuit since its output is equal and in phase with the input voltage. To proof this, assume an ideal operational amplifier is used, and refer to **Figure 14** with being the output of the voltage-follower:

Doing node voltage method at negative node (:

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

Applying node voltage method at the positive node as well ():

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

Since it is assumed as an ideal op amp, :

|  |  |  |
| --- | --- | --- |
|  |  | (6) |

### Offset Control

The minimum temperature to be measured as stated before is -200o C which leads to 0.0909V and the maximum temperature is 100o C which gives 0.6082 V at . In this case, we need to subtract the lower limit so that when the temperature is -200o C (0.0909 V), the voltage at becomes 0. So, an offset voltage divider circuit is designed so that it will output a constant 0.0909 V and is shown in **Figure 14** (upper left circuit). The variable resistor (R7) is used to adjust the voltage at () until it becomes exactly 0.0909V. The voltage-follower circuit is used with the same manner as before.

### Differential Amplifier

To subtract the offset voltage from the voltage produced by the change of the PT100, a differential amplifier is used as shown in **Figure 14** (right circuit). It has 2 input terminals isolated from the ground by some resistance. It amplifies the difference between the non-inverting input and the inverting input. Doing some math, and with , the output of the diff. amplifier which will be fed to the Arduino ( is given as:

|  |  |  |
| --- | --- | --- |
|  |  | (7) |

With, is the output from the PT100 voltage divider network and is the offset voltage (voltage at -200o C). Equation (7) has 2 extremities:

1. When the temperature is -200o C .
2. When the temperature is 100o C .

Here, the gain is expressed by the ratio . The output of the amplifier will be used by Arduino’s analog input. Thus, a proper reference voltage should be selected.

The default internal Analog-to-Digital converter reference voltage in Arduino is 5V with 10-bit resolution (1024 divisions). Thus, the ADC resolution at 5V is .

So, for a temperature range between -200o and 100o C, lower voltage = 0.0909 V and higher voltage = 0.6082 V which results in voltage difference of (0.6082 – 0.0909) = 0.5173 V.

The total number of divisions for this temperature range is: . Therefore, Arduino will show . In this scenario, the lowest temperature change per division the Arduino can detect is 2.83o which is not good and an amplifier is a must.

In order to increase the resolution of the Arduino, it is beneficial to use the internal 1.1V reference voltage in Arduino (which can be accessed by code). Thus, the resolution will become: .

Finally, the gain of the amplifier () can be calculated from the equation (7) above. Here, the maximum voltage to be measured is 1.1V which represents the maximum voltage difference between the two extremities (0.5173 V). So:

|  |  |  |
| --- | --- | --- |
|  |  | (8) |

The ratio of the feedback resistor should be 2.2 times greater than the resistor of the feedforward resistor. But it should be considered that:

1. The ratio should be as close to 2.2 as possible.
2. Higher value of resistance increases noise but reduces power consumption.

For this application, RA = 10 K and RB = 22 K.

