School of Engineering and Energy


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A report submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for the degree of Bachelor of Engineering.

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I, Noor Amnani Binti Ahmad declare that this thesis document is submitted to the School of Engineering and Energy, Murdoch University in partial fulfilment of the requirements for Bachelor Degree of Engineering. This thesis is my work and its ideas are referenced. It has not been submitted to any other degree, university or academic institution.

_____________________________ Date: ______________

Noor Amnani Binti Ahmad
Abstract

This thesis project will investigate, implement, test, and develop the model design of the controllers for a bench-scale integrated heat exchangers system. In the Instrumentation and Control laboratory (ICE lab) there are few different types of heat exchanger such as tubular heat exchanger, plate heat exchanger and cooling/heating batch mixer that can be used for control design purposes. These units have not been used for an extended period. The primary focus of the thesis project is to revise the functionality of these three pieces of equipment. The following task will be applied to each type of heat exchanger separately then the integrated system combining all three pieces. The first task was to develop a dynamic mathematical model if possible, or an approximate model of each type of heat exchanger. The second task was to calibrate all sensor and the flow measurements of the equipment and its accessories. The third tasks were to design and implement the control system for the heat exchanger and the integrated heat exchanger system.

The development of the program controller was developed using Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) and real-time data was monitored and recorded in Microsoft Excel. The approximate model was successfully implemented by using Identification Toolbox. The PI controller was implemented and was considered successful by looking at the response criteria of the process variables. The performance analysis of heat exchangers is tested with setpoint tracking and disturbance rejection. Based on the performance analysis result, the heat exchangers able to reach the desired setpoint.

Overall, this thesis objective was achieved. However, the investigation of integrated heat exchangers system was not fully developed. This is due to the time constraint and limitations that had faced towards the end period of the research. Besides that, there were few problems aroused with the equipment and instruments during the investigation of the thesis, made it difficult to implement an advanced control scheme to the system.
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1. Introduction

A heat exchanger is a piece of equipment that is designed to transfer heat from one medium to another. Various types of heat exchangers that are used in industries which include shell and tube, air cooled and plate type heat exchangers. The ICE lab provides different types of heat exchangers that are a tubular heat exchanger, plate heat exchanger and a cooling/heating batch mixer that can be used for control design purposes.

This project involves designing, modelling, and testing a control system by utilising three different types of heat exchangers as shown in Figure 1. Initially, the evaluation will be conducted to measure the performance of each heat exchanger, followed by the assessment of the performance of the integrated heat exchanger system. Similarly, the control system will be designed and tested for each type of heat exchanger and then for the integrated plant.

The medium for programming the control strategies is via LabVIEW software. LabVIEW works in real-time where data is collected then analysed to achieve the objectives of this project. Further development of the hardware and software connection will be explained in the following chapters.
Cooling/heating batch mixer

Tubular Heat Exchanger

Plate Heat Exchanger

*Figure 1: Different Types of Heat Exchanger*
2. **Aim of the Project**

The four primary objectives of this project are classified below:

- To develop programs for each heat each heat exchanger using Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) software.
- To calibrate all sensors and the flow measurement equipment and their accessories.
- To develop an approximate model for each heat exchanger.
- To design and implement the control system for the heat exchanger and the integrated heat exchanger system.

2.1. **Development of program using the LabVIEW software.**

The program controller was developed using Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW), and real-time data is monitored and stored in Microsoft Excel. The program allows the user to understand the temperature control strategies that are implemented to the system. Other than that, the program enables the user to monitor and control the heat exchangers.

2.2. **Calibration of all sensors**

The equipment used in the thesis investigation include the reservoir tank and heat exchangers. Five instruments are used to observe the performance of each heat exchanger, including a pump, a refrigerator, a flow control valve, a flow meter, and temperature sensors. All these instruments and equipment need to be checked, tested and run according to the optimal operating conditions for further investigation of the project.

2.3. **An approximate model for each heat exchangers.**

The mathematical modelling method is not convenient for tubular and plate heat exchanger because the influence of their length and thickness would make it hard to determine the energy and mass balances of the system. Therefore, the modelling of tubular and plate heat exchangers could be executed with the usage of the approximate model method with assistance from MATLAB Identification toolbox (Ident).
2.4. Control system for the heat exchanger and the integrated heat exchanger.

The next objective of this project is to implement the control system design of a bench-scale integrated heat exchanger system. The products of the heat exchanger, which are the hot and cold outlet streams are controlled to achieve the desired setpoint values. The LabVIEW software is utilised as a medium for the programming of the controllers, which allows monitoring and controlling real-time data of the temperatures. The heat exchanger will be examined with PI controller; then will be compared with a cascade controller, to seek for better performance.

3. Project Background

Each heat exchanger applied the heat transfer theory, which allows the energy in the system to reach the equilibrium state. The concept of heat transfer from one medium or fluid to another has several ground rules. The first rule, the heat is always transferred from hot medium to cold medium [1], meanwhile, for the second rule, it is essential to have a temperature difference between the two mediums [1]. The last rule for the concept of the heat transfer is heat loss of the hot medium shall be equal to the amount of the heat gained by the cold medium [1].

