SCHOOL OF ENGINEERING
TAYLOR'S UNIVERSITY

School of Engineering

PRJ60603
Mechanical Engineering Group Project 2

Final Report
Title: PCM Heat-Exchanger

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1.0 Introduction

Heat pump is a common product in 4 four season countries. Heat pump has the reversed cycle of a normal air-conditioning unit, which means that the heat pump is providing warm or hot air indoor and cold air is discharged outdoors. Due to humidity and low temperature outdoor, frost is formed on the outdoor coil (Lennard, 2019). The frost formed on the outdoor coil affected the overall heating performance of the heat pump which results the end-user to feel discomfort due to instability of the warm or hot air was discharged indoors. To overcome this issue, the heat pump was designed to have a defrost cycle which was meant to reverse the heat pump cycle to normal air-conditioning cycle (Formato, 2019). During the heat pump is running the defrost cycle, heat is stop providing indoor as the heat was used to defrost the outdoor coil which leads to the end-user to feel uncomfortable. Some heat pumps were implemented with a heater which consumes electricity to defrost. The aim of the project is to resolve the problems above by implementing a Phase-Change-Materials Heat-Exchanger (PCM-HE) to shorten the defrost cycle and enhance the overall heating performance in a green way. This is because PCM-HE does not require any fuel or additional energy to defrost (Formato, 2019). The concept of the PCM-HE is to allow the heat transfer to take place in between the PCM and the refrigerant. The Phase-Change-Materials (PCM) is the main component for the Heat-Exchanger and the PCM that used in the project has a low melting point and high heat storage capacity. As the PCM would trap and store heat from the refrigerant in the heat pump during the heating cycle, the heat would be released by heat transfer to the refrigerant from the PCM during the defrost cycle. By doing so, it could enhance the overall heating performance and shorten the defrost time.

In this project, the focus will be on implementing and operation stage as continued from MEGP1. Our main objective will be to integrate a Phase Change Material (PCM) tank which acts as a thermal storage to the existing heat pump system. As proposed before, PCM was used as it improves the heating efficiency of the heat pump and also shorten the time taken for defrost. In a nutshell, PCM absorbs and releases a large amount of latent heat from the surrounding environment when the surrounding temperature reaches the melting and freezing point of the PCM by changing its physical state. The PCM absorbs large amounts of latent heat from the surrounding environment while the PCM is in the process of melting. Conversely, the PCM releases an equal amount of latent heat that absorbed earlier to the surrounding during the PCM in the process of freezing.

During the early stages, the project was divided into two sections which is the PCM tank and the electric circuit. We were required to source for manufacturers which are able to manufacture a tank according to our copper coil. This process took slightly longer than expected due to several reasons. This is because we were required to modify the initial dimensions and also refabricate the copper pipe twice. This caused a delay with the sourcing of manufacturers. In addition, we only had two choices suggested by our supervisors which was plastic and metal. However, after much consideration which will be explained below, metal has been chosen as our tank material. The tank took around 2 weeks to be done. As for the electric circuit, it was mainly used to control the pathway of refrigerant during heating and defrost mode. The circuit consisted of an Arduino and solenoid valve which was provided by Daikin. We were able to apply the application of relay switch in our project as it helps to switch between cycles. For the cycle to switch, we needed an input data which we obtained from the temperature sensor. The team has been working on the circuit more than 3 weeks to ensure that it can be integrated to the existing heat pump system.

After the tank and electric circuit was done, testing took place at Daikin Sg. Buloh. The testing was done over the course of 3 days. Before we went over to Daikin, the mock up process was already done to integrate our tank with the existing heat pump system in the test room. After the mock up, we were able to connect our electric circuit which controls the cycle which switches two sets of solenoid valve between two cycles. After setting up, the whole system was allowed to run without PCM with two conditions to ensure that everything is running smoothly. We only managed to test one standard condition with the addition of PCM due to several difficulties encountered during the testing and insufficient time. Nevertheless, the results obtained were enough to meet our objectives, which was to reduce the time taken for defrost. The graphs obtained were able to show the time taken for the defrost to complete.

2.0 Objective

- To design a phase change material (PCM) heat exchanger for reduction in defrost time of heat pump.
- To integrate the phase change material (PCM) heat exchanger into the heat pump system.
- To improve the heating efficiency of the heat pump unit under various ambient conditions with the phase change material (PCM)

3.0 Engineering Analysis

Throughout the project, several detailed analyses were involved in the Engineering Analysis part. The project began with the calculation on the required length of copper pipe to immerse into the Phase-Change-Material (PCM). Design of the copper pipe was determined by Decision Matrix after the required length of copper pipe was obtained. Tank was constructed according to the dimension of the copper pipe design and with the design of the tank was constructed, calculation of the required amount of Phase-Change-Material (PCM) could be done. The team could notify Industrial Supervisor to reserve the required amount of Phase-Change-Material (PCM) for the team. Other than that, Simulation software, ANSYS and method, CFD was used to analyze the time required for the PCM to be fully changed from one phase to another phase during the design stage. Moreover, the Valves used in the project and Risk management was analyzed. Lastly, the testing results was analyzed during the Operate stage.

3.1 Calculation on the required length of copper pipe

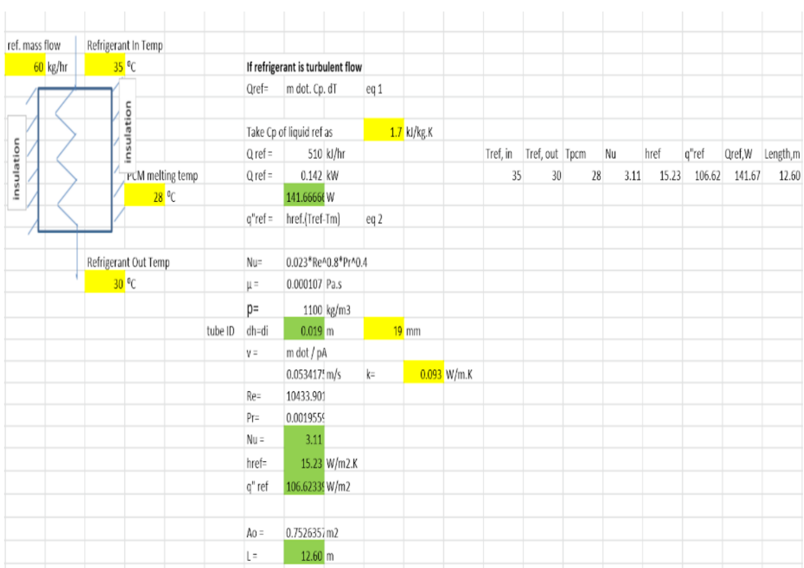


Figure 1: Calculation of the pipe length

As the aim of the project is to build a PCM Heat-Exchanger and to attach to the existing heat-pump unit, in short, the project is building an additional part to the existing heat-pump unit. By adding an additional part to the existing system, the calculation of the required length is necessary to obtain the maximum allowance length for the copper pipe due to the pressure drop across the additional part. The template above was provided by DAIKIN with some fixed input values for example the relative mass flow rate and thermal conductivity due to the existing system. The only input value to change is the Internal Diameter (ID) of the copper pipe. The team was recommended by Industrial Supervisor to choose the ID of 19mm for the project due to the fact of larger the copper pipe size, the greater the area of heat transfer. With the ID of 19mm, the required length that the team can obtain is 12.6m. Therefore, the required length of the copper pipe and the size of the copper pipe are 12.6m and 19mm respectively.

3.2 Analysis of the Copper pipe Designs

Three designs of the copper pipe were involved in the analysis which were rectangular design, circular design and spiral design. The spiral design was recommended by Industrial Supervisor whereas the other two designs were brainstormed by the team. The designs will be further analysed one by one and compared to each other with Decision Matrix to choose the best one.

3.2.1 Analysis of Rectangular Design

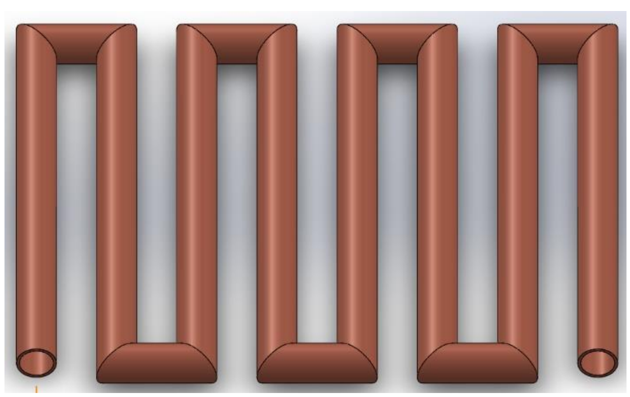


Figure 2: Rectangular pipe design

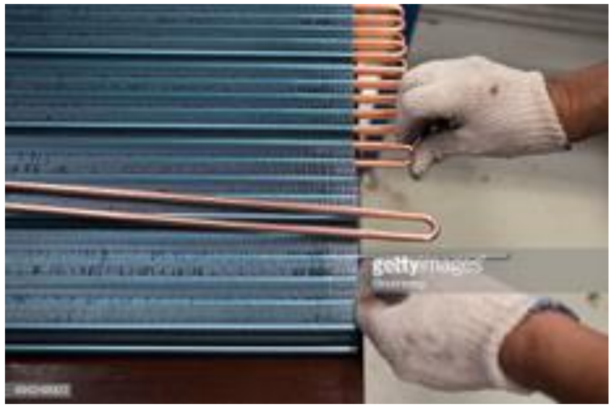


Figure 3: Coil in the evaporator

By applying the system thinking technique, the team came out with the idea of rectangular design of copper pipe was inspired by the coil design in the evaporator and the condenser which can be commonly found in the air-conditioning unit. The concept of the coil design in evaporator or condenser in an air-conditioning is by bending the number of copper pipes into U-shape and joining the copper pipes with U-Joints on the other end.

The team proposed the idea to Industrial Supervisor, and he advised that the idea wasn’t practical. As the Outer Diameter (OD) that the team chosen is 7/8”, which will result a huge radius of curvature when the copper pipe is bent and the U-Joint for the same sizing of copper pipe is rarely been found, therefore, it wasn’t practical. After taking the feedback from the industrial supervisor, the team decided to propose an improvised idea by using the 90-degree U-Joint as shown above. As this idea would eliminate the concern of the radius of curvature. After proposing the improvised idea, the industrial supervisor told us that the idea wasn’t practical as pressure drop would occur due to the collision of refrigerant happened in the 90-degree bent copper pipe.

3.2.2 Analysis of Circular Design

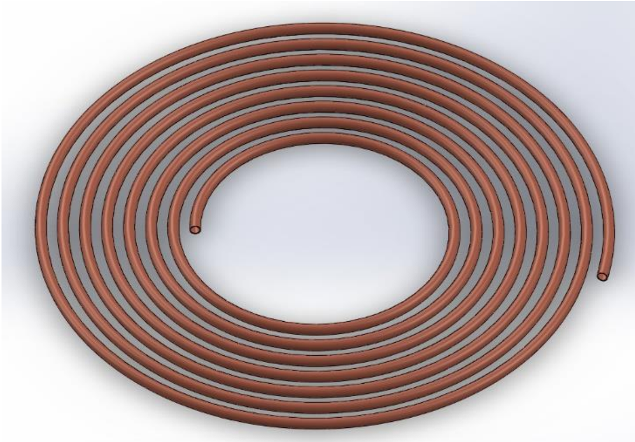


Figure 4: Circular pipe design

Figure 5: mosquito repellent

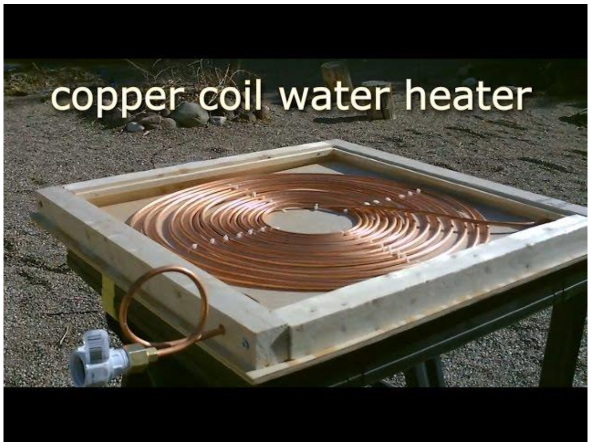


Figure 6: Water heater

The second idea was generated by applying the random entry technique which was inspired by the circular mosquito repellent. Besides, this design of coil can be seen in specific water heater as well. This design is thin in shape but large base area which was able to be installed into the walls, ceiling or under the floors. As the PCM Heat-Exchanger tank is proposed to be installed at the indoor. Therefore, this design is ideally space saving which the end user would prefer.

The team proposed the idea to industrial supervisor, and he told us that this idea is practical. However, the copper pipe was fabricated by man power in DAIKIN for the prototype usage, and they didn't have the machine to fabricate the shape. Other than that, this design would have a large base area of storage tank due to the sizing of the copper pipe, resulting it to be inconvenient to carry around as the prototype needed to carry around to DAIKIN and campus for testing purpose.