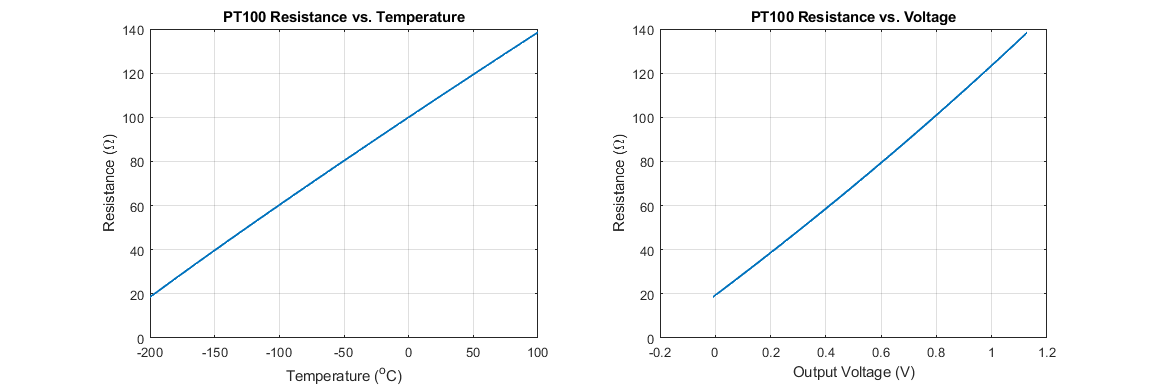
### Calculating The Temperature

The temperature can be calculate using the following equation found in the datasheet:

|  |  |  |
| --- | --- | --- |
|  |  | (9) |

Where, is the current resistance of the PT100, is the PT100’s resistance at 0o C (which is 100 Ω). Here, will be calculated from the output voltage measured by the Arduino.

**Figure 16** below shows the PT100’s resistance changes to temperature change and how the differential amplifier output is changing for different resistance values. It can be clearly seen from the figure below (right plot) that the resistance vs. voltage plot is not linear. So, a polynomial fitting tool is used (via Matlab) to estimate the 4th degree polynomial equation of this graph which will be used to calculate the exact resistance () value. The estimated polynomial equation of the resistance as a function of output voltage is shown below in equation (10).



**Figure 16. PT100 characteristics at the left (from datasheet) and PT100 resistnace with respect to differential amplifier output voltage at the right**

|  |  |  |
| --- | --- | --- |
|  |  | (10) |

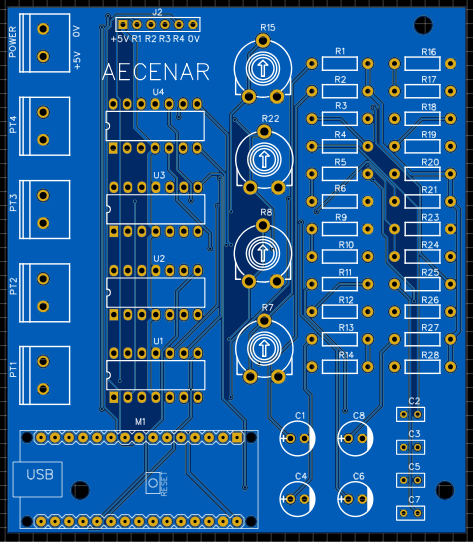
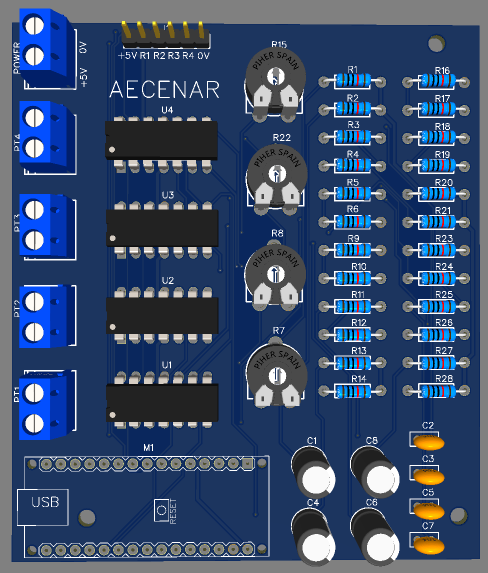
To sum things up, the Arduino’s role can be summarized as follow:

