Investigation of Model and Control System
Design of Three Independent System in IC Lab for
Educational Purpose

Bachelor of Engineering Honours [BE (Hons)] Instrumentation and Control &
Industrial Computer Systems Engineering

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Declaration

I, Siti Zainul Axmar, declare that this thesis writing and the research work is originally from my thesis project experiment and data collection. I have acknowledged all the help given throughout the thesis journey and clearly attributed others published work in the reference. This thesis content, as a whole, has never been submitted or released to any education institution.

Name: Siti Zainul Axmar
Date: July 2019
Abstract

Initially, the project is started with conducting design, implementation and testing for water pump with a pressure tank system. This system is a simulation prototype for a household application water system which consists of a pump, pressure tank and pressure switch. This project is constructed for the use inside the ICE laboratory. With the need for energy savings, this project is purposely designed for controlled water supply inlet. For instance, the system works by automatically switch on and off the pump depending on the pressure of the pressure tank, which gives a respective water flow in and out from the system. Thus, this system may reduce the use of a pump for the entire day, which may prolong the pump lifetime.

In the ICE laboratory, the pressure tank with pump is installed on a trolley so that it is easier to locate the system. This system consist of three main module which are heated water tank module, pressure tank with pump module and liquid flow control module. The heated water tank module as the water supply to the pressure tank. In this system, the water pump is pump in the water to the pressure tank when the pressure switch reading is lower than 30 psi and the water pump will stop pump the water when the pressure switch reaches 50 psi. Meanwhile, the liquid flow control module is use to control the output flowrate of water from the pressure tank into the storage tank inside the lab.

Next, the second system is the air-liquid heat exchanger. This system is typically found in the car's front hood, which use for car cooling system. In other words, the air-liquid exchanger system simulates the process flow between the car radiators, fan radiator, water pump and a car engine that involved in the car cooling system. This system is used to run the hot coolant from the engine to the car radiator and push back the cold coolant from the radiator to the engine. This process helps to provide engine running at the ideal temperature and to avoid overheating to the car engine which may lead to engine broke down and also cause failure to the component and parts which located nearby or attach to the engine.
For that, the air-liquid exchanger system is designed and the prototype is implemented inside the ICE laboratory. This system consist of liquid temperature control module 1, liquid flow control module, air-liquid exchanger module and liquid temperature control module 2 which are used for heat up the water to mimic the hot engine condition, to control the flowrate of water, to cool down the water inside the radiator by controlling the speed of fan and to store the water from the radiator respectively.

The last system is an air mixing system, which consists of instruments such as heater, resistance temperature detector (RTD), valve, pressure gauge and differential pressure transmitter. This system mixes air from the hot and cold stream. The hot air comes from the compressed air in the heater to heat the air, and the cold air comes from the air supply which at the room temperature. This panel consists of some failure device which later may need troubleshoot, repair and replace for some of the components. All of the work done has to be recorded and documented well to provide proper identification of the main issue that causes the failure of the system.
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List of Abbreviations

ICE Lab       Instrumentation and Control Lab
RTD           Resistance Temperature Device
TCR           Temperature Coefficient Resistance
DP            Differential Pressure
DPT           Differential Level Transmitter
LRV           Lower Range
URV           Upper Range
MOSFET        Metal–Oxide–Semiconductor Field-Effect Transistor
PD MOSFET     Power Dissipated MOSFET
PD max        Power Dissipated Maximum
PPM/K         Parts per Million/Kelvin
I/O           Input/Output
AC            After Calibration
BC            Before Calibration
SFC           Smart Field Communicator
PIC           Programmable Integrated Circuit
CHAPTER 1: Introduction

1.1 National LabVIEW System Platform

LabVIEW, the short for ‘Laboratory Virtual Instrument Engineering Workbench’, has been developed by National Instruments as a platform for designing, controlling and monitoring the real-time data of a system. LabVIEW consists of two main windows, which are a VI front panel and VI block diagram. The VI front panel is an interactive user interface which visualises the real instrument for input and output of the system such as, slide, knobs, control buttons, LED and graph. Besides, the VI block diagram is where all the graphical programming language is located. This block diagram contains constants, built-in functions and program execution control structures which user can use and connect the related component by merely drawing the wires to define flow data of them (Travis and Kring 2006). For that, the user can key in the input data on the VI front panel and later, can test and view the result on the screen produced by the program from the VI block diagram. All the data obtained from the programming can be stored via data logging function in Excel file CSV format.

1.2 PICAXE Microcontroller

A PICAXE microcontroller is one of the Programmable Integrated Circuit (PIC) that is available in the market. This device can be easily program by using a computer with PICAXE Editor 6 software as shown in Figure 1 and a PICAXE programming cable. The programming language for the editor is in traditional programming language which is in assembler code or known as ‘C’ language, BASIC language and flowcharts. Basic requirement circuit for the PICAXE microcontroller requires a power supply between 3V and 5.5V.
Besides, the circuit connection for the input and output to the microcontroller is varies depending of the chip sizes of the microcontroller and also the purpose of circuit project. There are few types of PICAXE microcontroller such as 08M2, 18M2 and 20M2. Each of the microcontroller has different range of the legs which defines the range of the input and output pins. It is always better to select a microcontroller that has more pins than the number of pins required for a circuit to fulfill the specification of a project and to have more backup pins if circuit adjustment is required.

Figure 1: PICAXE Editor 6 software.
CHAPTER 2: Water Pump with Pressure Tank System

2.1 Problem Statement

A year of 1994 model of Onga pressure tank with pump was discovered in the engineering building storage room. This equipment is connected together with the pressure switch at the outlet of the water pump. Additional devices are needed to make the system complete, which later this system can be installed inside the ICE laboratory. In future, students can explore the system functionality, do control and monitoring of the process as well as upgrading the prototype to a better version. A few problems have been identified in creating the whole pressure tank system stated as below:

i. What is the process flow of the pressure tank system?
ii. How to troubleshoot and calibrate each of the equipment in the system such as pressure switch, water pump, and pre-charged setting of pressure tank?
iii. How to design and implement the connection and setup of the pressure tank system in the ICE laboratory?
2.2 Project Objective

There are three main objectives for this pressure tank system:

i. **To understand the process flow of a pressure tank system**
   The process flow of the pressure tank system is essential to be explored and understand to provide a proper design of the prototype. Besides, it can provide useful information towards additional equipment that may be needed in conjunction with the existing equipment to make the system function as a whole.

ii. **To troubleshoot and calibrate equipment of pressure tank system**
   Before installing all the equipment together, it is crucial to do troubleshoot and calibrate. This step is crucial to determine all the device function well. For that, an accurate result can be obtained when all the equipment is fully functional. Each of the testings, the data has to be recorded for future reference.

iii. **To design and implement the connection and setup of the pressure tank system in the ICE laboratory**
   There are 3 existing components in the system, which are pressure tank, water pump and pressure switch. So, the design of the mechanical structure and electrical wiring has to consider the layout of this existing component. As this system is suitable on the floor and around the knee height, a trolley is needed to compliment this matter, and the system can be moved around easily.
2.3 Fundamental Concept

In the beginning, this water pump with pressure tank system will start with pumping in the water from the main water storage tank to the storage tank with faucet. For that, a water pump is a piece of leading equipment that supplies lab water usage. In conjunction with that, the other equipment is the pressure switch, which brings the water pump on which attach along the pipeline between the water pump and pressure tank. This equipment will try to bring the pump on to give about 50psi of pressure up at the faucet. As the water pump will burn out in no time if running continuously and is costly equipment, this is what makes pressure switch take control by switching the water pump on or of depending on the pressure detected inside the pressure tank and will switch on the water pump every time the faucet is open. Next equipment is the pressure tank which completed the system which this equipment consists of two sections inside it which are an air charge at the top tank and the water at the bottom tank that provides water reservoir ready to go under pressure. Thus, whenever the faucet is open, it will not bring on the water pump.