3.2.3 Analysis of Spiral Design

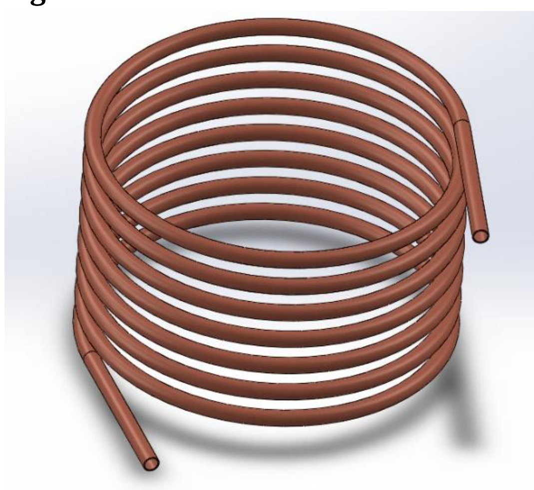


Figure 7: Spiral coil design

This idea was recommended and inspired by Industrial Supervisor initially. He proposed that this design is simple and straightforward, and it could maximise the heat transfer between the refrigerant in the copper pipe and the PCM in the tank. In production wise, this is easier to be fabricated by man power as it required to bend around a fixed cylindrical object. However, the con of this design was the size of the tank would be bulky and it would have difficulties to design or fabricate the storage tank. As the inlet and outlet of the copper pipe weren't in the same plane, therefore the concern of the storage tank leakage and the method of installing the copper pipe into the storage will be taken in to consideration during designing the storage tank.

3.2.4 Decision Matrix

Table 1: Decision Matrix

Attributes	Sub-Attributes	Weightage	Spiral PCM-HE	Circular PCM-HE	Rectangular PCM-HE
Productivity	Defrost Time	13	9	9	9
	Heat storing Time	12	9	9	9
	Precision	11	9	9	9
Cost	Material Cost (higher better)	10	7	8	5
	Manufacturing Cost	9	7	7	7
	Maintenance Cost	8	6	6	6
Reliability	Ease of Maintenance	7	5	5	5
	Leakage	6	1	1	1
	Lifespan	5	9	9	9
	Ease of Assembly	4	6	6	6
Safety	Leakage of PCM	3	1	1	1
Sizing	Space saver	2	5	8	7
Environmental Impact	Lesser usage of material	1	5	7	6
		TOTAL	634	651	618

According to the decision matrix table, it could be clearly seen that the Circular Copper coil design has the highest total score which indicates to be the best design among these coil designs. Due to limitations that mentioned earlier, the circular coil design has difficulties on fabricating, therefore, the team choose the second highest score design which is spiral coil design and recommended by industrial supervisor to be the final design for our project.

3.3 Basic Calculation for required mass of Phase-Change-Material (PCM)

Moving on, to obtain the required mass of PCM is necessary as the team was required to notify the industrial supervisor to reserve the PCM for the team. The data sheet of PCM SP-31 that provided by Rubitherm Germany was used to determine the required amount of PCM. As the density of the PCM SP-31 was stated in the data sheet as 1.31 kg/L or 1310 kg/m^3. The team would obtain the volume of the storage tank and the volume of the copper pipe coil. With the obtained volumes, using the volume of storage tank deducting the volume of copper pipe coil as the copper pipe was to immerse into the storage tank. Using the deducted volume to calculate with the density that obtained from the data sheet and get the required amount of PCM SP-31.

Density of PCM SP-31= 1350 kg/m^3

Base area of the storage tank = $(535.5^2 \text{ mm})^2(\pi) - (491.05 \text{ mm})^2(\pi)$

$= 143351 \text{ mm}^2$ or 0.143351 m^2

Height of the storage tank = 290 mm or 0.29 m

Volume capacity of the storage tank = 0.29 x 0.143351

= 0.041572 m^3

Volume occupied by the copper pipe = length of pipe x area of pipe

= 12600 mm x $(22.225\text{ mm})^2(\pi)$

= 19552575 mm^3 or 0.019553 m^3

Volume of PCM that is able to fit in the storage tank

= volume capacity of storage tank - volume occupied by the copper pipe

= 0.041572 m^3 - 0.019553 m^3

= 0.02202 m^3

Mass of PCM SP-31 required = density of PCM x volume of required PCM

= 1350kg/m^3 x 0.02202m^3

= 29.7 kg of PCM SP-31

Table 2: Data Sheet of PCM SP-31

Data Sheet of PCM SP-31		
Melting Area	31 - 33 Main peak: 32	**[℃]**
Congealing Area	28 - 30 Main Peak: 30	**[℃]**
Heat storage capacity	210	**[kJ/kg]**
Combination of sensible and latent heat in a temperature range of 23℃ to 38℃	58	**[Wh/kg]***
Specific heat capacity	2	**[kJ/kg.K]**
Density solid (at 15℃)	1,35	**[kg/L]**
Density liquid (at 35℃)	1,3	**[kg/L]**
Volume expansion	3 to 4	**[%]**
Heat conductivity	n.b.	**[W/(m.K)]**
Max. operation temperature	50	**[℃]**
Corrosion	corrosive effect on metals	

3.4 Analysis of suitable materials for the PCM storage tank

The PCM storage tank must withstand the weight of the PCM and the copper pipe coil. As both items were to store inside the PCM storage tank. Therefore, the idea of using Metal and Plastic as the material of the PCM came to the mind. However, referring to the data sheet of the PCM SP-31 provided by the Rubitherm Germany, the PCM SP-31 is corrosive to metal. Therefore, plastic was prioritised to be the material of the PCM storage. The team discussed with the industrial supervisor on choosing the material for the PCM storage tank, the feedback from him was to choose the plastic tank as the PCM SP-31 is corrosive to the metal, but he told us that to customize the plastic tank for one prototype unit would have difficulties due to the manufacturer or the cost. So, the industrial supervisor advised the team if using plastic as the material for the PCM storage tank was difficult, the team can choose the metal as the material to build the PCM storage tank and applying a layer of protective chemical on the surface that would be in contact with the PCM SP-31. As the PCM storage tank needed to fill with PCM SP-31 for the testing purpose in a short period, and the testing result wouldn't be affected much. Therefore, the team would choose plastic as the material for the moment.

3.5 Analysis of the Solenoid Valve

The solenoid valve that will be involved in the project is SANHUA-FDF8A08 which was provided by DAIKIN. This solenoid valve is specialised for refrigerant as it could withstand high operation pressure up to 4.2MPa. Dealing with such high-pressure fluid, the solenoid would be needed high voltage of direct current AC (220V – 240V) to operate. Moreover, this solenoid valve is applicable to operate with various of refrigerant such as R22, R407C, R410a, R134a, R32, etc. This solenoid valve is produced by a China company called SANHUA. Several of this same solenoid valve will be installed. This solenoid valve is used to control the path of the refrigerant flow by opening or closing the valve to direct the refrigerant flow during the cycle changes in the heat pump.

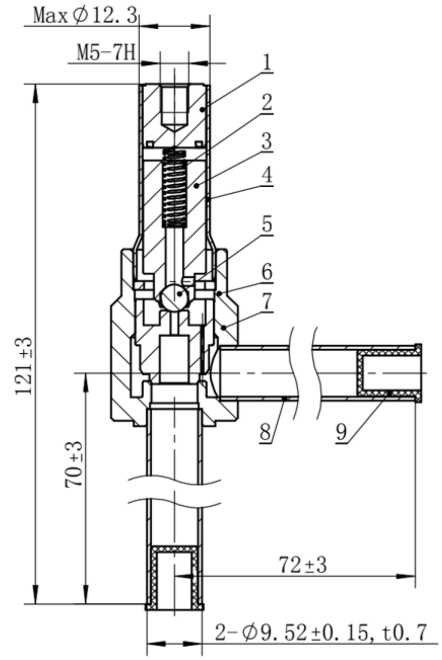


Figure 8: Solenoid Valve

3.6 Risk Analysis

The potential risks of using the PCM Heat-Exchanger was analysed by the team. Minor risks were found in the analysis due to the material used and the part of the product are relatively safe. Furthermore, the main component, PCM SP-31 is non-toxic material and not a high flammable material. Slightly irritating if direct contact with eyes and skin but this would not be likely to be happened as the PCM SP-31 would be sealed inside the storage tank and there wouldn't be any interaction between the PCM SP-31 and the end user. The person who would deal with the PCM SP-31 would be the technician during implement or maintenance, but they will be handling the PCM SP-31with safety coat and glove on. Safety sheet was provided by Rubitherm Germany and it was attached in the Appendix.

Table 3: Risk management table for risks and prevention methods

Identification	Prevention	Mitigation
Project prototype may not be completed on time due to its high technical complexity.	Divide assemblement of subsystem between members and chart a due date for each task and calculate timing and priority of each task.	Assign more members to the task that requires a larger amount of time and fast track the project by performing task parallel with other tasks.
The final product of the project may not achieve the expected performance.	Identify and run simulation to identify origins of poor performance. Research new materials or reexamine project design to improve performance.	Conduct further research and clarify any doubts with supervisors of the project.
Leakage occurring on the PCM storage tank.	Research and practice on how to wield two materials together properly. Ask for assistant from lab supervisors when needed.	Outsource the fabrication of the storage tank to a credible and reliable manufacturing workshop.

3.7 Analysis of the time taken for the PCM to be fully solidified or melted

During the design stage, the team decided to run simulation to determine the time needed for the PCM to be fully solidified or melted by applying the CFD method with the simulation software ANSYS. The team decided to run the simulation to determine the time for the PCM to be fully melted. As none of the team member learn or expertise on CFD, therefore the team tried to learn from tutorial on the YouTube and online tutorial to run the simulation.

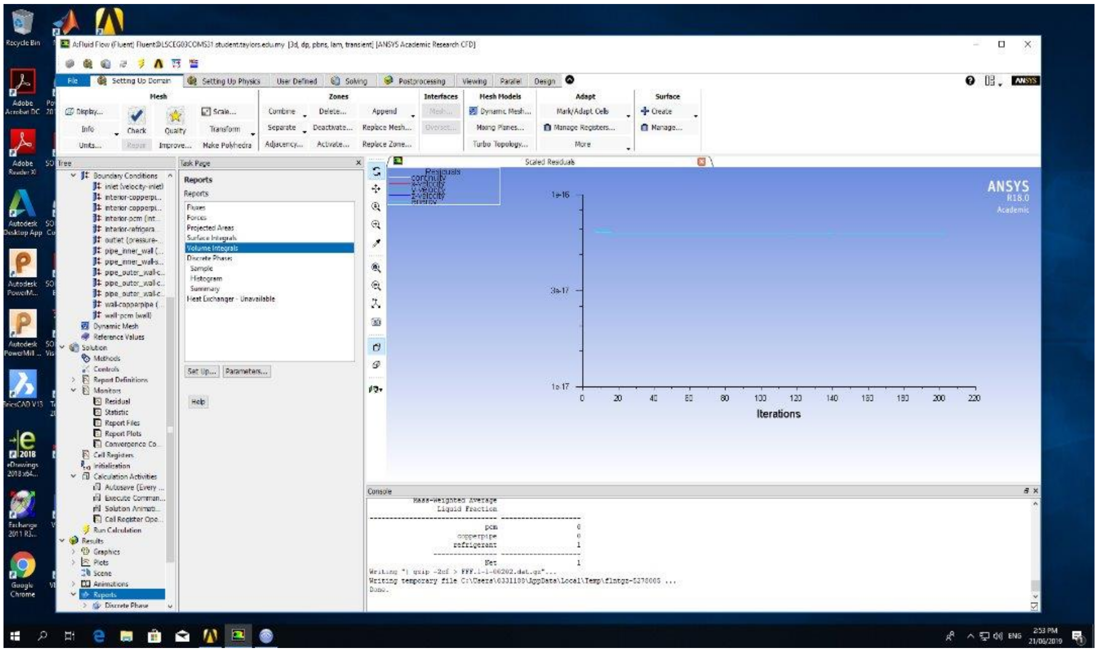


Figure 9: Results graph from ANSYS

After learning through online tutorials, the team gone through several simulations and couldn't get any results. The simulations kept showing the energy in the system graph to be constant as shown above which was invalid. In fact, the heat in the heat exchanger should always be flowing and there should be yield graph in the results which demonstrate the changes in energy.