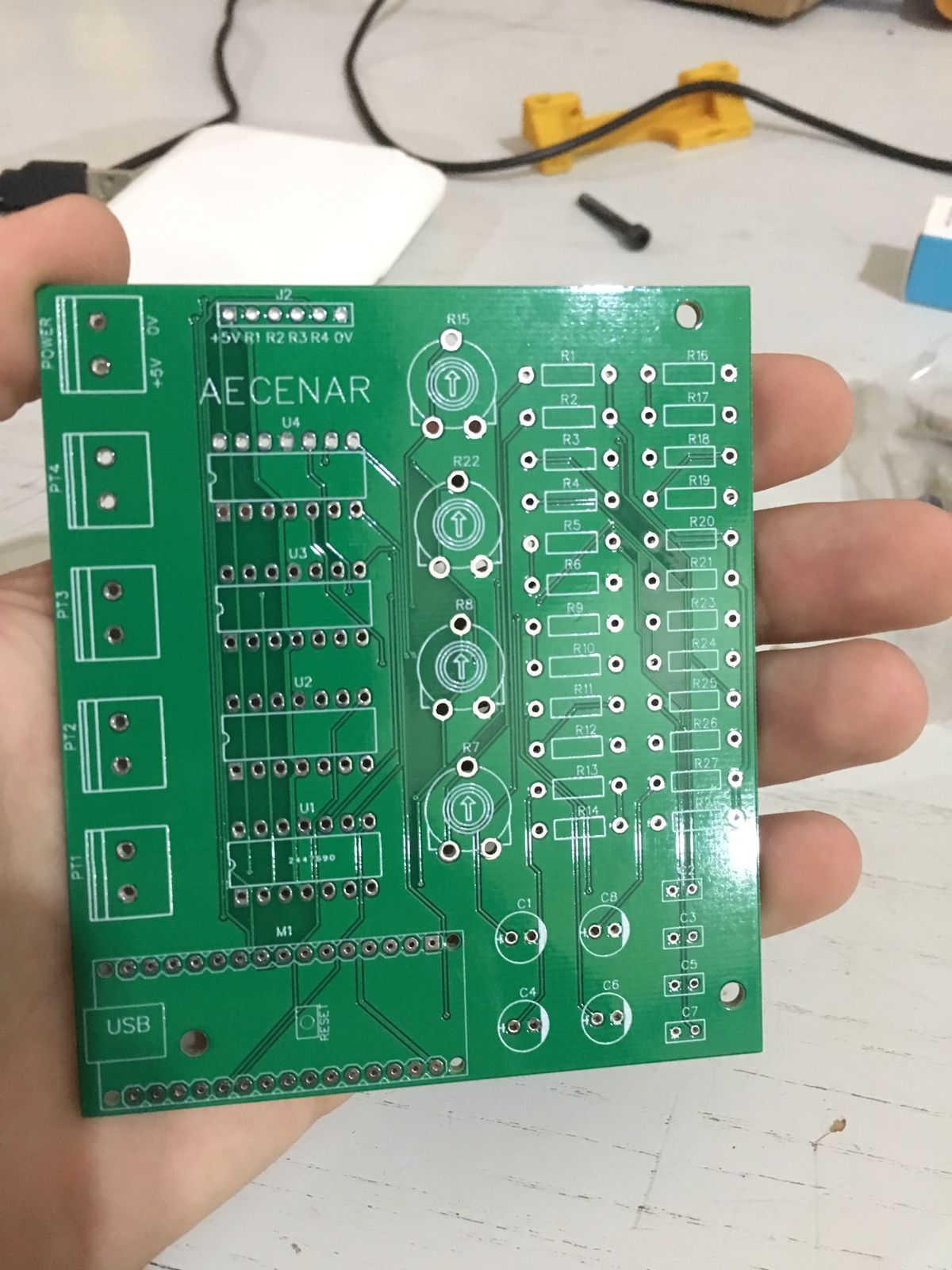
1. Measure the voltage coming from the differential amplifier (between 0 and 1.1 V for -200o and 100o C respectively).
2. is calculated from equation (10)
3. Temperature is calculated from equation (9).