This pressure tank is made out of steel and inside it there is no water touches the steel. Inside, there is a watertight liner at the bottom tank that works like a glove, which separates the water that coming into the pressure tank without touching the steel wall of pressure tank to avoid any kinds of funny odours or taste to the water. In between the top and bottom of the tank, there is a diaphragm. The diaphragm is like a membrane that separates the air and water inside the pressure tank. Both of the diaphragm and watertight liner are seam to the pressure tank which locking them in the place. At the top of the tank, the compressed air is pumped to it up until the pressure is at a specific limit which is 28 psi meanwhile, at the bottom of the tank, consist of water which later will be pushed by the compressed air at the top of the tank which push out the water whenever the faucet is open. For this case, the pressure tank should be made of durable, sturdy steel which gives firm support and corrosion-resistant, to avoid rust of the pressure tank which later prolongs the life of the pressure tank itself.
2.4 Design Structure and the Process Flow Diagram

A design structure and the process flow diagram of the water pump with pressure tank shows as in Figure 2 below. From the left part, there is a water supply tank which connected to the water pump inlet by low-pressure fitting and hose (LP). Meanwhile, the ball valve 1 is used to allow the flow out of the water from the water supply tank. Along the pipeline, there is the water pump and pressure tank. When the water pump is on, it will pump in the water to the pressure tank from the water supply tank up until the maximum limit that has been set on the pressure switch. Next, there is pressure switch which allows the water pump is switching on and off depending on the limit that has been set at the pressure switch and the pressure gauge and pressure transmitter are right next beside it, is used to measure and display the pressure in the pressure tank. The pressure tank is accommodated with an air valve on top of it which can be serviced without moving or replacing the entire tank. Lastly, the ball valve 2 at the outlet of the pressure tank is used for maintenance and tank drainage. Meanwhile, the ball valve 3 will allow the flow of water to the liquid flow control module to the storage tank through high-pressure fitting and hose (HP).
Figure 2: A process block diagram of the water pump with pressure tank
2.5 Instrumentation Functionality and Description

2.5.1 Water Pump

As shown in Figure 3 below, a water pump is connected before the pressure tank. This device is used to supply water from the water storage tank by pumping out water to the faucet for lab supply. The water pump is also connected to a pressure switch which responds by turning the pump on and off, depending on the pre-set point pressure on the pressure switch (Sevenson, Southern 2014). The low limit of the pressure switch setting will turn on the water pump. Meanwhile, the high limit of the pressure switch will turn off the water pump. For example, if the faucet from storage tank in the lab is open, and the pressure is at “on” setting (low limit) of the pressure switch, then the water pump is on, and the water will flow out of the faucet. Alternatively, if the faucet from storage tank in the lab is open, and the pressure is at “off” setting (high limit) of the pressure switch, then the water pump is off, the pipes will remain pressurised, and the water will flow out of the faucet.

For example, the system is set to turn on at 30 psi and 50 psi, which means the pump turns on at 30 psi and off at 50 psi. Meanwhile, the pressure tank pre-charged to about at least 2 psi below the set pressure of 30 psi, which is pre-charged at around 28 psi. When the pump is not operating, the air pressure in the top of the tank is used to push the water out of the tank. So during a normal pump cycle, the pump will turn on as the pressure has fallen below the low limit of pressure setting. Later, it will build up the pressure in the pressure tank and fill up gradually the pressure tank with water until the pressure reaches the high limit of pressure setting (The Pump House 2018). For example, the pressure tank has a drawdown about 5 gallons, so that the pump will operate around 5 gallons per minute or 5 gallons of usage, the pressure tank would be depleted, and the water pump will repeat the cycle (Clean Water Store 2017).
2.5.2 Check Valve

A non-return valve or one-way valve is the other common names for the check valve. This valve allows the flow of fluid in one direction only (Dickers 2016). The check valve is located after the water pump which merely to enable the water to flow in just one direction as shown in Figure 4 and also to prevent the backflow or reverse flow especially when the water in the pipeline reverses direction. This action is very crucial, especially when the pump is shut off.

![Check Valve Diagram](image)

Figure 4: Check valve (*ThePiping* 2015)
2.5.3 Pressure Switch

Without a pressure switch, the water pump will keep running continuously as the faucet from the lab is open which result the water pump will then exhaust in no time. With the pressure switch, it is passive and requires automatic operation in the system as if the inside pressure of the tank is high, the normally open contact open, cutting off the electrical circuit, deactivating the pump and the rest, and the water pressure will do it all. Meantime, when the pressure in the pressure tank is low, the contacts will close again and turning on the water pump (Bolich 2018). Figure 5 below shows the pressure switch that is used in this system and connected with the pressure tank.

Mostly, the pressure setting is set around the range of a minimum of 30 pounds per square inch (PSI) and a maximum of 50 (PSI) or a minimum of 40 pounds per square inch (PSI) and a maximum of 60 (PSI). The switch will activate the water pump and allow the water to flow into the system as the pressure inside the tank drops to 30. The water pump will keep engaging until the pressure reached 50 psi, the pressure switch will kick off; thus, deactivating the water pump.

![Pressure Switch Image](image_url)

Figure 5: Pressure switch
2.5.4 Pressure Gauge

A pressure gauge is a measurement device of fluid pressure (Heney 2014) inside a system. The pressure gauge functionality is to provide the measurement of the system is both reliable and predictable thus helps to ensure that there is no change in pressure drastically or leakage that may affect the operating condition of the whole system. The type of pressure gauge that is used in this system is bourdon tube gauge as shown in Figure 6, which the bourdon tube tends to straighten, and the pointer is turning to show the reading when the pressure inside the tube is higher than the outside pressure (Santora 2015).

Another function of the pressure gauge besides reading the measurement of water pressure from the pressure tank is to check the air pressure in the pressure tank. There is usually an air valve on top of the pressure tank and merely place the pressure gauge on top of the air valve just as only putting on a vehicle tire. This process can be done after the pump has been shut off, and the water pressure has drained from the system. Once the appropriate pressure has been measured and checked, move the pressure gauge form the air valve and close back the air valve. If ever notice water coming out of this air valve port, indicating the failure of the diaphragm which means, the tank needs to be replaced.

Figure 6: Pressure gauge (Santora 2015)
2.5.5 Pressure Tank

Pressure tank, as shown below in Figure 7, is one of the main components for a pressurised water pumping system. The reason behind it, one, protect and extend the life of the pump by reducing the number of cycles. The pump is often the most expensive component in a water system. By reducing the number of times that it cycles, this will reduce the amount of stress on the electrical components in the system. Number two is to provide storage of water under pressure for delivery between cycles. Without a pressure tank, the pump would have to cycle every time a valve was opened downstream. The process would add an incredible amount of wear to the pump and motor. Number three is to have a reserve capacity available, for periods of peak demand or in the instance of a power outage. When think about how much water is used, to water the lawn take a shower run, the dishwasher or even flush a toilet. It is quite a bit when everything adds it all up. Without some storage device, the water use is going to be limited to the amount of water the pump can produce, which is especially problematic if the system has a low producing well or a large number of occupants with a high flow requirement.

Figure 7: Pressure tank with water pump
The pressure tank is made of stainless steel, which stores pressurised water and can be distributed to the designated area or system. This tank consists of diaphragm inside, which helps to create a “balloon” of water build up below the diaphragm and pressurised air above the diaphragm (Sevenson, Water Handling 2014). The diaphragm divides the tank into two sections, which is the wet section and dry section. Typically, the range of the pressure tank is approximately around 20 psi. For the pump, it is activated once the pressure in the pressure tank drop below a certain point — this help to raise the pressure of the system until it is equal to the level of pump cut out. For that, the pump does not need to be on all the time, which contribute to energy saving and helps to prolong the lifespan of the pump itself (Sprinkler Warehouse 2007).

2.5.6 Air Valve

On top of the pressure tank, there is a welded air valve, as shown in Figure 8. This air valve is about the similar to the air valve that can be found on bicycle tire or car tire. The air valve can be filled with the same type of air filling devices such as a hand pump or compressor. Besides, the pressure tank is accommodated with an air valve on top of it for which can be serviced without moving or replacing the entire tank. There is some other air valve in the market called threaded air valve. The threaded air valve is cheaper than the welded air valve. However, the downside of the valve is the tendency of a higher possibility for system leakage, which later contributes to the system failure. When the pressure tank is not working correctly, the pump may increase its cycle until it just gets worn out prematurely. For that, regular check for the air pressure to make sure the setting is right, which may help the pressure tank operating correctly.
2.6 Circuit Design and Components of Water Pump with Pressure Tank System

Figure 8: Air valve

Figure 9: Electrical wiring of a Pressure switch and water pump.
The pressure switch is connected in series with the water pump as the pressure switch will turn on and off the water pump depending on the low limit and the high limit of the pressure in the tank. As in Figure 9, the power supply is connected to the load and line terminal of the pressure switch. Next, another load and line terminal of the pressure switch is then connected to the control box and next to the water pump. The control box consist of connection of 2 wire connection from the pressure switch to the 3 wire of water pump.

2.7 Troubleshoot and Equipment Setting

2.7.1 Pressure Transmitter

![Pressure transmitter calibration setup](image)

Figure 10: Pressure transmitter calibration setup.

Before assemble all the equipment and devices together, it is crucial to troubleshoot and calibrate each of the items to provide an effective and reliable system. Figure 10 above shows the setup to test and calibrate the pressure transmitter. An air supply, pressure gauge, Fluke 744 loop calibrator and pneumatic tube are needed in the setup. A certain amount of air pressure will be applied to the pressure transmitter, and the Fluke 744 will measure the current signal from the pressure transmitter.
Note that the pressure transmitter has a range of 0 to 10 bar which equivalent to the 0 to 100 kPa. For that, this info will be used to calculate the expected current signal when a certain amount of air pressure is applied to the pressure transmitter. The full calculation, as stated below:

Span = \frac{\text{Applied Pressure} - \text{LRV}}{\text{URV} - \text{LRV}} \times 100 \%

Percentage (%) = \left[\frac{(50 \text{ kPa} - 0 \text{ kPa})}{(1000 \text{ kPa} - 0 \text{ kPa})}\right] \times 100 \%

= 5 \% of span percentage

Current Signal = \% \text{ span} (\text{URV} - \text{LRV}) + \text{LRV}

(mA) = 5 \% (20mA - 4mA) + 4 mA

= 4.8 mA

Note: LRV is lower range value, and URV is upper range value of the transmitter.