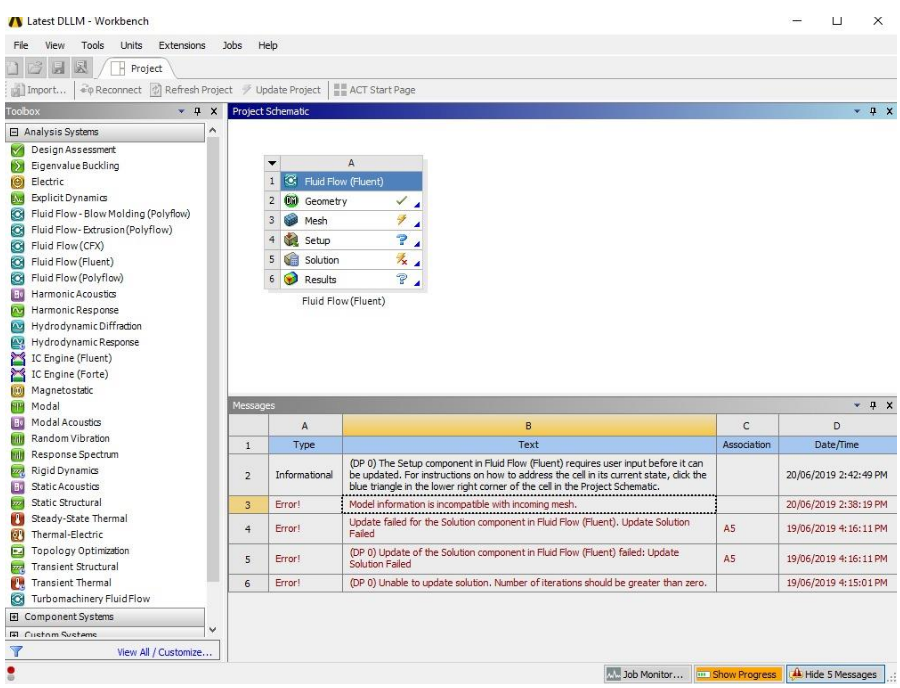


Figure 10: Error in ANSYS

During the simulation, the team got error messages in the software. Several attempts that had been done over two days, the team couldn't eliminate the errors and couldn't proceed to the next stage, therefore the team decided to consult the academic supervisor. Academic supervisor, Dr. Faizal advised the team to consult the CFD expert in the campus, Dr. Ng Khai Ching on the project.

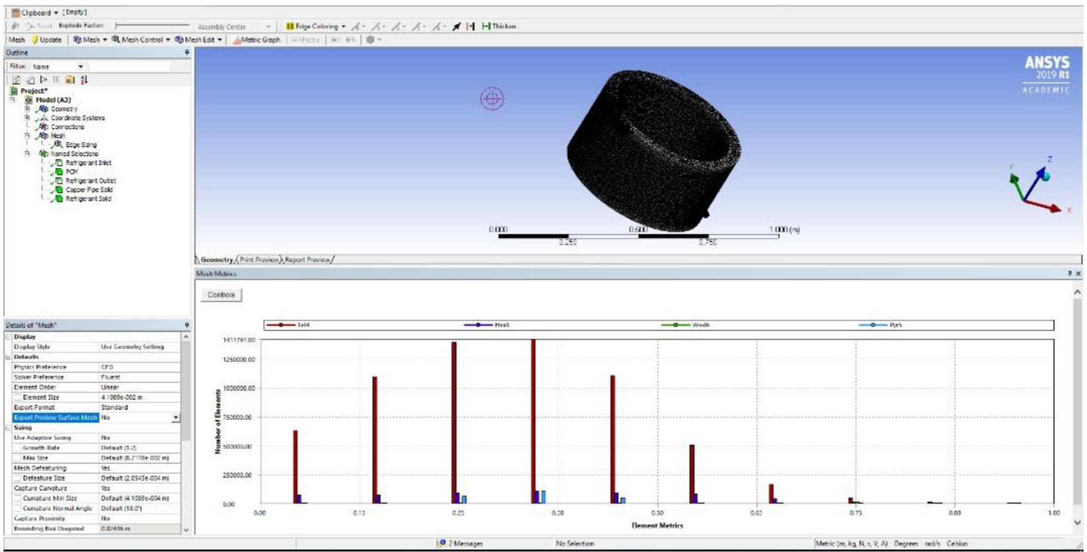


Figure 11: Meshing in ANSYS

After consulting Dr. Ng, he told us that he wasn't the expert on the specific field on what we are trying to achieve. However, he advised us some useful information and hopefully to obtain the result. He advised us to only create two entities which were only the refrigerant and the PCM to make them to have zero thickness contact. We proceed and retry the simulation according to the advises from Dr. Ng. The team completed the meshing with the entire object. The figure above shown the skewness of average 0.2974 after the meshing was done, and the maximum skewness was 0.6903. These values were excellent as the lower the skewness, the better the simulation results. The entire object took 30 minutes to be fully meshed.

After the meshing was done, the team proceed with simulation. After attempted several simulations, the team couldn't get any relevant results. This was due to lacking specific data, such as varying data line of the different viscosities of the PCM under different temperature conditions. Other than that, lacking experience and knowledge on CFD was one of the failure factors.

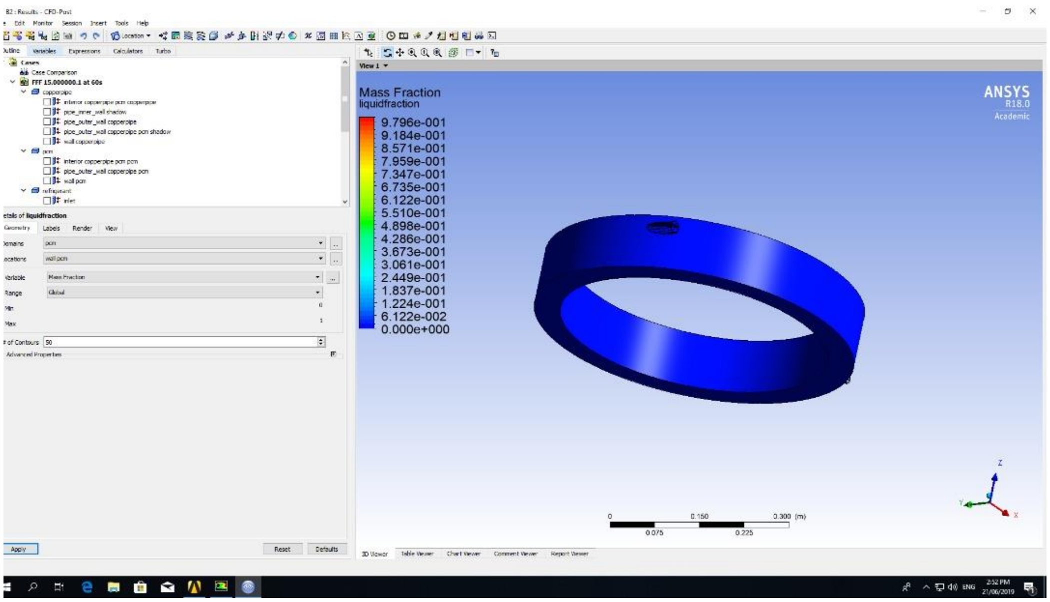


Figure 12: Final Analysis

The figure above showed the latest invalid results that we got from the simulation software. The results couldn't show the time for the object to be fully melted and couldn't get the expected results as well. Therefore, the team decided to terminate the testing with simulation as the simulation was one of the reasons of delaying the schedule. The team would proceed to get real results by hands-on testing during the operate stage. The team was still motivated as the team learnt and gain knowledge on using CFD even though the team did not get results of it but the team got to know how to utilize the features.

3.8 Analysis on the actual results

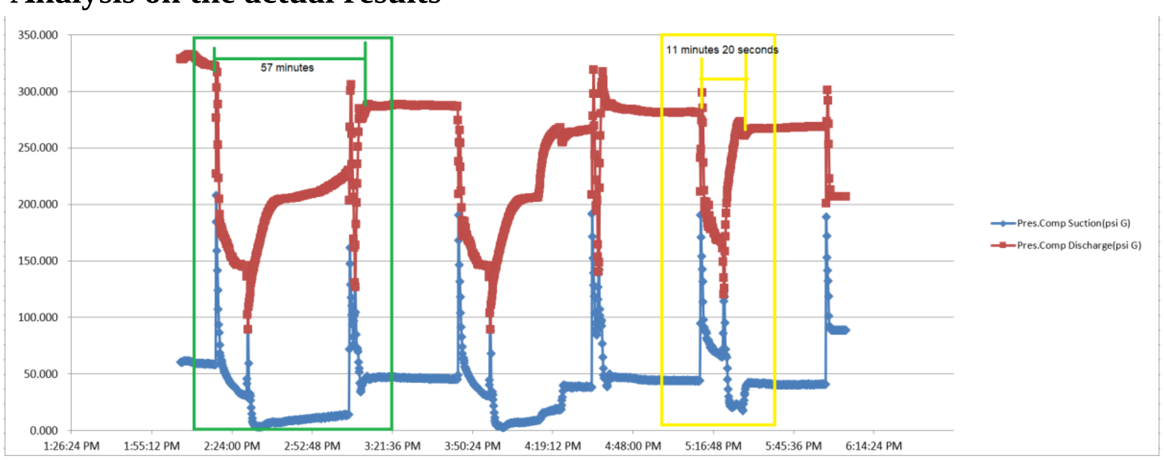


Figure 13: Result from testing

The graph above was generated by the computer software in DAIKIN test room. The team was proposed to run testing under 5 different conditions of outdoor Dry-Bulb temperature which were 5℃, 0℃, -5℃, -10℃ and -15℃. Due to the heat-pump unit was broke down and insufficient of time, the team could run the testing with one standard condition which was Dry-Bulb temperature 7℃. The graph was generated according to the testing results from the prototype at the standard condition. The green area indicated the time taken to defrost the frost that formed on the outdoor coil and it took 57 minutes to complete the defrost cycle without PCM. Whereas the yellow area indicated the time taken to defrost the frost that formed on the outdoor coil and it took 11 minutes and 20 seconds to complete the defrost cycle with PCM. On top of it, the copper coil and the tank weren't fabricated nicely and according to the desired dimensions, therefore, the required actual volume was greater than the desired volume. So, this prototype did not fill fully with PCM. Based on the result graph, it shows that the time was shortened by roughly 80% of time to defrost the frost that formed on the outdoor coil when the unit was added with PCM.

Furthermore, our prototype is an additional part that was attached into the existing heat-pump unit as mentioned earlier. The heat-pump unit has its own complete system and one of the challenges for the project is to make sure our prototype is synchronized to the system of the existing heat-pump unit. The main component must be synchronized with the heat pump unit would be the solenoid valve used in the project. As the solenoid valve must be switched on or off automatically and synchronize with the heat pump unit at the same time, otherwise the project will be failed, and the heat pump unit couldn't be run. This is because the heat pump unit has two cycles to run. When the cycle changed, the refrigerant in the heat pump would flow reversely. For our prototype, the team must generate two different paths for the refrigerant to flow when the cycle changed. The result graph shown above was generated by the heat pump unit with attached of our prototype. Hence, it proved that our project is succeed as the heat pump unit could run and generate the results.

4.0 Engineering Drawing

The team used the simulation software Solidworks to construct the prototype and to generate the Engineering Drawing for DAIKIN to fabricate the copper coil and for tank manufacturer to fabricate the storage tank. The team constructed all the three copper coil designs with Solidworks that we discussed earlier.