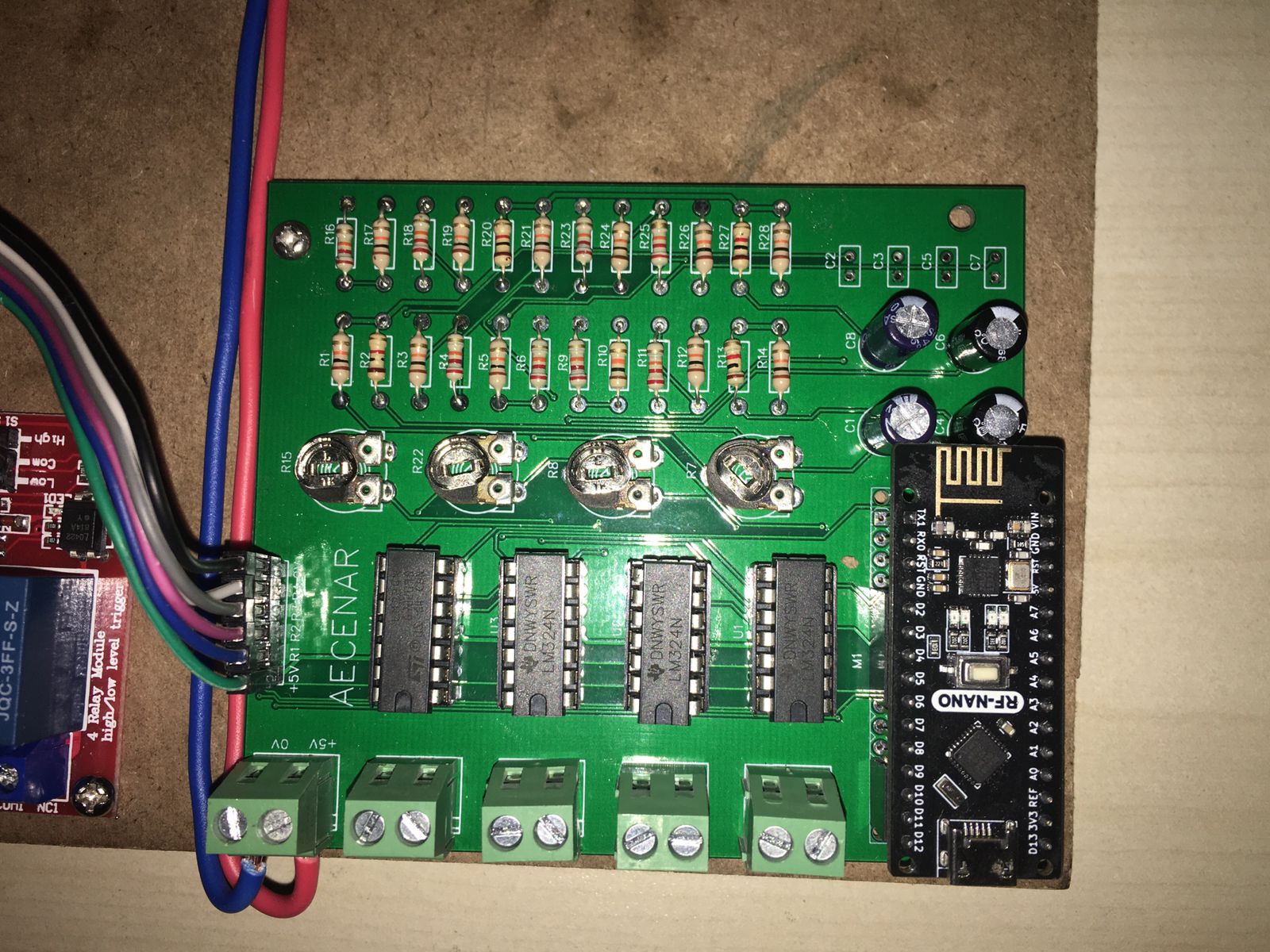
### Circuit Design

In order to get better accuracy in measuring the temperature, a PCB has been designed. The fabrication files required to make the same boards and the simulated PCB design are attached below.





After fabrication:



## GUI

The GUI is used to send commands like turning ON the compressor and monitoring the temperature at different points of the system.