Table 1: Pressure Transmitter calibration result

<table>
<thead>
<tr>
<th>Air Pressure (kPa)</th>
<th>Calculated Current Signal (mA)</th>
<th>Measured Current Signal – up (mA)</th>
<th>Measured Current Signal – down (mA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>3.997</td>
<td>3.998</td>
</tr>
<tr>
<td>25</td>
<td>4.4</td>
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<td>4.802</td>
<td>4.800</td>
</tr>
<tr>
<td>75</td>
<td>5.2</td>
<td>5.209</td>
<td>5.206</td>
</tr>
<tr>
<td>100</td>
<td>5.6</td>
<td>5.618</td>
<td>5.597</td>
</tr>
<tr>
<td>125</td>
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<tr>
<td>250</td>
<td>8.0</td>
<td>8.055</td>
<td>8.055</td>
</tr>
</tbody>
</table>
Therefore, as for 50 kPa air pressure that is applied to the pressure transmitter, it should be given a reading of 4.8 mA current signal as highlighted in Table 1 below. If the measured signal does not match the calculated current signal reading; thus, a calibration process needs to be done to get an accurate reading for the system. Other calculation and the measured result of the current signal can be referred to the table as well. Fortunately, the pressure transmitter has a 99% accuracy, which no calibration will be needed and ready to be installed to the system.

2.7.2 Pressure Switch Setting

![Pressure switch on system](image)

Figure 11: Pressure switch on system

The maximum air pressure to the pressure tank is 63 psi. For that, the selected setting for the pressure switch range is between 30 psi and 50 psi. Most of the pressure switch has a default setting of 40-60 psi. An adjustment to the range of the pressure switch has to be made to set it in between 30 psi and 50 psi. The range between the new setting and default setting has a 10 psi difference. The adjustment of the range is by turn the nut as in Figure 11, above the pressure switch in clockwise or counter-clockwise. Noted that 1 full turn of the nut is equivalent to 2-3 psi. For that, about 3-5 full turn of nut is needed for this adjustment.
After the adjustment, connect back the pressure switch to the voltage supply and monitor when the pressure switch on and off. The switch will activate the water pump and allow the water to flow into the system as the pressure inside the tank drops to 30. The water pump will keep engaging until the pressure reached 50 psi, the pressure switch will turn off; thus, deactivating the water pump. As the pressure switch has achieved this result, the nut adjustment is fixed to the current position.

2.7.3 Pressure Tank Setting

For example, the system is set to turn on at 30 psi and 50 psi, which means the pump turns on at 30 psi and off at 50 psi. Meanwhile, the pressure tank pre-charged to about at least two psi below the set pressure, which is pre-charged at around 28 psi. When the pump is not operating, the air pressure in the top of the tank is used to push the water out of the tank. So during a normal pump cycle, the pump will turn on as the pressure has fallen below the low limit of pressure setting.
To set the pre-charged pressure in the tank, drain the remaining water pressure in the tank and make sure the pump has been shut off. A pressure gauge and air supply are needed for this operation. Simply open up the black cap on top of the tank and apply the air supply, as shown in Figure 12. This is as simple as the procedure to fill up air pressure on bike tire or vehicle tire. Fill in the air and check with pressure gauge until it reaches exact 28 psi which is 2 psi below than the low limit of the pressure switch, 30 psi. After that, replaced the black cap back to the original position. Noted that if there is water coming out from the valve port, that could be a sign of a failure diaphragm inside the pressure tank. For that, the tank needs to be replaced.

2.8 HMI and Program Template

The front panel of this program imitates the mechanical structure of the pressure tank system. This LABVIEW program is created for further exploration of controlling and monitoring the whole process in this system. As in Figure 13, there are 3 analog input on the front panel, which is pressure in pressure tank reading, flowmeter and level of water in the storage tank. Meanwhile, the analog output consist of control valve opening reading and the digital output shows the water pump state either on and off condition.

With the log button, most of the data gain from LabVIEW can be stored in an excel datasheet together with a waveform chart which tells the outcome graph from the controlled process. As shown in Figure 14 is the second panel, the blocked diagram panel of graphical programming works by linking all the input and output together to obtain the required outcome. For manual control, the program template works as it should apart from for the additional wiring connection which is added to cater the program better. The program template is designed so that multiple functions can be added in the future, which gives room to test a more suitable control strategy for the whole process.
Figure 13: HMI of pressure tank system
Figure 14: Block diagram template for a pressure tank system
2.9 Recommendations

In summation, the pressure transmitter, pressure switch and pressure tank setup have been tested and set up to a specific setting that each of the devices requires. For that, they are all ready to be installed to the system and completed the whole process requirement. The wiring has been done to provide supply and communication for the water pump, pressure switch, and pressure transmitter to the I/O system in ICE laboratory. A LabVIEW template program has been designed according to the mechanical setup of the pressure tank system.

As for the recommendation, additional wiring is needed to monitor the pressure switch on and off as the pressure switch is a mechanical sensor which does not provide any output signal that is readable for the I/O system. Besides, it is advisable to implement a control strategy and modelling and to upgrade the program template after the additional wiring has been done. This procedure will provide a detailed and more information regarding the variable changes in the system which can easily be monitored and controlled by the LabVIEW program.
CHAPTER 3: Air-Liquid Heat Exchanger System

3.1 Problem Statement

There are two of the main components of the car radiator system that have been left abandoned in the engineering building storage room for a quite a long time, which is a car radiator and a fan. For that, from the two-component available, a complete air-liquid exchanger system can be created, which later can be a good use for a future student to explore the process and control for the whole system. Then, this system will be placed inside the ICE laboratory in the engineering building. A few problems have been identified in creating the air-liquid exchanger system stated as below:

i. What is the operation flow of the air-liquid exchanger system?

ii. How to design and implement the connection and setup of the air-liquid exchanger system in the ICE laboratory?

iii. How to control the physical system from the software?
3.2 Project Objective

There are three main objectives for this air-liquid exchanger system, which consist of:

i. **To understand the flow operation of the air-liquid exchanger system**
   
   It is crucial to understand the flow operation, and the process involves in the car radiator system as the two-component available, a car radiator and a fan, are the real component used for the car cooling system. For that, the process involved and the variable to be controlled in the system can be decided to run the system smoothly.

ii. **To design and implement an air-liquid exchanger system concept in ICE Lab**

   This project will use these two component to mimic the process of the car radiator system, which the system is suitable to be implemented inside the ICE laboratory. All the connection and setup has been taken into account to suit the process. The design of the system will take place starting from mechanical design to electrical design and later to the programming structure.

iii. **To understand and control the air-liquid exchanger system**

   As this is one type of cooling system, the critical variable to be controlled inside this system is the outlet temperature of the air-liquid exchanger system. As proposed, the speed of the fan will vary according to the inlet temperature of the air-liquid exchanger system.
Literature Review

This section discusses the relevant theories and background information related to the system. This section also reveals the methodology and technology that have been done and used in the research process and procedure.

3.3 Fundamental Concept

The main component of the air-liquid heat exchanger is the radiator and the fan as in Figure 15 below. The radiator is in a rectangular shape which consists of aluminium mesh fin attach to the tube. Meanwhile, the radiator fan is located right in front of the radiator, which helps the radiator to dissipate heat quicker. Firstly, when the engine is about to start, the coolant inside the engine is still cold. If the coolant temperature is below 160 °F or 190 °F, the thermostat will retract and close the valve to stop the coolant from the engine to enter the radiator. For that, the coolant will maintain to recirculate inside the engine until it reaches the high temperature.

The thermostat, which is a mechanical sensor beside the engine, will always check the temperature of coolant running through the engine. The thermostat is located between the car engine and radiator. When the engine runs until it gets warm up and the coolant temperature inside the engine increase up to around 160 °F or 190 °F, the thermostat will extend and open up the valve to allow the hot coolant from the engine to enter the radiator. The hot coolant enters the inlet tube of the radiator, going through along the tube, which to give off the heat from the coolant to the aluminium mesh. The aluminium mesh is high thermal conductivity, which takes out heat very quickly. Besides, the aluminium mesh dissipated heat quicker as it is cooling down, by the air passes through it from the radiator fan. The coolant that passes
through the tube inside the radiator will later come out the cooler from the outlet radiator and being push back to recirculate inside the engine.

As for the summary, as the system running, this will go to heat the engine. The engine is going to create much heat which going to heat the coolant as well. So, heat energy will transfer starts from the engine to the coolant. Next, the heat inside the coolant will pass through the radiator, then to the aluminium mesh and lastly, the heat dissipated to the air with the help of a radiator fan. This process will keep on the same cycle as long as the engine is kept running. This is the fundamental concept of the real car radiator system which will be used as a reference to design and construct the suitable structure inside the ICE laboratory.

Figure 15: Car Radiator System (Girish 2017)
3.4 Design Structure and the Process Flow Diagram

In Figure 16 below, is a piping and instrumentation diagram (P&ID) of the air-liquid exchanger. From the right part, there is a water tank with a heater which simulates the engine warm up. The heater can heat up the water inside the tank up to a maximum of 80 °C. Then, the water is transferred to the radiator system through liquid flow module.

The control valve will be open at a certain percentage to allow the flow of water to the radiator system. The water will pass through the tube inside the radiator which the water temperature cools down by the radiator fan blowing on to it and the heat losses through the aluminium mesh in between the tube which helps heat loss quicker.