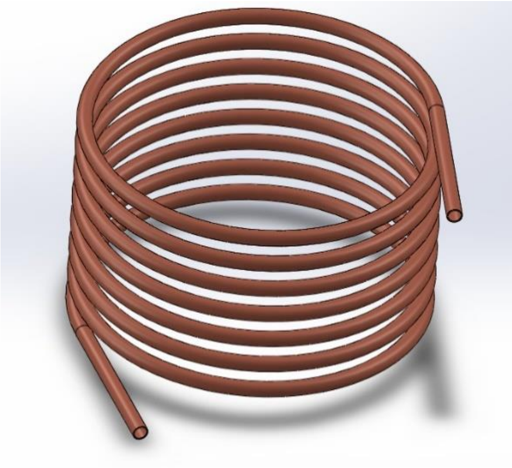


Figure 14: Spiral Coil design

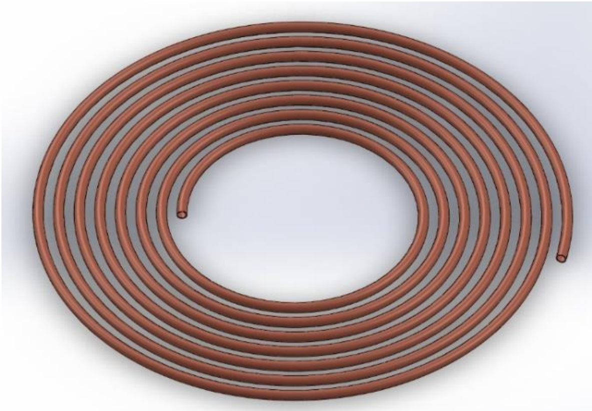


Figure 15: Circular Coil Design

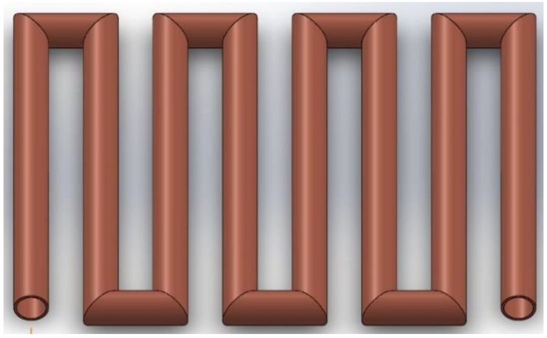


Figure 16: Rectangular Coil Design

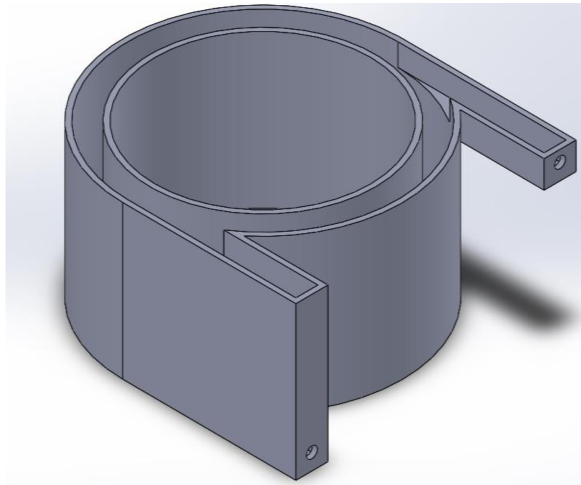


Figure 17: Storage Tank Design

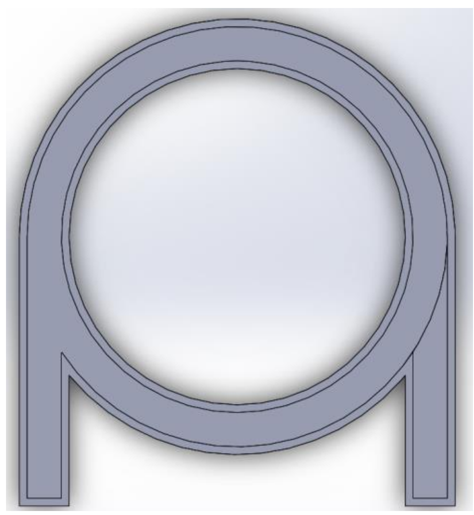


Figure 18: Top view of storage tank

As mentioned, the team chose the spiral coil as the final design due to limitation and it was recommended by industrial supervisor. Storage tank was designed according to the final design of spiral coil. Industrial supervisor fabricated a draft copper pipe according to the first final copper pipe design. Based on the draft prototype, the team understood that the copper pipe was difficult to install into the storage tank due to the inlet and outlet of the copper pipe were not in the same plane. Therefore, the team decided to improvise the final design of the copper pipe by making the inlet and outlet of the copper pipe to be in the same plane with the bend angle of roughly 35-degree. After the team submitted the Engineering drawing of the improvised final copper pipe design to DAIKIN, the team decided design the storage tank after they fabricated the copper pipe.

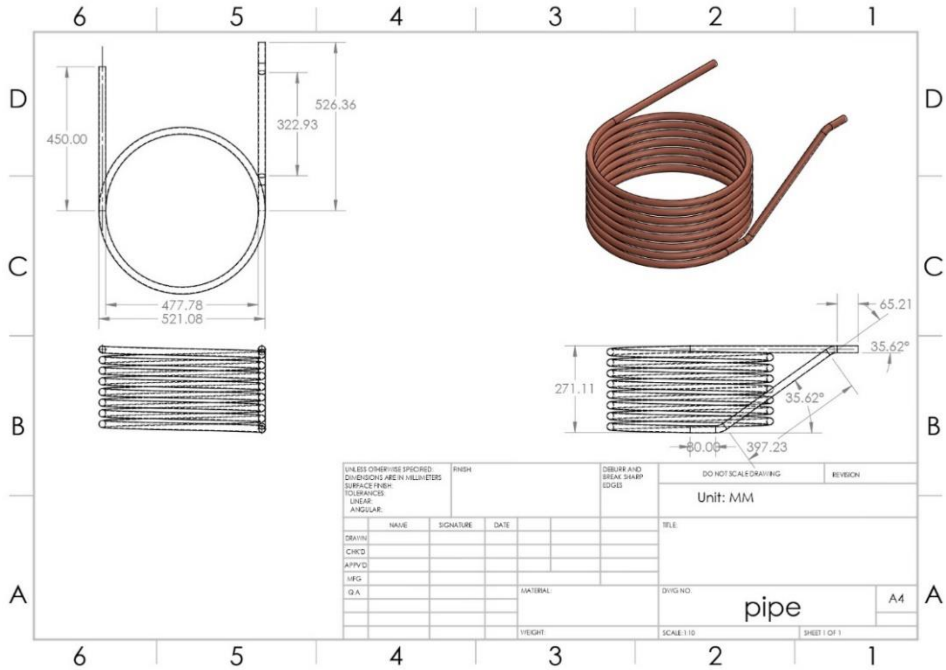


Figure 19: Engineering Drawing of modified pipe

The copper pipe for the prototype was finally fabricated. Unfortunately, the copper pipe wasn't fabricated according to the Engineering Drawing that the team provided. Industrial supervisor told that it was because DAIKIN did not possess the machine that can bend the copper pipe to 35-degree but 90-degree. Therefore, the copper pipe was fabricated with the bend of 90-degree instead of 35-degree.

Figure 20: Pipe fabricated by DAIKIN

5.0 Implement

5.1 Controlling System

For PCM Heat-Exchanger, the controlling system for this project is to control the pathway of the refrigerant flow during the heating cycle and the defrosting cycle. The figure below shows the pathway of heating cycle which is in red arrow and the defrosting cycle which is the blue arrow. During the heating cycle, the valve number 1, 3 and 4 should open so the hot refrigerant from the outdoor unit will pass through valve number 1 to the indoor coil then passing through the valve number 3 into the PCM Heat-Exchanger tank where the PCM in the tank will absorb the heat from the refrigerant to and stored in the PCM. The solid PCM will absorb the heat from the refrigerant and the PCM will experience melting process therefore the PCM in the tank is now in a liquid state. The refrigerant which has less heat then enter valve number 4 back to the outdoor unit. In this heating cycle, the valve number 2 and 5 will be closed. During the defrosting cycle, the valve number 2 and 4 will switch on, while the valve number 1,3 and 5 will switch off. The pathway for the refrigerant now will be the other way around meaning the refrigerant from the outdoor unit will travel through the valve number 4 into the PCM Heat-Exchanger tank. When the cold refrigerant from the outdoor unit travels into the tank, the refrigerant will absorb the heat from the solid PCM to store more heat into the refrigerant. During this cycle, the liquid PCM will release heat to the refrigerant, the liquid PCM will solidify upon releasing heat. Thus, the refrigerant which has more heat will pass through valve number two back to the outdoor unit. Initially, we need to control all 5 valves, however after we discussed with Daikin Supervisor, we found out that we just need to control 3 valves which is valve number 1,2 and 3 because valve number 4 is always open and valve number 5 is always close.

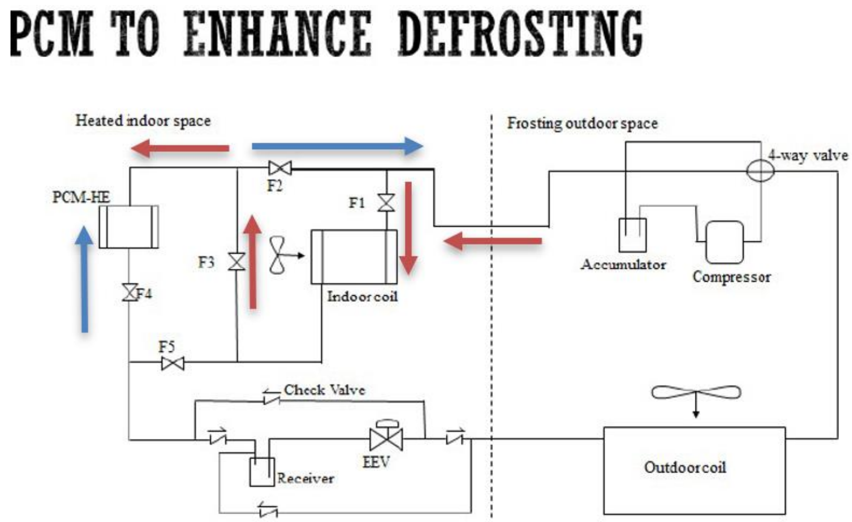


Figure 21: Pathway of the refrigerant

Therefore, the control system for this project is to control the valve between the heating cycle and defrosting cycle. The condition to switch between the cycles are when the outdoor coil temperature drops to 0 °C or below, the cycle will switch from heating cycle to defrosting cycle as there is frost form on the outdoor coil therefore hot refrigerant is needed to pass through the outdoor coil to defrost the frost on the coil. The other condition is that if the outdoor coil temperature is above 5 °C or above for 2.5 minutes then the cycle will switch from defrosting cycle back to heating cycle. To control this system, the team decided to use Arduino as we have experience on using it for the previous semester, as the control board, a temperature sensor to detect the outdoor coil temperature, a valve to control the pathway. The table below shows the initial and the final materials used for the control system.

Table 4: Initial and Finalize Design

Description	Initial Design	Finalize Design
Arduino	Arduino Mega	Arduino Uno
Temperature sensor	TMP35	DS18B20 Temperature Sensor
Valve	SG90 Servo motor	Solenoid valve
Switch	-	5V Relay
Resistor	-	4.7 Ohm Resistor

Initially we decided to use Arduino Mega because we assume the valve provided by Daikin would be like the servo motor. For servo motor, there is a total of 3 pin per servo motor which consist of 5V terminal, Ground terminal and the Digital pin for controlling the servo motor at desired standard. Initially the total valve needed for this system is 5 which has a total of 15 pins to plug into the Arduino therefore we decided to use Arduino Mega as it is bigger compared to Arduino Uno and we need a few more pins for the temperature sensor. However, after receiving the actual valve from Daikin, there is only two wires which is the live and the neutral wire. Therefore, we decide to change it back to Arduino Uno which is smaller than the Arduino Mega.

Figure 22: Arduino Mega

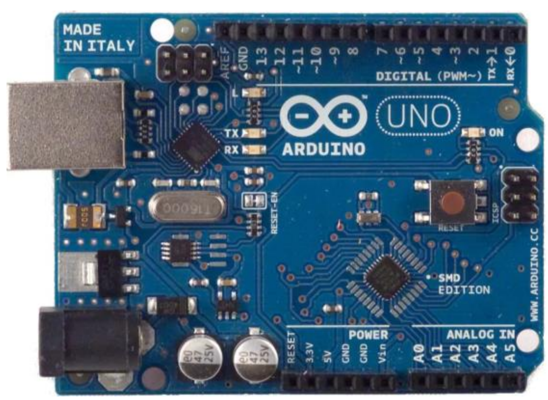


Figure 23: Arduino Uno

As said previously, the type of valve used has changed to solenoid valve instead of servo motor type. For the solenoid valve the power source is directly from the plug which is a 250V and 2.5A plug. Therefore, to overcome this we need to use a direct source from the plug instead of Arduino while using the Arduino to control the valve. To tackle this problem, we decided to apply from what we had learned from module Electronics and Microprocessors which taught us about the use of relay. Relay is like a switch, but it is an electromagnetic switch that controls the switch by turning on or on a larger electrical circuit by applying as small electrical current depending on the type of current as for this project, we decided to use 5V relay with the help of the electrical lab assistant.

Figure 24: Server Motor

Figure 25: Solenoid Valve

Figure 26: 5V Relay

As for the temperature sensor, initially we decided to use the model TMP35 which is a common temperature sensor for Arduino which can be obtained from the electrical lab. This type of sensor is used to sense the surrounding temperature. After meeting up with Daikin Supervisor, we found out that the sensor needs to touch the outdoor coil and it may contain moisture when there is a change of temperature in the refrigerant. They gave us the temperature sensor that is attached to their unit that the sensor is touching with the outdoor coil and it is waterproof. However, we could not detect any reading after testing out with arduino as it has two wires which is the 5V terminal and the ground terminal. After researching for the suitable temperature sensor, the team managed to find a similar temperature sensor that is compatible with Arduino which is the DS18B20 waterproof temperature sensor. However the way to connect this sensor to the Arduino needs a resistor of 4.7 Ohm because the Arduino can only read voltage reading but not current reading therefore the resistor is there to convert the current reading from the resistor to voltage.

Figure 27: TMP 35

Figure 28: DS18B20

5.2 Testing for Control System

The testing for this control system includes the testing of Arduino, controlling the valve, obtaining reading from the temperature sensor and implementing all into one code. The first testing was the testing of the Arduino whether that the Arduino we borrow from the electrical lab is functioning like normal. To test whether the Arduino is working, we uploaded the sample code of blinking from the Arduino platform. The LED that is built into the Arduino will blink according to the time interval that was set. The Arduino that we borrowed is working as usual just like we expected.