The heat could be transferred in three ways: radiation, conduction and convection. Radiation is an energy which is transferred by electromagnetic radiation [1]. In contrast, an energy that is channelled between stationary or solid fluids through the movement of molecules or atoms is known as conduction. Lastly, convection is energy that is transferred by mixing substances of medium with another substance. There are two types of convection; natural and forced convection. Convection is known as natural convection when there is a movement of medium and blending of liquid induced by density variation, resulting from the contrast of temperature within the liquid. The forced convection occurs when the movement of the medium is influenced by external factors such as the influence of using a pump to move a fluid. The forced convection concept is greatly utilised in this research project.

There are two types of heat exchangers, direct heat exchanger and indirect heat exchanger. The direct heat exchanger occurs when one medium is in direct contact with another medium [1], and this can be proven when the heat exchanger in a cooling tower is cooled down directly when it is in contact with air. Contrastingly, the indirect heat exchanger happens when a wall separates two modes at the same time the heat transfer occurs. As for this investigation, all the used examples are indirect heat exchangers.
The heat transfer technologies consist of shell-and-tube heat exchanger- the traditional solution as well as expansive, the spiral heat exchanger- where its features are opposite from the former and plate-heat-exchanger- the solution is modern, compact and associated with fundamentally quality thermal efficiency. The working principle of the plate-and-tubular heat exchanger will be further discussed below.

3.1. Plate heat exchanger
This heat exchanger is designed to optimise the heat transfer between two different temperatures by providing the greatest surface area for the liquid or the gas. It is also functioning as to render the maximum efficiency for heat transferring between two mediums, to ensure the turbulence is maximised as each fluid passes through.

3.1.1. Working Principle
It comprises of a series corrugated, thin metal plates that are welded, gasket or in both combinations and this condition is depending on the liquid that passes through it [2]. The arrangement of the parallel flow channel is created by compressing the plates together. The fluid, which travels in the plate-heat-exchanger, is in an even-numbered channel meanwhile the channel for remaining liquids would be in an odd-numbered channel [2]. As shown in Figure 2, plates that are arranged together would have an identical pattern, in contrary for the even-numbered plate, as the plates would have to rotate to the angle of 180° for its pattern to be adjacent in the opposite direction. Due to the identification of the channel geometries, it will cause a limitation of pressure drop for one liquid, which results in lower than the desired pressure drop on the other fluid. It can be solved by connecting the one pass channel at one side and the next pass channel at the other side, in which case, one-half of the heat exchanger will be counter-current, and the other part is co-current. All plate heat exchangers that are available in the market will appear alike on the external appearance. However, the differences are lies in sealing technologies and the internal arrangement.
Each different manufacturer of the plate heat exchanger has a difference in their design. As for example, the single-step pressing of plates causes less physical stress, greater uniformity, and great efficiency for heat transfer and thinner plates. The other example is the patented distribution area design which resulting from the greatest turbulence in the flow, maximum use of the heat transfer area, higher design pressure capabilities, optimum fluid distribution and minimal fouling. The heat exchangers are selected according to their sizes, designs and applications as to provide a full optimisation that meets the desired operational specifications.

3.1.2. Advantages

Plate heat exchanger has several advantages:

- Greater scalability and flexibility.
  The plate heat exchanger is designed to achieve greater flexibility. The specification and the number of plates could be reduced, increased or altered according to the capacity that required over time. Due to that, it means that the capital cost that tied to the application specific equipment is reduced [2].

- Ensure smoother system.
  The operation of using plate heat exchanger has lower start-up volume and easier to control. This heat exchanger is subject to less stress, vibration, and material fatigue [2].

- Cut down on service, maintenance, and cleaning.
Plate heat exchanger can make a radical contrast to service schedule, maintenance and cut down the time that involves maintenance. If compared to shell and tube exchanger it has a better flow pattern. This gives considerably greater heat transfer efficiency with significant advantages of less fouling and essentially no erosion and corrosion. Then the outcome will make rapid cleaning and quicker inspections [2].

- Create a practical technology upgrade path.

Shell and tube heat exchanger indeed give the solutions of traditional technology, however, it fundamentally heavy, expensive and obsolescent. As compared with the plate heat exchanger that is relatively cheaper in capital cost, installation cost and service cost, and lighter in weight. Other than that, plate heat exchanger manages to deal with continually expanding temperatures and pressure, as well as fluids with higher fibre content and greater viscosity [2].

3.2. Cooling/Heating Mixer

Batch-mixer-temperature-control is vital to production rate, product quality and operating cost. Typically, a batch mixer demands objectives such as fast cool down or heat up to a new set point with a minimal overshoot [3]. Meanwhile, the other aim is to stabilise the response to the load disturbances, such as an exothermic reaction. An exothermic reaction is a chemical reaction that releases energy from the heat [4]. As to achieve the mentioned objectives, controller logic with attention to the equipment followed by a systematic optimisation and testing of a feedback control loop is needed to speed up the set point of temperature process.