The speed of the fan will vary regarding the inlet temperature of the air-liquid exchanger system. The second water tank in the system is used to store the cold water coming out from the outlet of the radiator, which later will be transferred to the heated water tank to reduce its temperature.

Lastly, the radiator cap is used to eliminate the overpressure inside the radiator by allowing the water to pass through it to the overflow hose. The actual system has been finalised and built, and the prototype is located inside ICE laboratory, as shown in Figure 17.
Figure 16: A process block diagram of air-liquid exchanger
Figure 17: Actual air-liquid exchanger system
3.5 Instrumentation Functionality and Description

The heated water tank is mimicking the heat generation inside the car engine. Thus, the heater may increase the temperature of the water in the tank to warm up the tank and later, the excess heat needs to be removed from the system to avoid overheating and keeping the system running at operating temperature. For that, there are a few significant components that involve in this cooling system such as control valve, water pump, radiator, radiator fan, RTDs and radiator cap.

3.5.1 Control Valve

The liquid flow module, as in Figure 18, consists of 3 component which are check valve, flowmeter and control valve. The check valve function to avoid the backflow of the water direction. The flowmeter is used to measure the flowrate of the water to the radiator while the control valve is used to control the flowrate of the water from the heated water tank to the radiator. The opening and closing of the control valve can be varied to increase or decrease the flowrate of the water from the heated water tank to the radiator system.

Figure 18: Liquid flow control module
3.5.2 Water Pump

The first water pump is connected together with the heated water tank in this system. The water pump 1 is used to transfer the water from the heated water tank to the liquid flow module and next to the inlet of the radiator. Besides, the water pump 2 is connected together with the water tank 2, which stored the water from the radiator outlet. When necessary, the water pump 2 will transfer the water from the water tank 2 to the heated water tank to reduce the temperature to the set point.

3.5.3 Radiator

Next component is the radiator, as shown in Figure 19. The radiator is considered one of the heat exchangers that is used to transfer the excess of heat from the heated water tank to the atmosphere and also by the air blown through the radiator by the radiator fan. This radiator consists of the inlet and outlet port, tube, aluminium mesh, drain plug, and radiator pressure cap. For the core of the radiator, it includes a tube with attaching to the aluminium fin. This aluminium mesh is high in thermal conductivity, which means, it is effective in takes out the heat very quickly. For that, the heat transfer from the heated water tank and pass to the water which then carried to the radiator, and next to the aluminium mesh and finally being carried away from the system to the air stream.

![Figure 19: Radiator (Auto-Tech Labs 2015)](image-url)
3.5.4 Radiator Fan

Another device that use to help cool down the heated water tank or the hot water is radiator fan. This fan required 12 VDC input supply and drew 8.1 A of current. It is usually mounted at the back of the radiator, which generally consists of electric fans inside a housing just as shown in Figure 20 above. It has about more than four blades of the fan which spin rapidly to provide sufficient air to cool the heated water tank. The housing designed to keep up the safety during maintenance and operation and to direct the flow of air towards the radiator, which helps in the process of cooling.

This radiator fan will turn on when the RTD sense and detects the inlet water temperature up to a certain level. This data is sent to the controller and activate the fan relay if additional air flow through the radiator is necessary. The speed of the fan will vary regarding the inlet temperature of the air-liquid exchanger system. For instance, as the inlet temperature of the radiator increases, the speed of the fan will also increase.
3.5.4 Resistance Temperature Device

Two RTDs are used in the system. One of the RTD is placed at the inlet of the radiator to determine the inlet temperature of the water that went inside the radiator. Meanwhile, another RTD is placed at the outlet of the radiator to identify the outlet temperature of the water that went out from the radiator. The RTD that has been used is the type of PT 100 with 4-20mA transmitter. The RTD with a transmitter is very useful for the application as the I/O system inside the ICE lab requires 4-20mA input or output signal.

3.5.5 Radiator Cap

Figure 21: Radiator cap (*Unique Cars and Parts 2001*)
This radiator cap, as shown in Figure 21, is constructed with a spring-loaded valve mechanism which withstands a high pressure up to 15 psi. The primary function of the radiator is to help pressurise the system when it is heated by sealing the system (Unique Cars and Parts 2001). Besides, when the pressure in the system becomes overpressurized due to the thermal expansion, the radiator cap will blow off the excess water and redirect it to the overflow hose.

Later, when it cools off, the water will draw back into the system. For example, when the system is pressurised up to 15 psi, the radiator cap valve will be pushed upward to allow the flow of water to the overflow hose. After the system is cooled down and the pressure back to the average operation level, the vacuum inside the system sucks back the water from the overflow hose. Meanwhile, if there is a failure to the system, which makes the pressure getting higher for too much, the water will be pushed through the overflow hose.

3.6 Circuit Design and Component

Figure 22 below shows a complete circuit of wiring diagram for the air-liquid exchanger system. The circuit can be divided into four different sections, which are AC-DC converter circuit, Signal Converter circuit, PICAXE Circuit and MOSFET Circuit. Each circuit carries its own specific function in the process to power up the whole system.
Figure 22: Electrical diagram of air-liquid exchanger system
3.6.1 AC-DC Converter Circuit

The power supply inside the ICE laboratory is 240 VAC, and the load to power up is the radiator fan which required 12 VDC input supply and drew 8.1 A of current. This means, the AC-DC Converter Circuit is necessary to support the conversion of alternating current (AC) to direct current (DC), step down voltage from 240 V to 12 V and to derive a total of 97.2 Watts radiator fan. For that, an industrial switching power supply has been selected as the AC-DC Converter circuit, which is so reliable in meeting all those criteria above. As a result, this industrial power supply converts the 240 VAC power supply to 12 VDC with 20 A supply which is ideal to power up the 12 VDC radiator fan.

The key towards the perfect selection of power supply to the radiator fan is, the voltage has to be the same voltage rating needed by the radiator fan. If the voltage supply to the radiator fan is more significant than what is required, it may lead radiator fan to damage. Besides, if the voltage supply is below than 12V, the radiator fan may not work at all. If it still works, the radiator fan may not operate at the appropriate speed; thus, decrease the efficiency of the radiator fan. As for the current supply, there is no issue regarding the current supply is more significant than 8.1 A as the radiator fan will only use the current that is required. But if the current supply is lower than 8.1 A the power supply can breaks and damage. In summary, the best specification for the industrial switching power supply is the voltage supply has to be the same as the radiator fan voltage, which is 12 V, and the current should be higher than 8.1 A.
3.6.2 Signal Converter Circuit

The radiator fan speed is controlled from the computer system inside the ICE laboratory through the program created in the LabVIEW which give a 4-20 mA signal. For that, the radiator fan is the analog output for the system is connected to the 4 pin connector. Besides, the radiator fan is controlled by a microcontroller, PICAXE 18M2 which contains programming that read the signal from the I/O system in the lab. Unfortunately, the PICAXE cannot receive 4-20mA signal directly as it is only receiving the signal in voltage. For that, a signal conversion is needed by connecting in parallel of a 250 ohm resistor in between 4-20mA signal and PICAXE input signal, as shown in Figure 23 below.

The resistor rating is simply calculated by using Ohm’s law, which calculated the voltage drop between the signal. The Ohm’s law calculation is $R = \frac{V}{I}$, which represent $R$ is the resistor, $V$ is the voltage and $I$ as the current. As for this case, the 250 ohm resistor results from 5V divided by 20mA. This means, at 4 mA signal through the 250 ohm resistor, the voltage will drop to 1 V meanwhile, at 20 mA signal through the 250 ohm resistor, the voltage will drop to 5 V. Therefore, the signal range conversion is from 4-20 mA to 1-5 V signal. Another vital thing to remember is the measured voltage drop is always below the calculation result, and the errors are affected by the tolerance of the resistor. The best selection of the resistor is the one with the lowest tolerance as much as 0.1%, which will give more accurate voltage as close as to what has been calculated.
3.6.3 PICAXE Circuit

The PICAXE requires 5 VDC supply; meanwhile, the power supply given 12 VDC. For that, a voltage regulator is needed to lower down the power supply. For this circuit, LM 7805 has been used as it gives output of regulated 5 V and can receive input supply from the range of 7 V to 35 V. This regulator is a three-pin IC whereas the first pin is received incoming DC voltage, the second pin is connected to the ground and the third pin is the output pin that taken out the regulated the 5 V DC (Electronicsforu 2019).

Figure 23: Signal convertor (in blue) and voltage regulator circuit (in orange).
MOSFET or known as Metal Oxide Semiconductor Field Effect Transistor is a widely used component in a circuit board. The primary function is generally used as a switch either to turn on and off a load. An enhanced mode MOSFET can be used to also amplify electronic signals in high voltage circuit when being used in. The reason why MOSFET is used extensively in electronics is because of its ability to received analog and digital signals. It is crucial to note the type of MOSFET used with a microcontroller in one system.