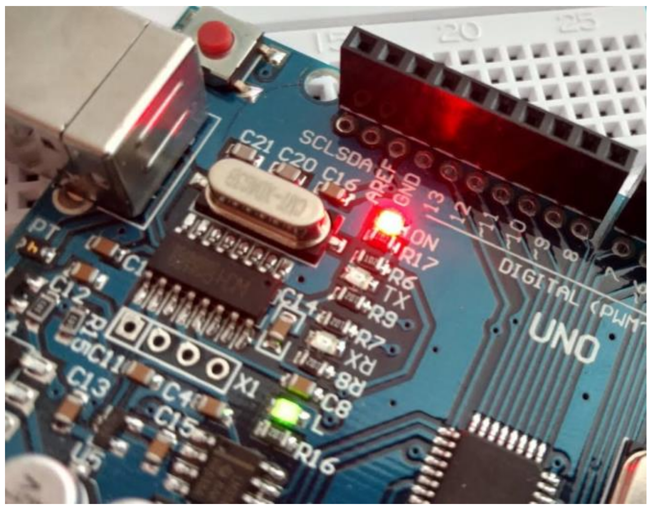


Figure 29: Blinking LED for Arduino

Blink | Arduino 1.8.10

File Edit Sketch Tools Help

Blink §

```
//Blink

// the setup function runs once when you press reset or power the board
void setup() {
  // initialize digital pin LED_BUILTIN as an output.
  pinMode(LED_BUILTIN, OUTPUT);
}

// the loop function runs over and over again forever
void loop() {
  digitalWrite(LED_BUILTIN, HIGH);   // turn the LED on (HIGH is the voltage level)
  delay(1000);                       // wait for a second
  digitalWrite(LED_BUILTIN, LOW);    // turn the LED off by making the voltage LOW
  delay(1000);                       // wait for a second
}
```

Figure 30: Code for Blinking

The next testing that we did was the test to control the valve. For this we have to set the conditions for this valve which is the heating cycle and the defrosting cycle. As said previously, the conditions are when the outdoor coil temperature drops to 0 °C or below, the cycle will switch from heating cycle to defrosting cycle while the other condition is that if the outdoor coil temperature is above 5 °C or above for 2.5 minutes then the cycle will switch from defrosting cycle back to heating cycle. Before implementing the condition into the code, the first testing was to check how the solenoid valve works. The solenoid valve will turn on or open the pathway when there is a power source which is from the AC power plug. All 6 of the solenoid valve sponsored by Daikin is working fine. The next step is to use the Arduino to control the solenoid valve, with the help of electrical lab assistant and experience from the module Electronics and Microprocessors. This process includes the soldering the relay and the power source to the PCB board and connection to the power source which is the plug and the Arduino digital pin. The code we use is like the sample blinking with the time interval of 2 seconds the valve will switch between heating cycle and defrosting cycle.

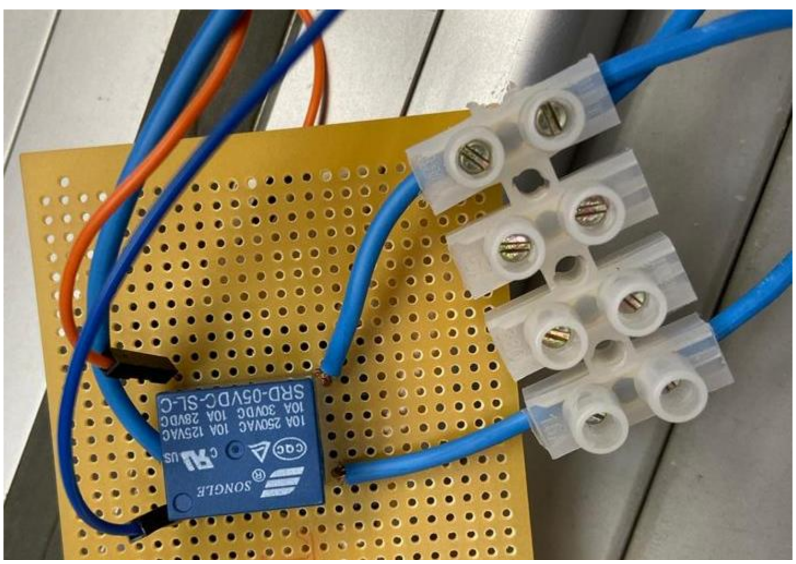


Figure 31: Connection for the relay and the valve

Figure 32: Code controlling the valve with relay

The next testing for the control system is the testing for temperature sensor. Initially we plan to use TMP35 which is a temperature sensor that sense the surrounding. The first testing was by using this TMP35 and everything turns out fine as normal then we decide to combine this temperature sensor code with the controlling valve. Everything works and the team show this to Daikin Supervisor, the feedback is that we need to change this temperature with a temperature sensor that can be attached to the outdoor coil by making contact with the coil. Thus we took back the temperature sensor that is built in their outdoor unit by Daikin and tested to get reading. However, there is no reading from the sensor because the temperature sensor has only two pin which is the 5V terminal and the ground terminal and there is no digital pin for the input to be taken from the sensor to the Arduino. After researching online, we managed to find a similar temperature sensor from online which is the DS18B20 waterproof temperature sensor. The testing for this sensor is similar to the first temperature sensor except we need to include a specific library which can be found in the Arduino platform. The next step is to combine the new temperature sensor with the controlling valve coding together. For this testing we alter the temperature condition as it is easier for us to check the circuit is working or not. After several testing and altering the value for the timing of the valve changes, we build a small container to fit in all the circuitry for easy portability.

PCM_Heat_Exchanger | Arduino 1.8.10

File Edit Sketch Tools Help

PCM_Heat_Exchanger

```
#include <OneWire.h>
#include <DallasTemperature.h>
#define ONE_WIRE_BUS 4
int Relay = 7;
OneWire oneWire(ONE_WIRE_BUS);  // Setup a oneWire instance to communicate with any OneWire devices
DallasTemperature sensors(&oneWire);  // Pass our oneWire reference to Dallas Temperature sensor
unsigned long counter = 0;
void setup(void)
{
  Serial.begin(9600); // Start serial communication for debugging purposes
  sensors.begin(); // Start up the library
  pinMode(Relay, OUTPUT);
}
void loop(void){
  // Call sensors.requestTemperatures() to issue a global temperature and Requests to all devices on the bus
  sensors.requestTemperatures();
  Serial.print("Celsius temperature: ");
  // Why "byIndex"? You can have more than one IC on the same bus. 0 refers to the first IC on the wire
  Serial.print(sensors.getTempCByIndex(0));
  Serial.print(" - Fahrenheit temperature: ");
  Serial.println(sensors.getTempFByIndex(0));
  delay(1000);
  if (sensors.getTempCByIndex(0) > 31){
    counter++;
  }
  else if (sensors.getTempCByIndex(0) < 28){
    counter = 0;
  }
  if(counter > 5){
    digitalWrite(Relay,LOW);
  }else{
    digitalWrite(Relay,HIGH);
  }
}
```

Figure 33: Coding for the whole control system

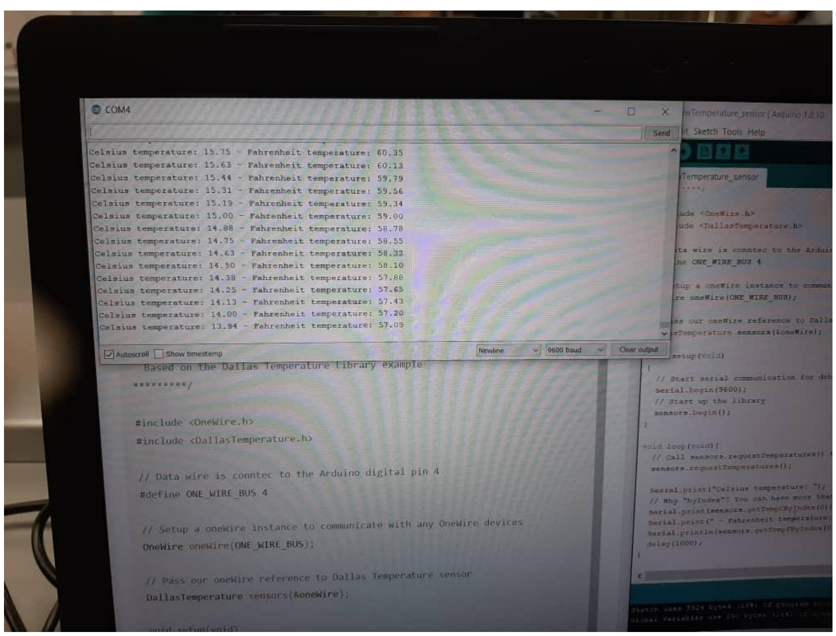


Figure 34: Reading from the temperature sensor

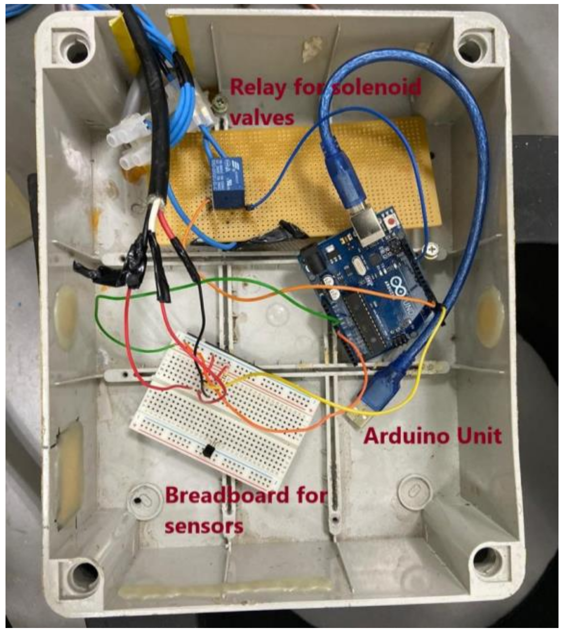


Figure 35: Container for control system

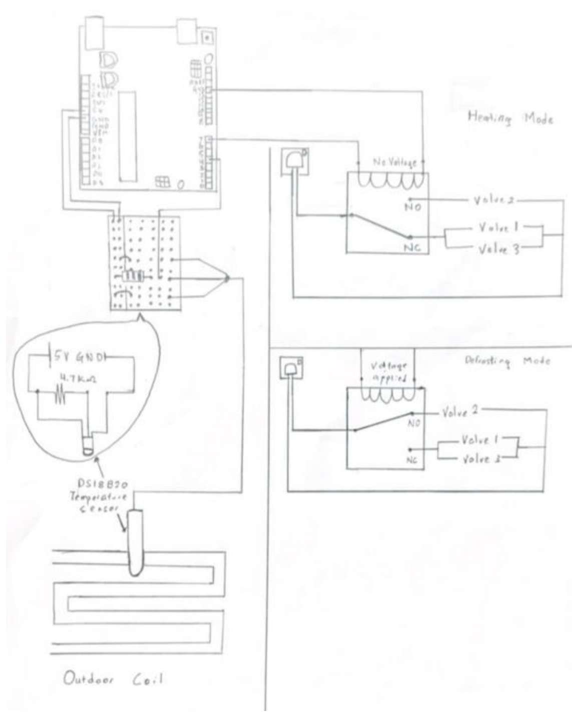


Figure 36: Circuit diagram of the control system

PCM Heat-Exchanger

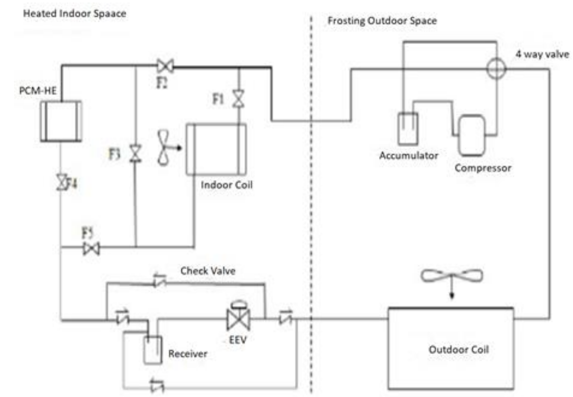


Figure 37: Schematic diagram with PCM

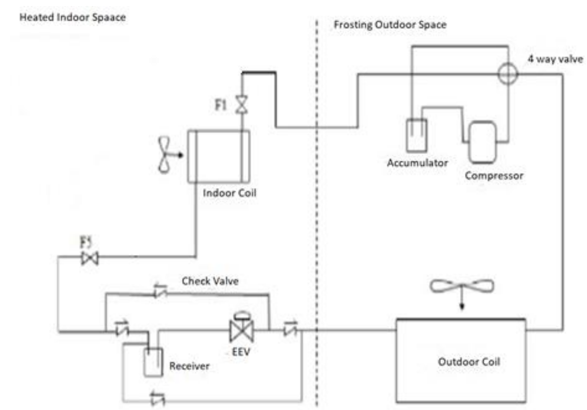


Figure 38: Schematic diagram without PCM

Based on the figure above, the PCM Heat-Exchanger is an additional unit that is located at the indoor space. This tank is filled up with Phase-Change-Material which is to absorb and release heat from the refrigerant from the copper pipe. This tank is used to reduce the time to defrost the frost formed on coil of the outdoor unit. The PCM Heat-Exchanger tank consist of the tank, the copper pipe, PCM and the connection of the solenoid valve.