All MOSFET consists of three pins, Gate, Drain and Source. The Gate is connected with the output pin of the microcontroller, the drain is connected to the load, and the source is connected to the ground. For P-Channel MOSFET, the source is connected to the positive voltage. An additional transistor is required if this MOSFET needs to switch voltages higher than 5 V. Then, the gate is connected to the microcontroller, the voltage on the gate determines the flow of current from drain to the load, and there is unavailability of the flow of current from or to the gate. For example, this phenomenon can happen if the microcontroller is reset by the user. This statement means that the gate float which will turn on or off the FET in response to the small current exists at the gate or in response to the ambient electrical fields. In process to overcome this circumstance, a pull-down resistor is installed between the gate and source to ensure the MOSFET will still remain off after the resetting of a microcontroller or even if the pin is not connected (Pur3 Ltd 2017).
As the MOSFET working principle is like a switch to a load, which means that the MOSFET can control the flow of current and voltage between the drain and source. This process can happen because in between the drain and source terminal, there is a semiconductor surface below the oxide layer. When there is a positive or negative voltage at application at the source terminal, it will be inverted from p-type to n-type MOSFET (Agarwal 2019).

For P-Channel MOSFET, a positive voltage is applied to the source terminal. If the gate voltage is below the source voltage, it will turn on the FET (Vgs<0). As for the N-Channel MOSFET, a negative voltage is applied by connecting the source terminal to the ground, and the drain gate is connected to the load. If the gate voltage is applied with the positive voltage, it will turn on the FET. The N-Channel MOSFET is widely used as it has almost double good performance than P-channel MOSFET beside available at a lower price and easier to manufacture (Pur3 Ltd 2017).

Besides, there are two modes of MOSFET, which are enhancement mode and depletion mode. In general, the enhancement mode is like a normally-off device. Meanwhile, the depletion mode is a normally on device. The enhancement mode is called a normally-off device as when the gate voltage is zero, there will be no flow of current in between the drain to source. However, when the gate terminal receives a voltage, it makes the drain to source terminal less resistive, which allow more current to flow between the drain to the source terminal.

The depletion mode is called a normally on the device as when the gate voltage is zero, there will be a maximum flow of current in between the drain to source. However, when the gate terminal receives a voltage, it makes the drain to source terminal more resistive, which reduce the current to flow between the drain to the source terminal. When the cut-off level voltage is reached between the gates to the source terminal, the flow of current will be
terminated entirely. For that, there is a current flow with a gate voltage, and there is no current flow without the gate voltage.

As the circuit contains a connection between microcontroller and MOSFET, it is essential to choose logic-level MOSFET rather than the standard MOSFET. A logic-level MOSFET is commonly the most ideal to use with a microcontroller as the MOSFET only require 4.5 V or less to fully turn on meanwhile a standard MOSFET will need about 10 V to turn on fully. The fact that the microcontroller only provides an output signal of less than 5 V supported the selection of logic-level MOSFET to be installed in this system. Like this, the radiator fan is a high load with 12V and 8.1 A, the usage of the heatsink is required to eliminate the risk that the MOSFET will be overheating which later reduce the efficiency and damage the electric component. In a high load circuit, it is important to choose MOSFET, which rated higher the load current rating.

The FQP30N06L is chosen as the MOSFET used in this project. This MOSFET has all the criteria required that is suitable for the system performance. It is known as a logic level MOSFET because the voltage from gate to source VGS is lower than 5 volts. In other words, the threshold of turning the MOSFET on is low enough to be used by the PICAXE microcontroller. Besides, this MOSFET is an N-channel enhancement MOSFET as the N-Channel has better performance than P-Channel and the enhancement mode is suitable for this case, which makes the MOSFET as a normally turn off device or switch.

Furthermore, this project used two of this MOSFET which connected in series to provide inverted voltage. This is because using just one N-Channel Voltage when the gate to source voltage is high, the speed of the fan is low and vice versa. But, with two of MOSFET connected in series, when the voltage at gate to the source is low, the speed of the fan is low, and when the voltage at gate to the source is high, the speed of the fan is high as well.
As shown in Figure 24 below, there is a resistor that is connected from the microcontroller output pin to the gate pin of the first MOSFET. This resistor is called a gate resistor which functions to protect the MOSFET when MOSFET is turned on by program logic from microcontroller by limiting the current surge into the gate. Secondly, a 10k ohm resistor is connected in between the gate to source terminal which called a pull-down resistor. This resistor is used to ensure the MOSFET will still remain off or at zero volts after the resetting of a microcontroller or even if the microcontroller output pin is not connected. Even if the processor is booting and the pin is not yet correctly set, the MOSFET will remain off. As the circuit is used for the high current application, it is the best to place a diode across the radiator fan and between the drain terminal to positive supply which protects the MOSFET from reverse voltage and reverses EMF. As when the reverse voltage happens, diode act as an open switch as the current flow is only allowed in one direction or in one polarity (Gammon 2015).

![MOSFET circuit diagram](image)

Figure 24: MOSFET circuit.
3.7 Troubleshoot and Equipment Setting

3.7.1 RTD

Two RTDs are used in the system located at the inlet and outlet of the radiator to measure the temperature of the water that goes in and out. The testing of the RTD is taken place by comparing the RTD reading with the digital thermometer reading. If the RTD reading is out of calibration, made a zero and range adjustment to the RTD. As a result, Table 2 below is the result taken before calibration, and Table 3 is the result after calibration to the RTD. It shows that the RTD 1 is accurate and does not need any calibration; meanwhile, RTD 2 is a little out of calibration around 3 to 5 °C.

Table 2: RTD reading before calibration

<table>
<thead>
<tr>
<th>Temperature to Measure (°C)</th>
<th>RTD 1 (°C)</th>
<th>RTD 2 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20.5</td>
<td>24.0</td>
</tr>
<tr>
<td>40</td>
<td>40.9</td>
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<tr>
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<td>60.7</td>
<td>65.3</td>
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<tr>
<td>80</td>
<td>80.4</td>
<td>84.2</td>
</tr>
</tbody>
</table>

Table 3: RTD reading after calibration

<table>
<thead>
<tr>
<th>Temperature to Measure (°C)</th>
<th>RTD 1 (°C)</th>
<th>RTD 2 (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>20.5</td>
<td>20.8</td>
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<tr>
<td>40</td>
<td>40.9</td>
<td>40.5</td>
</tr>
<tr>
<td>60</td>
<td>60.7</td>
<td>60.6</td>
</tr>
<tr>
<td>80</td>
<td>80.4</td>
<td>80.6</td>
</tr>
</tbody>
</table>
3.7.2 Heatsink Requirement

A heatsink is generally attached to an electronic component such as processor and MOSFET as in Figure 25. It is usually made out of aluminium alloy or copper which most of the design consist of thin slices metal or often called as fins. The design helps to absorb and spread out the heat from MOSFET to limit the temperature of the MOSFET to a safe value. The heat is transferred by physical contact of the MOSFET and the heatsink from the high-temperature region to a low-temperature region (Techopedia Inc 2019).

To begin the calculation for heatsink requirement, it started with the calculation of the maximum power dissipation that is safe for the MOSFET without using a heatsink. The formula for this needs the maximum junction temperature, which in this case is 175 °C minus with the ambient temperature, 25 °C. Continue with dividing the result with the junction-to-ambient coefficient, which is r-theta-ja, 62.5 °C per Watt, which the result for maximum power dissipation of 2.4 Watts. This number is as a reference if the MOSFET may need or may not need the heatsink. If the MOSFET power dissipation is lower than 2.4 Watts; therefore, no
heatsink is required. Meanwhile, if the power dissipation of the MOSFET is more than 2.4 Watts means, it involves the usage of the heatsink.

For this MOSFET, FQP30N06L the datasheet by the Fairchild gave two value of RDS-on at two different voltages from gate to source. The RDS-on is about 35 milliohms at 5 V and 27 milliohms at 10 V. As this project use microcontroller which gives a signal voltage of maximum 5 V, thus, the RDS-on of this MOSFET is 35 milliohms. On determine how much power the MOSFET dissipates, the formula is RDS-on, 35 milliohms multiply with current squared, \((8.1 \, A)^2\) And the result is 2.296 Watts. As the calculation, the MOSFET power dissipation is lower than 2.4 Watts. Therefore, no heatsink is required. But as the difference of the result is only 0.56 Watts, to make it safer and have ease of mind, it is suggested to introduce the heatsink to the system as this application requires a long run experimental which may increase the power dissipated by the MOSFET.

Heatsink requirement calculation:

- Load : 12V , 8.1 A
- PD max: \((\text{max}(Tj)-\text{Ta}) / \text{Rja}\)
  \[
  = (175-25) / 62.5 \\
  = 2.4 \text{ Watts}
  \]
  Therefore, Maximum Power dissipated (not required heatsink): 2.4 Watts

- PD mosfet: \(\text{RDS-on} \times \text{Id}^2\)
  \[
  = 35m \times 8.1^2 \\
  = 2.296 \text{ Watts}
  \]
- PD mosfet < PD max, heatsink not needed
3.7.3 One N-Channel MOSFET

The circuit setup, as in Figure 26 shows the one N-channel MOSFET circuit test, which given the result, as shown in Table 4 below. The result indicates that one N-Channel Voltage used when the gate to source voltage is high, the speed of the fan is low, and when the gate to source voltage is low the speed of the fan is high. This case occurs as the behaviour of the MOSFET itself that acts as a voltage inverter. For that, doubled the MOSFET in series will reverse back the voltage inversion.

Table 4: One N-Channel MOSFET result

<table>
<thead>
<tr>
<th>LV (%)</th>
<th>SIGNAL OUT (MA)</th>
<th>SIGNAL OUT (V)</th>
<th>MOSFET, VGS (V)</th>
<th>FAN (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>0.93</td>
</tr>
<tr>
<td>10</td>
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<td>20</td>
<td>7.2</td>
<td>7.2</td>
<td>1.8</td>
<td>1.68</td>
</tr>
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<td>8</td>
<td>8</td>
<td>2</td>
<td>1.87</td>
</tr>
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<td>8.8</td>
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<td>2.43</td>
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<td>2.8</td>
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<td>13.6</td>
<td>3.4</td>
<td>3.17</td>
</tr>
<tr>
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<td>15.2</td>
<td>15.2</td>
<td>3.8</td>
<td>3.53</td>
</tr>
<tr>
<td>75</td>
<td>16</td>
<td>16</td>
<td>4</td>
<td>3.71</td>
</tr>
<tr>
<td>80</td>
<td>16.8</td>
<td>16.8</td>
<td>4.2</td>
<td>3.89</td>
</tr>
<tr>
<td>90</td>
<td>18.4</td>
<td>18.4</td>
<td>4.6</td>
<td>4.23</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>20</td>
<td>5</td>
<td>4.57</td>
</tr>
</tbody>
</table>
3.7.4 Two N-Channel MOSFET

![Two N-Channel MOSFET circuit](image)

Figure 27: Two N-Channel MOSFET circuit

Furthermore, this project used two of this MOSFET, which connected in series to provide inverted voltage as shown in Figure 27. This is because using just one N-Channel Voltage when the gate to source voltage is high, the speed of the fan is low and vice versa. But, with two of MOSFET connected in series, when the voltage at gate to the source is low, the speed of the fan is low, and when the voltage at gate to the source is high, the speed of the fan is high as well. This statement is supported by the circuit test result, as shown in Table 5 below.

Two manual test have been conducted for this circuit labeled as Test 1 and Test 2. The Test 1 is conducted with the Two N-Channel MOSFET circuit without the 1N4001 diode. Meanwhile, the Test 2 is conducted with the Two N-Channel MOSFET circuit with 1N4001 diode. The Test 2 circuit provide better result of circuit efficiency than the Test 1 circuit, as it gave stable voltage supply to the system especially, higher and stable voltage supply to the fan. The Test 1 circuit experienced reverse-voltage on MOSFET 1 when it received 12mA
input signal supply and above. Besides, the voltage received on MOSFET 2 is decreasing which lessen the maximum operating voltage of fan. For example, at maximum input signal supply, the fan on TEST 1 operated at 8.06V meanwhile, the fan on Test 2 operated at 9.86V.

In result, is shows that, the Test 2 circuit is more reliable than Test 1 circuit as it consists 1N4001 which helps to prevent the reverse polarity of current or in other words, the diode is used to eliminated flyback. During the reverse polarity situation, the cathode voltage is higher than the anode voltage but the diode will not conduct the current to flow because the diode function like an open circuit thus, it isolate the whole circuit from the reverse polarity condition. This helps to prevent damage to the circuit of the system but could not avoid the disadvantage of experienced more than 0.6V voltage drop of the output. For this system, the voltage drop of the fan is almost 1.2V as the fan is operated at maximum of 9.86V.

<table>
<thead>
<tr>
<th>LV (%)</th>
<th>SIGNAL OUT (MA)</th>
<th>SIGNAL OUT (V)</th>
<th>MOSFET 1, VGS1 (V)</th>
<th>MOSFET 2, VGS2 (V)</th>
<th>FAN (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Calc.</td>
<td>Act.</td>
<td>Calc.</td>
<td>Act.</td>
<td>Test 1</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>6.49</td>
</tr>
<tr>
<td>10</td>
<td>5.6</td>
<td>5.6</td>
<td>1.4</td>
<td>1.303</td>
<td>5.21</td>
</tr>
<tr>
<td>20</td>
<td>7.2</td>
<td>7.2</td>
<td>1.8</td>
<td>1.667</td>
<td>3.68</td>
</tr>
<tr>
<td>25</td>
<td>8</td>
<td>8</td>
<td>2</td>
<td>1.844</td>
<td>2.295</td>
</tr>
<tr>
<td>30</td>
<td>8.8</td>
<td>8.8</td>
<td>2.2</td>
<td>2.020</td>
<td>2.081</td>
</tr>
<tr>
<td>40</td>
<td>10.4</td>
<td>10.3</td>
<td>2.6</td>
<td>2.367</td>
<td>0.1</td>
</tr>
<tr>
<td>50</td>
<td>12</td>
<td>12</td>
<td>3</td>
<td>2.711</td>
<td>-1.9</td>
</tr>
<tr>
<td>60</td>
<td>13.6</td>
<td>13.6</td>
<td>3.4</td>
<td>3.054</td>
<td>-2</td>
</tr>
<tr>
<td>70</td>
<td>15.2</td>
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<td>3.8</td>
<td>3.451</td>
<td>-2.1</td>
</tr>
<tr>
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<td>16</td>
<td>16</td>
<td>4</td>
<td>3.619</td>
<td>-2.2</td>
</tr>
<tr>
<td>80</td>
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<td>16.8</td>
<td>4.2</td>
<td>3.777</td>
<td>-2.3</td>
</tr>
<tr>
<td>90</td>
<td>18.4</td>
<td>18.4</td>
<td>4.6</td>
<td>3.99</td>
<td>-2.4</td>
</tr>
<tr>
<td>100</td>
<td>20</td>
<td>20</td>
<td>5</td>
<td>4.37</td>
<td>-2.5</td>
</tr>
</tbody>
</table>
3.8 HMI and Program Template

LabVIEW program, as in Figure 28 and Figure 29, is used as the best program template for this air-liquid exchanger system as it provides an environment of graphical programming, which is user-friendly. Besides, it is the main software that is used in ICE laboratory. The front panel of this program imitates the mechanical structure of the air-liquid exchanger system. The design structure gives a precise reading towards the process involved and can reduce confusion in monitoring and control the variables in the process. On the panel, there is 4 digital input which is to switch on or off the heater, water pump 1, water pump 2 and radiator fan. The analog input for this system is the flowmeter reading, inlet and outlet temperature of the radiator; meanwhile, the analog output is the control valve opening and the fan speed control.

Besides, there is also a waveform chart which displays the outcome from the control process, and the log button is used to store all the data taken inside excel datasheet. The second panel is called block diagram panel. This panel consists of graphical programming which links all the input and output to work together in providing the desired outcome. This program template is tested and fully functional for manual control. For the automatic control, it requires tuning parameters for the system to fully function which is why this program template is designed for the future arrangement to explore the functionality of the system as well as to explore the suitable control strategy that is ideal for the whole process.
Figure 28: HMI of air-liquid exchanger system
Figure 29: Block diagram of air-liquid exchanger system
In conjunction with the LabVIEW, PICAXE editor 6 is used for the radiator fan speed control. As from the LabVIEW, the speed control output is sent in 4-20 mA signal, and the PICAXE is only receiving in the voltage signal. Thus, a signal converter circuit is implemented to the electrical connection, and inside the PICAXE editor 6 program, there is C programming language program which used to read out the analog signal given by the LabVIEW and sending out the signal to the radiator fan. As an example, the radiator fan speed control in LabVIEW is set at 25%, the signal is given in 8 mA and radiator fan is on and operate at a certain speed. As in the radiator fan speed control in LabVIEW is increasing, the speed of the radiator fan will also increase.

3.9 Recommendations

In summary, each of the equipment and device use in the system is well calibrated and tested. The wiring for the system is completed and running correctly without any conflict with each of the component. As for the program template, it is all set for manual and semi-auto control as all the control and reading in the program work accordingly to the physical equipment behaviour. Besides, there are a few recommendations that can be taken into account. First, additional RTDs are required for the heated water tank and water tank 2. This is to provide a more accurate temperature reading of water inside the tank. As for now, the temperature reading of both tanks is used as the same reading as the inlet and outlet radiator temperature for reference. This reading is only partially accurate and can only temporarily use as not suitable if the system requires a detailed and exact result and outcome. Next recommendation is to implement the control strategy and to model to provide a suitable controller for the whole system. As for example, to implement the automatic control and PID tuning of the whole process. This procedure is crucial to obtain an effective automatic control mode for this system.
CHAPTER 4: Air Mixing System

4.1 Problem Statement

There is a whole panel of an air mixing system that has not in used with unknown status of operability. This panel has been unused for more than 5 years at least. For that, testing and commissioning of the whole system device and equipment need to be done to check the operability status of the system and identify if there is any problem or faulty equipment existed which causes the whole panel to remain unused and not functioning. The system may be a good use for a future student to explore the process and control for the entire system. Later, this system will remain placed inside the ICE laboratory in the engineering building. A few problems have been identified in the process of troubleshooting the whole air mixing system stated as below:

i. What is the operation flow of the air mixing system?

ii. How to troubleshoot and calibrate the air mixing system?

iii. How to control the physical system from the software?
4.2 Project Objective

There are three main objectives for this air mixing system, which consists of:

i. **To understand the flow operation of air mixing system**
   It is crucial to understand the flow operation, and the process involves in the air mixing system as all the equipment has been installed properly on the panel except the status of the operability of each component that remains unknown. For that, the process involved and the variable to be controlled in the system can be decided to run the system smoothly.

ii. **To troubleshoot and calibrate the air mixing system**
   All the connection and setup has been taken into account on how it is related to each other and the functionality. Troubleshoot and calibrate process will take place starting from mechanical equipment to the electrical devices. Data is taken and documented for each of troubleshooting and calibrate the process.

iii. **To understand and control the air mixing system from LabVIEW**
   A LabVIEW template is designed and programmed to control and monitor the air mixing system. Two significant controlled variable which is flow control and temperature control both taken place by the process of mixing the hot and cold air stream.
Literature Review

4.3 Fundamental Concept

This panel is located inside the IC lab with all the device and instrument still attach appropriately to each other. Unfortunately, this system is not running for quite some time due to the suspected significant issue of the broken heater. There might be some other problem of the equipment which later can be track and trace after doing proper testing to them. Significant work may involve in fixing and maintaining the system before; it can be able to run correctly again and maximise the operability. During the troubleshooting process, some circumstances may lead to repair the system, replace the system or upgrade and downgrade the system. This decision comes after each of the equipment has been tested. For example, the broken heater, if the test result comes out that only require a small repair to the wiring; thus, fixing it will put into consideration. Meanwhile, if by replacing the heater would be much cost effective then, fixing becomes unnecessary.