Copper pipe

To manufacture the copper pipe, calculation must be done to get the total length needed for the PCM Heat-Exchanger. This calculation was calculated from previous semester which is MEGP1 during the Conceive stage. Daikin Supervisor gave us a spreadsheet to calculate the total length of the copper pipe needed. The outer diameter of the copper pipe is set to ⅞ inch to as it the biggest size available to fabricate in Daikin, with this we just need to put into the spreadsheet to calculate the total length of copper pipe needed for the PCM Heat-Exchanger which is a total of 12.6m long.

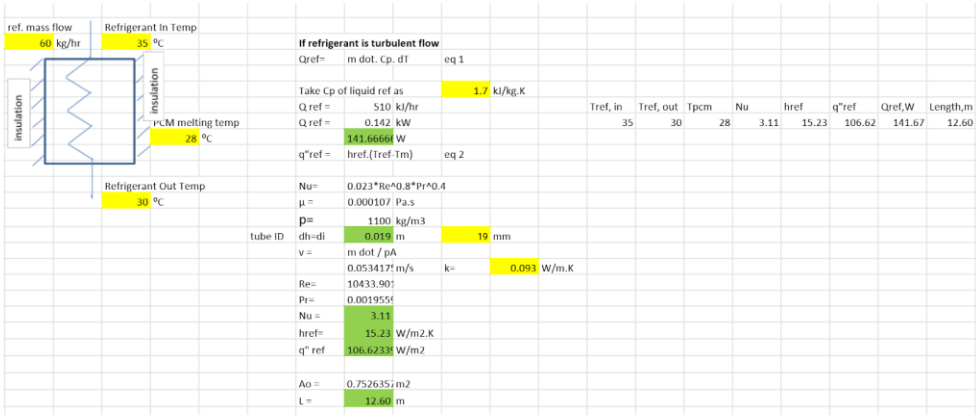


Figure 39: Calculation for copper pipe length

After calculation this length, is it the Design stage of the copper pipe, based on MEGP1, the team finalize with a design of the copper pipe to be the spiral design. This design is drawn on Solidworks with the data we got and the requirement. The condition for designing this copper pipe is that the length of the pipe must be a total of 12.6m long and the space between each pipe must be at least the size of one copper pipe which is ⅞ inch. The finalized design was then sent to Daikin Supervisor to let them fabricate the copper pipe.

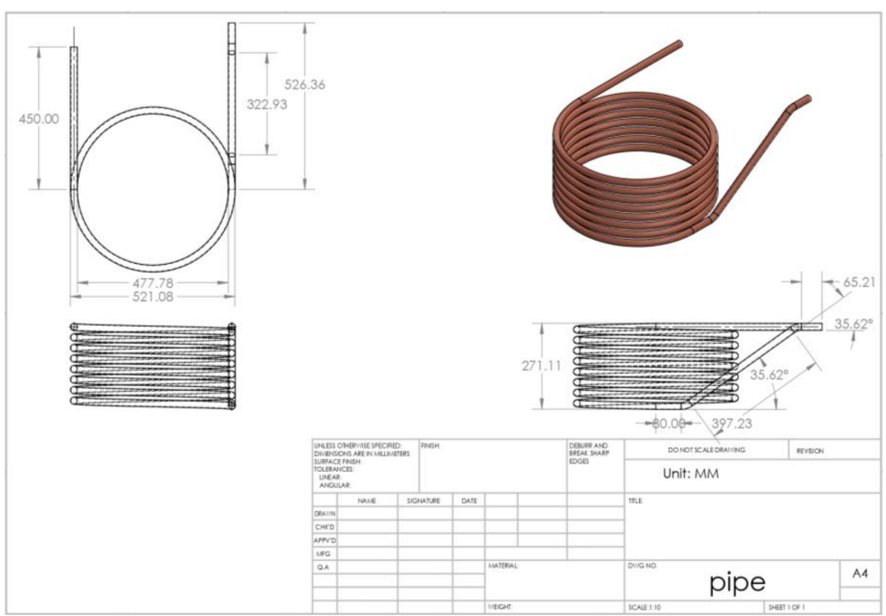


Figure 40: Engineering Drawing of copper pipe coil

The first fabrication of the copper pipe by Daikin was sent to us to check if the design was correct. However, the first fabrication, has few errors whereby the outer diameter of the copper pipe used is wrong dimension and there is no gap between each copper pipe due to the weight of the copper pipe the whole copper pipe collapse and each pipe is touching with each other. After discussing with Daikin Supervisor, they fabricate the second copper pipe coil with correct outer diameter of ⅞ inch however the failure for the space between the copper pipe cannot be solved as the weight of the copper pipe coil and the total length of the copper pipe is longer than the initial proposed length of 12.6m long. The team came out with a solution of add in a support between each copper pipe. This support was designed with Solidworks and printed out with 3D printing which is made out of plastic. The support for the copper pipe coil is essential as this will create space for the PCM to flow and get a better contact surface area between the PCM and the copper pipe.

Figure 41: First (left) and second(right) fabrication of copper pipe coil

Figure 42: Second fabrication of copper pipe coil

Figure 43: Support for copper pipe coil

Fabrication Process

Table 5: Initial and Finalized Material

Description	Initial Material	Finalised Material
Material	Polyethylene (Plastic)	Metal
Process	Plastic Injection	Welding
Mould	Yes	No
Corrosive	No	Yes
Cost	High	Low

For the PCM tank, the material choice was initially plastic. We approached Quality Results plastic manufacturer to fabricate our tank. The company was using plastic injection moulding which involves the melting of plastic pellets which will then be injected into a mould cavity and subsequently fills and solidifies the final product. This method is suitable for mass production as we are only fabricating one unit for our project. In addition, this process requires them to create a mould in which the cost of production is very high. Although there is other process of plastic fabrication, not many plastic manufacturers are willing to fabricate our tank due to the large size of the copper coil and the quantity.

The next choice of material was metal. Although PCM is corrosive to metal, this could be done as our project is meant for testing and it is only for a short term purpose. Corrosion could also be lengthen for a short term by applying the anti-rust coating on the inner surface of the tank. In addition, metal fabrication does not require any mould which could save cost. The process of fabrication chosen was welding. We approached a welding shop called Rajini Welding Works and proposed our design and requirements. Our initial design of the tank was as shown in the figure below.

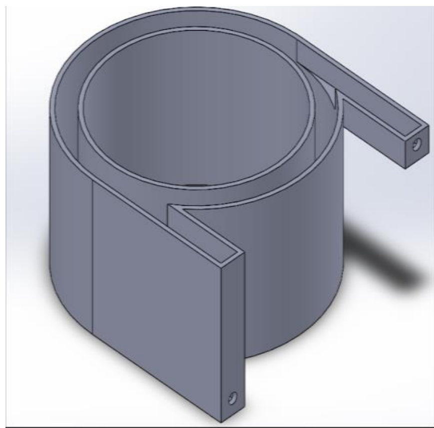


Figure 44: Initial proposed design

After consulting the welder, he said that this design is very complicated as it involves many precision bending which requires a machine. The initial inlet and outlet of the tank was also located on different plane which makes it hard to fabricate. Hence, our group decided to make both the inlet and outlet on the same plane since the copper coil was also modified for easier welding works and to prevent leakage. The whole process of fabrication took around 1 week till the tank was handed over. The early stages of the process require marking and shaping of the tank. As our copper coil has to be fitted perfectly into the tank, all the measurements of the tank is based off the copper coil for accurate and precise marking.

Figure 45: Marking based on the copper coil

Figure 46: Early stages of shaping

After shaping the tank on the metal sheets, the inner piece has to be bent which will circulate around the tank to hold the copper coil in place. In addition, the base of the tank must also be fully welded in order to prevent leakage of the PCM. The process of welding and bending took around 2 to 3 days.

Figure 47: Early Stages of welding and bending

Once the tank was fully welded, a cover was fabricated based on the measurements of the tank. This cover was meant to make the process of refilling or disposing PCM easier and also to prevent heat loss during heat transfer.

Figure 48: Cover of the tank

Figure 49: Front view and top view of fully welded tank

After the welding was done, the tank has to be tested for water leakage and also to ensure that every corner has been welded perfectly. A blow torch was used to check for metalworking and also to ensure the metal are welded.

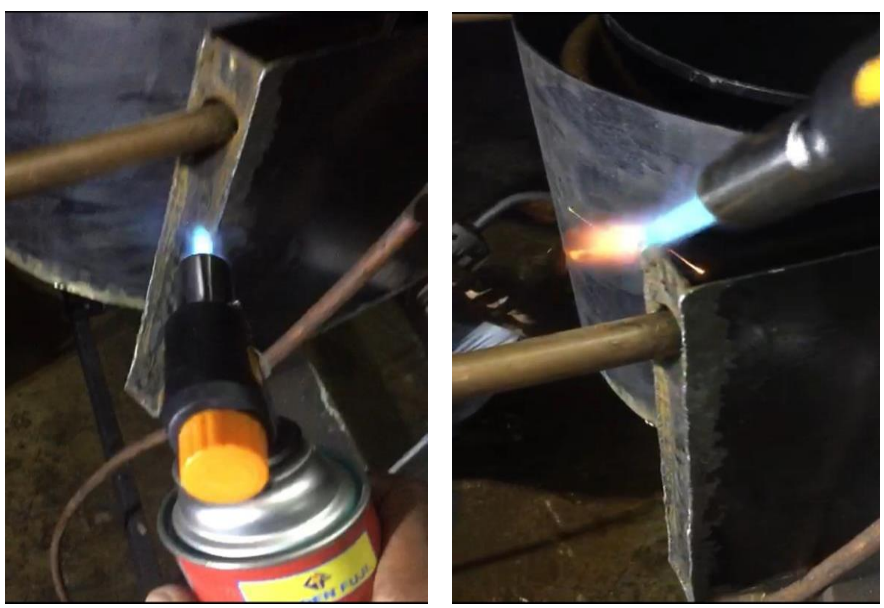


Figure 50: Blow torching the weld part

After everything is done, the final step is to apply the anti-rust coating to the tank with the PYE rust converter to tank and paint the whole tank with a black paint for aesthetic wise.

Figure 51: PYE Rust Converter

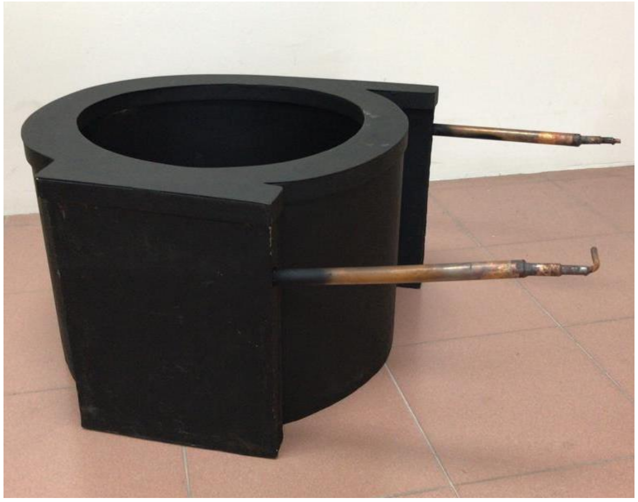


Figure 52: PCM Heat-Exchanger Tank

Connection of solenoid valve

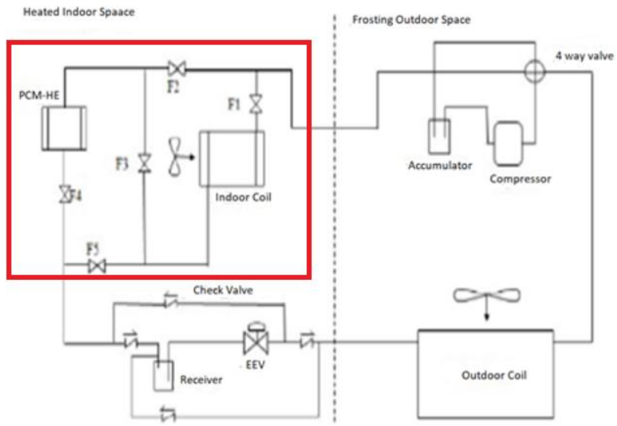


Figure 53: Connection of solenoid valve

The connection of the solenoid valve was fabricated by Daikin at Daikin according to the figure above however after discussing with Daikin Supervisor, we found out that the valve 4 and 5 does not affect the system as valve number 4 is always open and valve number 5 is always close. With the new information, Daikin fabricate a new connection for us and it was used during the testing period.