4.4 Design Structure and Process Flow Diagram

The third project is a completed panel consist of the air mixing system. The instrument panel consists of few instruments such as heater, resistance temperature detector (RTD), control valve, transducer and differential pressure transmitter, as shown in Figure 30. This system is mixing the air from the hot and cold stream. This process can get done by getting the compressed air in the heater to heat the air; meanwhile, the cold air at the room temperature. There are two valves on the panel which controls the flow of the hot and cold air stream to achieve the desired point of temperature. Meanwhile, the RTDs measure the temperature of the cold air stream, the hot air stream and the mixed air stream. Two significant controlled variable which is flow control and temperature control both taken place by the process of mixing the hot and cold air stream.
Figure 30: P&ID of air mixing system
4.5 Instrumentation Functionality and Description

4.5.1 Resistance Temperature Device (RTD)

A resistance temperature device (RTD), is one of a kind of temperature sensor that operates with the principle of a positive temperature coefficient which means the resistance of RTD is proportional to the changes in temperature. The measurement of the RTD is accurate, and consistent compared to another temperature sensor. It is because the relationship between the temperature surrounding and resistance of RTD is highly predictable. The resistance of RTD can be calculated by supplying an RTD with a constant current. Next, measure the resulting voltage drop across the resistor, which is then used to calculate a change in temperature.

Furthermore, the correlation between the resistance and the temperature is called TCR, which is temperature coefficient resistance. Commonly, the achievable TCR is the platinum 3850 ppm/K. The unit of ppm/K means, the resistance will change by 3850 parts per million per 1 Kelvin change in temperature or in other words, when the temperature is increased by one degree, the sensor resistor will increase by 0.385 ohms (Innovative Sensor Technology - USA Division 2010).
4.5.2 Differential Pressure Transmitter

The most common application of a differential pressure transmitter is the DP flow rate measurement. The measurement is used to calculate the flow rate of the fluid by measuring the difference in fluid pressure through a pipeline. This device can be classified into two elements, which are a primary element and the secondary element. For the primary element, the design purpose is to produce pressure difference when the flow increases. While as for the secondary element is the differential pressure transmitter which to measure accurately pressure difference produced by the primary element.

For that, it is crucial for the measurement is unaffected with the fluid pressure changes and temperature changes. Besides, the purpose of this device is to provide transmission to a remote process control instrument by the electrical signal, as shown in Figure 31. The output signal of the differential pressure transmitter is 4 – 20 mA, whereas it might include other digital communication protocol such as Fieldbus, Modbus 485 RTU, HART and Profibus (Coulton 2017).

![Figure 31: DP transmitter flow rate measurement (Coulton 2017)](image-url)
4.6 Circuit Design and Component

This system has no document to be referred so that a proper drawing for P&ID and electrical drawing has been made for future reference. From the P&ID, all the piping and physical connection are shown started from the air supply for the system to the pressure regulators, transducers, control valves, RTDs and differential pressure transmitter.

Figure 32 and Figure 33 show the electrical connection and wiring for the air mixing system. There are 5 RTDs used in the system, and each of the RTD is connected to the loop transmitter as the RTD only given output in ohm meanwhile the loop transmitter will convert the ohm reading on to the 4-20mA signal which can be readable for the I/O system. Next, there is also the wiring connection for differential pressure transmitter which connected to the analog input pin meanwhile the transducers are connected to the analog output as the transducer will be receiving a signal from I/O signal in 4-20mA signal and given out the output to the control valve in 3-15 psi. Lastly, the heater is connected to the power controller system, which connected to the analog output pin to be control and monitor by the LabVIEW program.

Figure 32: Electrical diagram of air mixing system
4.7 Troubleshoot and Equipment Setting

4.7.1 RTDs Test
There are 5 RTDs in the system to be tested and calibrated. Figure 34 above shows the setup for the RTD testing, which requires the RTDs, multimeter, digital thermometer and source of different water temperature. For example, a 30 °C of water is provided, and the reading is taken from the digital thermometer. Next, each of the RTD is measured by using the multimeter and the reading taken is in ohm measurement reading. A detailed result is taken and can be referred to Table 6 below.

From the result, the RTD 3 is completely broken and require a new 2 wire RTD replacement. Other RTDs are in good condition as they can measure the water temperature, but some of the RTD is a bit off which can state that they have an accuracy of +/- 2 °C. This matter is no big issue as a more accurate adjustment can be made when the RTD is connected to the loop transmitter as it provides zero and range adjustment on the device. For that, the RTD Heater provide the most accurate or closest reading to the digital thermometer and followed by RTD 4, RTD 2 and RTD 1. RTD 1 may require slight adjustment for the span and zero if the +/- 2 °C tolerance cannot be ignored.

<table>
<thead>
<tr>
<th>TEMPERATURE TO MEASURE (°C, Ohm)</th>
<th>RTD 1 (Ohm)</th>
<th>RTD 2 (Ohm)</th>
<th>RTD 3 (Ohm)</th>
<th>RTD 4 (Ohm)</th>
<th>RTD HEATER (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15, 105.84</td>
<td>107.0</td>
<td>106.6</td>
<td>N/A</td>
<td>106.6</td>
<td>105.6</td>
</tr>
<tr>
<td>30, 111.67</td>
<td>112.8</td>
<td>112.6</td>
<td>N/A</td>
<td>112.6</td>
<td>111.4</td>
</tr>
<tr>
<td>35, 113.60</td>
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<td>114.6</td>
<td>N/A</td>
<td>114.6</td>
<td>113.4</td>
</tr>
<tr>
<td>40, 115.54</td>
<td>115.6</td>
<td>115.6</td>
<td>N/A</td>
<td>115.4</td>
<td>115.2</td>
</tr>
<tr>
<td>45, 117.47</td>
<td>118.6</td>
<td>118.6</td>
<td>N/A</td>
<td>118.2</td>
<td>117.2</td>
</tr>
<tr>
<td>50, 119.39</td>
<td>120.4</td>
<td>120.4</td>
<td>N/A</td>
<td>120.2</td>
<td>119.0</td>
</tr>
</tbody>
</table>

Table 6: RTD test result
4.7.2 Transducer Test

In Figure 35 below is the setup to calibrate the two of the transducer. As the transducer requires a 4-20mA signal, a 744 Fluke Loop Calibrator is used in this testing to provide a 4-20mA signal to the transducer. During starting the calibration, it is crucial to focus on the minimum, and the maximum signal received by the transducer. The minimum signal is 4mA, which give 3 psi output pressure, and the maximum is 20mA, which offers 15 psi output pressure. The air supply is connected to the transducer of the inlet port. Meanwhile, the pressure gauge is connected to the outlet port of the transducer to take the reading for each signal given to the transducer.

Figure 35: Transducer test setup

As for Table 7 below is the result of the transducer 1 before and after the calibration process. Before calibration, when 4mA signal is injected to the transducer 1, it gives a reading of 28 kPa which is 8 kPa exceeded than expected reading meanwhile, when the transducer receives 20mA signal, the measured pressure exceeded by 12kPa than the expected result. For that, zero adjustments involved by turning the nut in anti-clockwise or clockwise until the 4mA signal gives air pressure output around 20.6 kPa.
Besides, span adjustment is needed to adjust the range of measurement until the 20mA signal gives air pressure output maximum at 103 kPa. After some alteration has been made, the transducer 1 is tested at 5 point calibration started from 4mA to 8mA, 12mA, 15mA and 20mA input signal. As a result, all the input signal given the expected output pressure that tally with the calculated air pressure output with only +/- 0.5 tolerance to the measured reading.