Figure 54: Connection of solenoid valve

Testing for PCM Heat-Exchanger tank

The testing done for this PCM Heat-Exchanger tank includes the testing of the support before printing out in a mass scale, testing of the tank to check whether there is any leakage of the tank to ensure that the tank is completely sealed with no leakage when the tank is filled up with PCM during the Operate stage, and the mock up test which is done by Daikin Supervisor at Daikin. The first testing done is the testing of the support. We first print two support from the design with 3D printing. The support we first printed was slightly longer but it managed to hold the pipe in place. The second design we sent and finalize on is the design we decided to go with which is shorter compared to the first one. We printed out a total of 36 support with the 3D printer from 3D printing lab. The next testing that we made is the testing of whether there is any leakage by pouring a 5 litre of water into the tank and let it sit for 5 minutes to see if there is any leakage. Once this is done, the whole PCM Heat-Exchanger tank was sent to Daikin to run a mock up test with normal condition. During the mock up testing and the rest of the testing, we did it with heat pump unit of 1 horsepower. This 1 horsepower is enough for the heat pump with the initial length of the copper pipe coil which is 12.6m long. However, after combining all the system for the testing, the whole unit broke due to the lack of horsepower as the horsepower calculated is enough to power up the heat pump unit and the copper pipe coil but not enough to power the new copper pipe length, the connecting valve and the heat pump unit. After consulting with the Daikin staff, they recommended a total of 1.5 horsepower to power up this whole system. With the new horsepower, we run few testings for the whole system with and without PCM and get the result from Daikin.

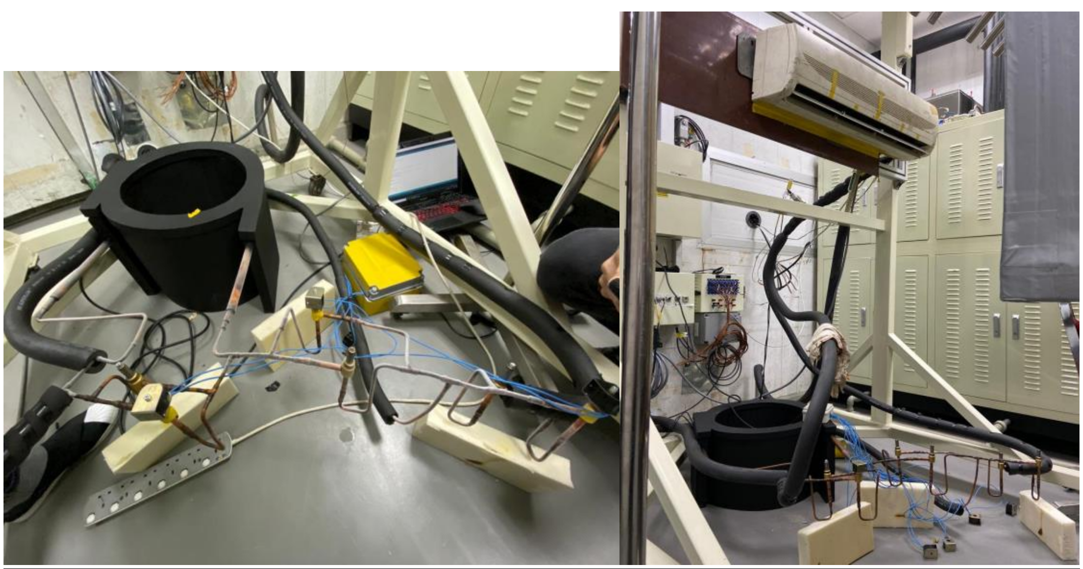


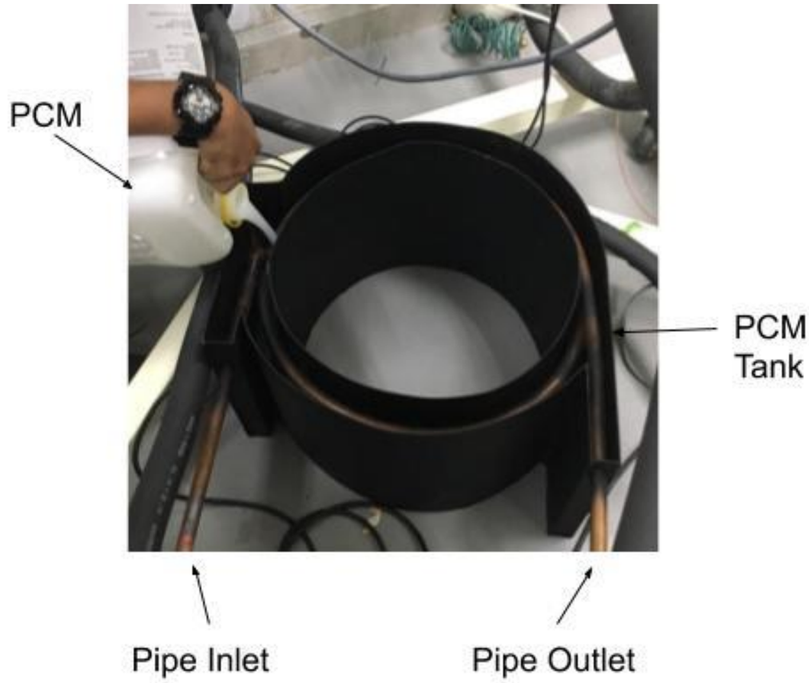
Figure 55: PCM Heat-exchanger whole system

6.0 Operate

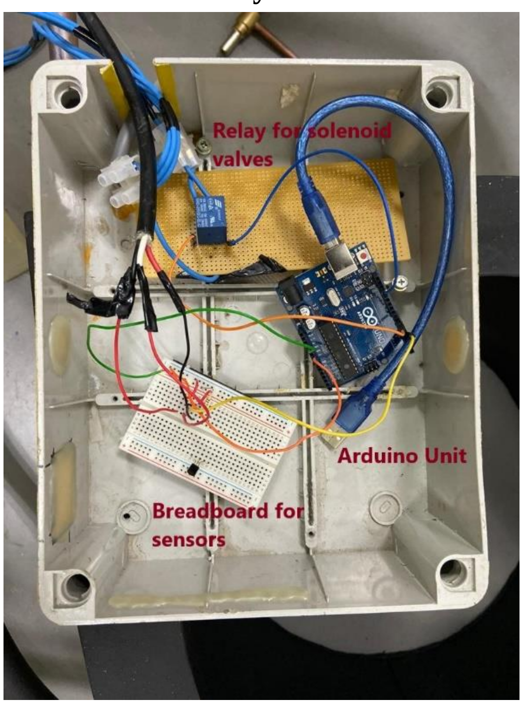
Technical Operation and Maintenance Manual

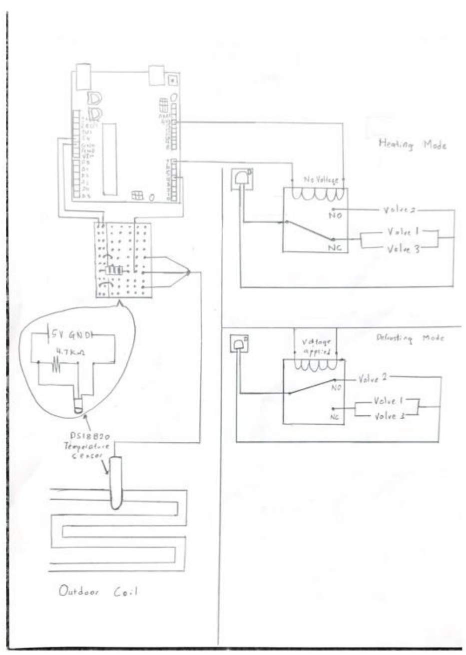
Table of contents

1. **Part Identification**
   PCM Tank

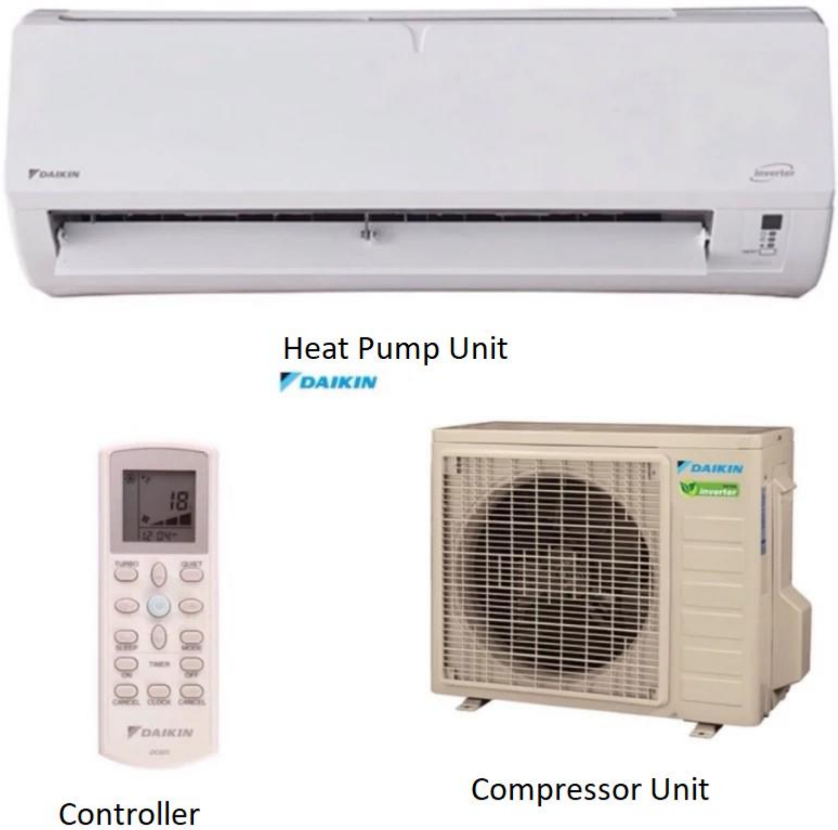


Electrical Circuitry





Heat Pump, Controller & Compressor Unit



2. Specifications.

Heat Pump Unit Horsepower	: 1, 1.5, or 2 Horsepower unit.
Compressor Unit	: Horsepower according to heat pump unit.
Control Board	: Arduino Uno.
Relay Model	: SRD-05VDC-SL-C DC 5V.
Temperature sensor	: Waterproof DS18b20 Temperature Sensor Probe.
Solenoid Valve	: Sanhua FDF-A02080-008-RK.
PCM Tank Capacity	: 10 Litres.
PCM Tank Copper Pipe	: 7/8” Copper pipe for standard HVAC.
PCM Used	: Rubitherm SP-31.

3. Installation Instructions

1. For installation, first ensure that all parts listed in the **Part Identification** section is available and does not appear damaged.
2. The heat pump is first installed by manufacturer or private contractor beforehand, with a mention of the modified piping for the PCM heat exchanger.
3. Then, bring in the PCM-tank for connection to the heat pump modified piping.
4. The PCM heat exchanger is connected by flange nuts which are locked using standard or adjustable wrenches of appropriate size according to pipe.
5. Next up, run a test run to ensure heat pump is able to run with the PCM heat exchange connected, and ensure a smooth run for at least 120 minutes.
6. If there are no problems, proceed to add PCM into the PCM tank.
7. If there are pressure issues, or if the compressor or heat pump stops running during the test run, contact the manufacturer immediately for optimization or troubleshooting.

4. Caution

1. Please consult a certified professional to install a standard heat pump unit, and for the modification of heat pump unit piping for installation of the PCM heat exchanger.
2. Do not attempt to install, weld, or make any piping modification without the consultation of a professional.
3. Do not continue using the PCM Heat exchanger if there are any leaks or abnormalities during operation.
4. If there are any leaks or abnormalities, please contact your manufacturer or professional engineer.
5. Before first time usage, ensure all required tests have been done to ensure the heat pump is able to run smoothly.
6. After test runs are done, add PCM into the PCM Tank.
7. For PCM Rubitherm SP-31, allow PCM to liquify properly for an hour before filling into the PCM Tank.

8. Properly ensure that the electrical circuitry is covered in a power box after installation and kept or placed at a safe location.
9. The PCM Tank is meant for enhancing the efficiency of the heat pump unit, do not attempt to use it for other purposes.
10. PCM in the tank is non-toxic but keep children away to prevent unwanted exposure or ingestion.

5) Cleaning and maintenance of the PCM Tank and Heat Pump.

1. For the heat pump unit, follow standard heat pump cleaning and maintenance procedure provided by heat pump manufacturer.
2. For cleaning and maintenance of PCM Tank, open the cover of the PCM tank and drain existing PCM. Then, use water to fill the tank and wait for an hour. Finally, drain the water and allow the PCM Tank to dry before adding new PCM, and closing the cover.
3. Only use water and no cleaning agents such as detergents or dishwashing liquids to prevent rusting or the wearing of the anti-rust coating inside.
4. Ensure that the PCM Tank cover is properly closed to prevent contaminants from entering the tank.
5. Ensure that the heat pump is off during maintenance and cleaning process.
6. In case of faults in the circuitry, contact a professional for maintenance or repairs. Ensure that the power box is connected to a power source afterwards.

6) Usage Instructions

1. On first use, turn on your heat pump power supply, and switch on the heat pump using your controller.
2. Next, turn on the power supply for the PCM heat exchanger.
3. The heat exchanger will work automatically when frost forms on the outer coils.

7.0 Project Management

7.1 Gantt chart

No.	Task	Duration (Days)	August	September				October				November				December
			W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14
3	**Implement**															
3.1	**Purchase all meterilas required**	14 days														
3.2	**Construction of the container**	14 days														
3.3	**Construction of the circuit**	14 days														
3.4	**Quality control of main systems**	14 days														
3.4.1	Check for leakage of the systems															
3.5	**Quality control of sub systems**	21 days														
3.5.1	Run multiple simulations on subsystem to test functionality under room temperature															
3.5.2	Check conditions of all components in subsystems															
3.5.3	Run multiple simulations under different temperature															
3.5.4	Check conditions of all component under different temperature															
3.6	**Quality control of whole system**	21 days														
4	**Operate**															
4.1.1	Test whole systems under room temperature conditions															
4.1.2	Test whole systems under different temperature conditions															
4.2	**Evaluations and modifications**															
4.2.1	Collect all simulations data and review the results															
4.2.2	Apply any necessary modifications to further improve the performance															
5	Engineering Fair															

7.2 Sponsored Items

Table 6:Bill of Material for sponsored item

Materials	Unit	Total Cost (RM)	Vendor
Air conditioner	1	1200	Daikin Malaysia
PCM (SP31)	1	300	Daikin Malaysia
Solenoid valve and coil	6	210	Daikin Malaysia

7.3 Purchased Items

Table 7: Bill of material for purchased item

Materials	Unit	Total Cost (RM)	Vendor
PCM tank	1	1900	Rajini Welding Works
PYE rust converter	1	15.3	Shopee
Temperature sensor DS18B20	1	9.3	Robotedu
Relay 5V	1	-	School Lab
Arduino Uno	1	-	School Lab

The materials used for the project were separated into two categories. Daikin Malaysia sponsored three items for the project while the rest were either purchased from reliable vendors or obtained from the electrical lab at Taylor’s University.

7.4 Linear Responsibility Chart

Table 8: Linear Responsibility Chart

Name	Role	Responsibilities
Teoh Zhi Heng	Leader	• Distribute tasks to all members • Ensure that project progress according to initial plan • Assist in the design of tank and coil
Alwyn Yip Winn Sheng	Resource Manager	• Ensure all materials required were purchased • Keep tracked of materials • Assist in the design of tank and coil
Hong Jian Hua	Designer	• Design and draw tank and coil • Assist in programming
Jason Chong Jia Joon	Treasurer	• Manage project budget • Lead programmer • Ensure all electrical systems are in order
Tan Jia Hao	Secretary	• Record all meeting minutes • Ensure all documentation were done correctly • Assist in the construction of electrical systems

7.5 Work Breakdown Structure

Table 9: Work Breakdown Structure

Implement
3.1 Purchase all material required **3.2 Construction of main systems** **3.3 Construction of sub systems** **3.4 Quality control of main systems** 3.4.1 Check for leakage of the system **3.5 Quality control of subsystems** 3.5.1 Run multiple simulations on subsystem to test functionality under room temperature 3.5.2 Check conditions of all components in subsystems 3.5.3 Run multiple simulations under standard condition **3.6 Quality control of whole system** 3.6.1 Test whole system under standard conditions 3.6.2 Collect test data
Operate
4.1 Evaluation and modifications 4.2 Create operational manual

As shown in the table above, the implementation stage was broke down to 6 stages. These stages consist of purchasing the materials required for the construction of the prototype and constructing the prototype. For the main system, which was the PCM tank and the coil were outsourced to Raijini Welding Works and Daikin respectively. For the subsystem, most component could be obtained from the Electrical lab at Taylor’s University, any additional component was purchased from an electronics shop. Both systems were subjected to quality control and testing to ensure that all systems were safe for operation.

8.0 Ethics and Professionalism

Throughout the duration of the project, all members always make sure that the code of ethics as an engineer were always adhered to as it serves not only as a guideline but also as a reminder to all engineers to carry out our duties with the utmost professionalism. For example, according to the fundamental canon, an engineer should only perform services only in areas of their competence (NSPE, 2019). The group leader always assigned tasks to all group members according to their abilities throughout the duration of the project to ensure not only to deliver a safe and functional prototype but also make sure that all members only work on areas that they were able to deliver quality results. If tasks were not distributed according to individual capabilities, mistakes could be done which not only delay the progress of the project but also cause injuries to not only the individual in charge but also to the user. Whenever a challenge faced was beyond the capabilities of the person assigned to the task, the challenge would be discussed among other members or seek assistance from the lecturer or lab technicians which are more experienced for their opinion on how to resolve the issue.

Other than that, an engineer should hold paramount the safety, health, and welfare of the public (NSPE, 2019). After receiving the project, the team first conduct research to have a better understanding of the project. This allowed the team to identify the risk and hazardous conditions that might be present and develop a solution. For example, the PCM used was found to be corrosive in nature and could be harmful to humans if consumed. The solution that the team develop was to coat the tank with a anti-rust resin and ensure that the tank was fully sealed and no leakage before proceeding to carry out testing at the lab at Daikin. The subsystem of the prototype consists of many electronics and could be dangerous as high voltage electrical component was used. Hence, a plastic control box was used to hold all the electronics.

The professional obligations of an engineer states that an engineer shall be guided in all their relations by the highest standards of honesty and integrity (NSPE, 2019). Throughout the duration of the projects, some mistakes were made as it is inevitable. Whenever a mistake was done, the member responsible would report it to the leader and other members of the team. A discussion would be held to develop a solution rectified the mistake. This quality is important as the consequences of not disclosing a mistake could be detrimental such as the injury of another member that could be prevented or causing a delay on the progress of the project. Other than that, being honest is also important to maintain the integrity of the company or organization that an engineer is representing and maintain the confidence of the client that the person who made the mistakes who take responsibility for the mistake done and deliver a quality product or service (NSPE, 2019).

Another professional obligation of an engineer is to give credit for engineering work to those who contributed when credit is due and recognize the proprietary interest of others (NSPE, 2019). Since the project that our team was a partnership with Daikin Malaysia, an acknowledge letter was requested that clearly states the materials and cost that were sponsored by Daikin Malaysia. Our team leader would also give compliments to members who had completed a task that was assigned. The acknowledgement of an individual’s achievements provides them a feeling of satisfaction and that their efforts were not to no avail. It also serves as a motivation for the members to continue their hard work and deliver better and more quality results.

9.0 Societal, Health, Safety, Legal, Economical, and Cultural Issues

The health and safety factor of every user is of ultimate importance, and our design was made with safety in mind. Although most of the PCMs used in the industry are non toxic to human beings and animals, PCM ingestion should still be avoided, as well as long term exposure to the skin. To enforce this, cautionary information was written in the technical operation and maintenance manual. As for disposal, PCM materials are land-fillable, and the PCM that we are using has low flammability and is not considered a hazardous material. Nevertheless, proper disposal steps should be taken as there is little information regarding the impact of PCM on the environment, incineration may be a better way to dispose of PCM (Wu, Zhimin, Chin, et. al, 2018). As for the PCM tank, it does not pose any safety and health issues except for leaking of PCM, which may lead to accidental ingestion of PCM by children. This can be prevented by safety sealing the tank, as well as proper maintenance.

9.2 Society

In the past years, the increased fuel consumption and release of CO2 emissions have affected the environment all around the world. To improve the defrost performance, many heat-pumps utilize electrical energy or some form of fuel consuming system to produce heat. The usage of PCM as a heat storing and release method would not consume any additional fuel or energy. This in turn helps the society by lowering CO2 emissions, and reducing the effects of global warming as well as acid rain.

9.3 Legal

The use of PCM and our PCM tank design does not violate any existing laws, patents or copyrights. However, it is to be noted that the PCM SP-31 used in the project is a patented product by Rubitherm, and thus in the future if there are any plans to mass produce, discussion and contracts would be required with Rubitherm Germany. As for the PCM tank and the electrical circuitry, there are no problems in the legal aspect for the design and use.

9.4 Economical

For the economical aspect, it is projected that the usage of PCM would be able to lower electricity costs. As the team do not have industrial data regarding consumption of energy for standard heat pumps that use heaters or fuel for enhanced defrosting, we had to do some rough estimations and research based on information online. Due to lack of conclusive and recorded data, information from heat pump users were taken online. With the use of emergency heat, which is a form of supplementary heating to complement heat pumps, the electricity usage was an additional 350% (Lennard, 2019). The user recorded that the energy used without emergency heat and with emergency heat was 9 kWh and 2 kWh respectively, which is a huge difference (Early Retirement, 2009). Hence, with the successful application of PCM Heat Exchanger, it should theoretically be more economical compared to a standard heat pump.

9.5 Cultural

For cultural impact, our project is able to encourage more energy saving in the thinking of our society and push for the gradual shift towards usage of devices that require no fuel or additional energy. This will bring a positive impact to the society, because when more people begin to have the prioritise energy saving, such positive thinking will be able to spread easily. The team hopes to be able to encourage the use of fuel consumption free alternatives such as PCM, which relies only on absorbing and releasing waste heat as a method of heating. However, more progress and research would be required so that usage of materials such as PCM will be more widely implemented compared to fuel consuming alternatives.

10.0 Conclusion and Recommendations

The first recommendation for improvement that can be made is the improvement to the tank, in terms of overall design, type of material, ease of maintenance, and future easing of manufacture. In terms of overall design, the PCM tank has myriads of room for improvement. The shape of the PCM tank can be redesigned to be more easily moulded, and a drainage pipe with a cap can be added to allow easy maintenance and built in brackets can be added to hold the copper pipe in place. The PCM tank,is current using steel as material, and it can be changed into plastic to decrease the overall weight of the PCM tank, as well as prevent the possibility of rusting. Currently, the main reason why the PCM tank cannot be manufactured using plastics is because of the size of our design that do not allow 3D printing. In the future, further research can be done by using newly designed models, and research into rapid prototyping is recommended to produce a future prototype in plastics instead of steel. As for taking the product into mass production, injection moulding can be considered as the PCM tank has a fixed design with a complicated shape.

Another possible improvement is to improve the coil copper pipe used in the PCM tank. Currently, due to the thickness of the pipe used, there was difficulty in bending the pipes into the desired shape according to our design. The use of a spiral bender that is currently in the industry would solve this problem and allow the pipes to be bent into the exact required dimensions. Also, it is possible to change the design of the piping into an entirely new design to replace the current spiral coil design. This would require additional research, and hopefully it will result in a more compact and efficient design in the future, such as a spherical shape or a flat plate shape.

An improvement to the circuitry is also possible, by simply replacing the Arduino Uno unit used with a specialized Programmable Logic Controller (PLC) unit. PLC units are desirable because they are more reliable, responsive, and accurate compared to Arduino units in terms of long-term usage, and also they are able to handle a high voltage of 240V from household sockets. The ability to handle 240V from sockets also removes the need of using a relay, as arduino units cannot handle high voltages. This allows for the PLC unit to directly control individual solenoid valves, unlike Arduino units that can only control two predetermined sets of valves. This makes PLC units a pre-programmable, easy maintenance, flexible and cost-effective control system.

Replacement of the currently used PCM into a better one is also a means of improvement.

From the specs sheet and information provided by Rubitherm, the manufacturer company of the PCM SP-31, it can be seen that the thermal conductivity and thermal storage capacity of the SP-31 is somewhat low when compared to other PCMs available in the market. Also, PCM can be designed as it is a manmade material. The design or discovery of a PCM with higher thermal storage capacity and thermal conductivity would improve the efficiency of the PCM heat exchanger. Also, the switch to a non-corrosive PCM would widen the range of materials available for use of manufacture of PCM Tank. Also, if the improved PCM is more easily available than the current SP-31, it would be desirable.

As the PCM tank is a heat storage, heat loss is a factor that needs to be considered. The heat loss from the PCM tank can be reduced by applying insulation, such as using a layer of insulation foam on the outside of the tank. Reducing heat loss would increase the total heat transferred to the refrigerant during defrost cycle and contributes to the increment of efficiency of the heat pump.

In conclusion, the team was able to achieve all the required deliverables of the project and obtain test results during testing at the Daikin Test Lab. Results obtained shows that the implementation of PCM heat exchanger improves the defrost time, and thus successfully shows that integration of PCM heat exchanger is beneficial but requires more research and optimization. Also,the PCM heat exchanger benefits society and solve multiple issues, and more research should be done as a step forward into a future with eco-friendly technology such as PCM.

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