Table 7: Transducer 1 test result

<table>
<thead>
<tr>
<th>Current Signal (mA)</th>
<th>Calculated Air Pressure (psi)</th>
<th>Calculated Air Pressure (kPa)</th>
<th>Before Calibration - Measured Air Pressure (kPa)</th>
<th>After Calibration - Measured Air Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>20.6</td>
<td>28</td>
<td>21.0</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>41.3</td>
<td>N/A</td>
<td>42.0</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>62.0</td>
<td>N/A</td>
<td>61.0</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>82.0</td>
<td>N/A</td>
<td>82.5</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>103.0</td>
<td>115</td>
<td>103.0</td>
</tr>
</tbody>
</table>

The result of the transducer 2 before and after the calibration process is shown in Table 8 below. Before calibration, transducer 2 gives a reading of 8 kPa, which is 12 kPa lesser than expected reading when 4mA signal is injected to the transducer 2. Meanwhile, the measured pressure lower by 38 kPa than the expected result when the transducer receives a 20mA signal. For that, span adjustment is needed to adjust the range of measurement until the 20mA signal gives air pressure output maximum at 103 kPa. Besides, the zero adjustments involved by turning the nut in anti-clockwise or clockwise until the 4mA input signal gives air pressure output around 20.6 kPa. After calibration, the transducer 1 is tested at 5 point calibration started from 4mA to 8mA, 12mA, 15mA and 20mA input signal. As a result, only +/- 0.7 tolerance to the measured reading when the input signal is given the normal output pressure that tally with the calculated air pressure output.
Table 8: Transducer 2 test result

<table>
<thead>
<tr>
<th>Current Signal (mA)</th>
<th>Calculated Air Pressure (psi)</th>
<th>Calculated Air Pressure (kPa)</th>
<th>Before Calibration - Measured Air Pressure (kPa)</th>
<th>After Calibration - Measured Air Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>3</td>
<td>20.6</td>
<td>8</td>
<td>20.0</td>
</tr>
<tr>
<td>8</td>
<td>6</td>
<td>41.3</td>
<td>N/A</td>
<td>42.0</td>
</tr>
<tr>
<td>12</td>
<td>9</td>
<td>62.0</td>
<td>N/A</td>
<td>62.0</td>
</tr>
<tr>
<td>16</td>
<td>12</td>
<td>82.0</td>
<td>N/A</td>
<td>82.0</td>
</tr>
<tr>
<td>20</td>
<td>15</td>
<td>103.0</td>
<td>65</td>
<td>102.5</td>
</tr>
</tbody>
</table>

4.7.3 Control Valve Test

Figure 36: Control valve test setup
As for the control valves, the control valve 2 given expected output meanwhile the control valve 1 is out of calibration as the control valve already fully open when 16mA signal is provided as shown in Figure 37. For that, only control valve 1 need to be calibrated by connecting it to transducer 1, as shown in Figure 36. At the minimum signal of 4mA, a zero adjustment involved by turning the nut in anti-clockwise or clockwise of the transducer 1 until control valve 1 is fully closed or in other words, at 0% of control valve opening.

Next, span adjustment is needed to adjust the range of measurement as when the 20mA signal is given the control valve1 is fully open, which is at 100% of the opening. After some configuration has been made, the transducer 1 is tested at 5 point calibration started from 4mA to 8mA, 12mA, 15mA and 20mA input signal and the valve opening percentage is recorded. The result shows that the control is given the expected valve opening percentage after the calibration process. There are only two line graph as the calculated valve opening, blue line, and the measured valve opening, grey line is on top of each other.

![CV1 Calibration](image_url)

**Figure 37: Control valve 1 test result**
4.7.4 DPT Test

In Figure 38 above is the first setup to test a differential pressure transmitter (DPT). As the DPT is an analog input for the system, the configuration is a little bit different than the transducer calibration setup. The DPT require 16.28 VDC supply with a 250 ohm resistor connected in series between the negative DC supply to the negative pin of DPT. A minimum 250 ohm resistor of loop resistance is necessary to support the communication of the system, which is also suitable for below 16.28 VDC supply operating area.

The air supply is given at the inlet port indicated as H port. For example, when 40 kPa of air pressure supply to the DPT, the reading indicated 16 mA signal is received; meanwhile, the expected signal received is 10.5 mA. For that, it is concluded that the DPT is out of calibration. More detailed result is given in Figure 40 below.
This ST 3000 Smart Transmitter requires a hand-held Smart Field Communicator (SFC) which is a battery-powered device to configure and calibrate setting of the DPT. Over the existing signal lines, the SFC establishes secure two-way communications between the user and Honeywell Smart Transmitters. For that, the connection setup between the SFC and DPT is precise, as shown in Figure 39.

After the SFC detecting the DPT connection in line, the configuration of this device is started from the model type up until the specification of the device. It is also essential to adjust the setting of the lower range (LRV) and upper range (URV) of the DPT. For this case, the LRV is 0 mmBar, and the URV is 1000 mmBar. The manual operation guide for the SFC and DPT is available online on the Honeywell webpage. The operation guide is very detailed and easy to follow (Honeywell 1995).
After the configuration of the DPT with SFC, the DPT is connected back as in the first calibration setup. This is to ensure that the calibration and configuration setup has been done correctly. The DPT is tested at 11 point calibration started from 0 kPa, and the next point is the increment of 10 kPa up until the maximum of 100 kPa to be received by the DPT. As a result, all the input signal given the expected output pressure that tally with the calculated current signal with only +/- 0.3 tolerance to the measured reading.

![DPT Calibration](image)

**Figure 40: DPT test result**
4.8 HMI and Program Template

This LABVIEW program, as in Figure 41 and Figure 42, is created for the future student to explore and control the system. The front panel of this program imitates the mechanical structure of the air mixing system. The design structure gives a precise reading towards the process involved and reduce confusion in monitoring and control the variables in the process. On the panel, there is 6 analog input, which is 5 of the RTDs reading and a differential pressure transmitter reading. Meanwhile, the analog output consists of two reading of control valve opening.

The log button is used to store all the data taken from LabVIEW to the excel datasheet and a waveform chart which display the outcome graph from the controlled process. The Auto button will be switched on to control the process automatically, especially after tuning the PID parameter that suits the process control strategy.

The second panel is called block diagram panel. This panel consists of graphical programming which links all the input and output to work together in providing the desired outcome. This program template is tested and fully functional for manual control except for the heater as the heater is broken and requires replacement. For the automatic control, it requires tuning parameters for the system to fully function which is why this program template is designed for the future system to explore the functionality of the system as well as to explore the suitable control strategy that is ideal for the whole process.
Figure 41: HMI of the air mixing system
Figure 42: Block diagram of the air mixing system
4.9 Recommendations

In conclusion, the transducers, control valves and DPT are all well tested and calibrated. All the broken wiring as in Figure 43, Figure 44 and Figure 45 has been fixed and label which helps to provide complete information regarding the connection and equipment as well as to make the troubleshooting process more manageable in the future. Some of this equipment is out of the calibration in the first place, but after some calibration, these equipment give accurate reading and measurement which shows that they are an all good function to support the system process. The RTD has an accuracy of +/- 2°C from the reference temperature reading, which is still considered as reliable measurement reading for the system. But, if the precise measurement is needed, a little adjustment can be made by simply adjust the zero and span range.

Next, the recommendation for the future work is an additional 2 wire RTD is required to replace the RTD 3 in the system as the RTD is wholly broken which does not give any reading or measurement at all. Besides, the heater is needed to replace as it cannot be switch on or off. Thus, the control and monitor process for the heater is discontinued. Lastly, if the broken component has been replaced and tested, it is advisable to implement a control strategy and to model to provide a suitable controller for the whole system especially for automatic control mode as the system now only run in manual mode. This procedure is crucial to obtain an effective automatic control mode for this system.
Figure 43: Front panel before (left) and after (right) calibration

Figure 44: Back panel before (left) and after (right) calibration

Figure 45: Control box after calibration
CHAPTER 5: Control Strategy

5.1 Prediction of Suitable Control Strategy

There are a few types of control strategy that can be used in controlling a system. For example, there are an on-off controller, PID controller and cascade controller. All of these control strategies can be used for most of the system depending on what variable to be controlled and how it wants to be control. Each of the control strategies has its advantage and disadvantage regarding how efficient toward a specific control measure of a system.

The simplest control strategy is an on-off controller which operate just like a switch either it will be fully open or fully closed. For example, in temperature control, the on-off controller will turn on the heater until the temperature below the set point and will turn off the heater when the temperature reaches the desired set point.

Lastly, is the PID controller, which is the most commonly used primarily for an application that need continuously modulated control. The P means proportional gain, which will increase the response speed of the system by increasing the proportional gain. Meanwhile, the integral action is required to eliminate offset and the D, a derivative action is to reduce high noise and high-frequency gain.
CHAPTER 6: Conclusion

LabVIEW is used for all three systems to provide monitor and control for the whole system. Besides, all data are recorded with the data logger in conjunction with LabVIEW. This step helps to provide very accurate data for every test run. In conclusion, with the features and process flow for all three sets of small independent system, it is possible for the system to be implemented and installed in the IC lab for educational purpose.

The testing and commissioning have to be done thoroughly to have an ethical decision making to fix or replace the equipment or defective component. Lastly, each of the systems should come with appropriate documentation for each system that consists of primary information such as, description of the system, list of equipment involved, mechanical arrangement and drawing, wiring diagram, P&ID diagram and standard of the procedure (SOP) document.
CHAPTER 7: References


   TechOne.


   https://www.fluidpowerworld.com/what-are-gauges/.