3.3. Shell and Tube Heat Exchanger

Shell and tube exchangers are the most famous types of exchanger due to the allowance for a wide range of temperatures and pressure. There are two main types of shell and tube heat exchanger. The categories are those that used petrochemical industry and power industry such as power plant condenser and feedwater heaters [5]. A shell and tube heat exchanger consists of some tubes that are mounted inside a cylindrical shell. Figure 3 shows a unit that is normally found in the petrochemical plant.
The shell and tube exchanger consists of several major parts which are:

- Front Header is the place that liquid enters the tube side of the exchanger.
- A rear Header is a place that where a liquid return to the front header in the heat exchanger or tube side liquid leaves the heat exchanger.
- The tube bundle is consisting of baffles, tube sheets and tie rods that are used to hold the bundle together.
- Shell is where the tube bungle located.

The popularity of the shell and tube heat exchanger has given impact in the standard nomenclature being developed for their use and designation by the Tubular Heat Exchanger Manufacturers Association (TEMA). This classification is characterised regarding diagrams and letters. The first letter illustrates the front header types, the second letter is the types of shell, and the last letter is for the rear header type. The Figure 4 below shows the full TEMA classification.

Figure 3: Shell and tube heat exchanger [3]
Figure 4: TEMA classification [5]
4. Experimental Equipment

4.1. The Facility

The equipment and instruments that are used for investigation of this project are:

4.1.1. Plate Heat Exchangers

This heat exchanger is used to transfer two liquids at different temperatures. The cold-water stream is set at 18°C while the hot water temperature is set at 75°C. Four Resistance Temperatures Detector (RTD) measures the heat transfers of these two liquids that are located at the end of the inlet and outlet of the heat exchanger.

4.1.2. Cooling/Heating Mixer

This equipment is used to investigate the performance of the cooling and heating in a batch process. A built-in heater coil in the mixer is used to heat up the water in the mixer while the coil inside the mixer used to transfer the coolant from the reservoir.
4.1.3. Tubular Heat Exchanger

This heat exchanger is used to transfer two liquids at different temperatures. The cold-water stream is set at 18°C while the hot water temperature is set at 75°C. Four Resistance Temperatures Detector (RTD) measures the heat transfers of these two liquids that are located at the end of the inlet and outlet of the heat exchanger.
4.1.4. **Stand Alone Refrigerator**

The stand-alone refrigerator has the built-in PID controller that used to cool the temperature of the water bath. The function of the controller is to ensure the temperature of the water bath remains at the set point value. The setpoint value could vary, as shown in the red box below. The cold fluid inside the refrigerator is circulated through the copper cooling coil to the reservoir tank. The setpoint value remains constant at 2°C throughout the thesis investigation.

![Figure 8: Stand Alone Refrigerator](image)

4.1.5. **Flow Control Valve**

Control valves are used as the Final Control Element (FCE) in the control loop which is to control the opening and closing of the valves according to the set-point value. The controller compares the measured value with the setpoint. The difference between the setpoint value and the measured value is called error. From the calculation of error value, the valve is controlled by opening and closing according to the required flow.
4.1.6. Temperature Sensor

The temperature sensor that is used in this project is Resistance Temperatures Detector (RTD). The function of the RTD is to measure the temperatures of the inlet and outlet stream of the heat exchangers.

4.1.7. Other instruments

The other instruments that are used in this project are the two water reservoir tanks, one is for the cold water supply that is connected to the stand-alone refrigerator, and the other one is for the hot water supply reservoir tank with the inbuilt heating element. The water reservoir tank is connected to the pump which regulates the water flow to the heat exchanger.
5. Experimental Description

Two liquids at different temperatures can transfer heat between each other; one liquid flows outside of the tube while the other one would flow through the tube. The fluids can flow in parallel or counter-current arrangement. The counter-current is where the fluids enter in the opposite directions and leaving at the opposite ends. The concept of counter-current configurations is shown in Figure 12. Figure 13 indicates the parallel (co-current) configuration, where the flows of the fluids enter and leave from the heat exchanger in the same directions.

Figure 12: Counter Current [6]
When the hot fluid enters the heat exchanger, its temperature gradually decreases along the length of the heat exchanger as the fluid is cooled down by the cold fluid stream wall. Therefore, the average temperature differences (Logarithmic Mean Temperature Differences) can be calculated. The formula for LMTD is given in Equation (1) below.

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\frac{\Delta T_1}{\Delta T_2})} \quad [7]$$

LMTD method is used to analyse the heat transfer coefficient of the heat exchanger that relates to the relationship between the inlet and outlet fluid temperatures that also contributes to the efficiency of the system.

**5.1. Process Hardware Setup and Testing**

Before operating the heat exchanger system, the instruments should undergo calibration test. The calibration is to test the instruments works according to the operating condition. The instrument that involves in this calibration process flows control valves and temperature sensors.
5.1.1. Calibration of Flow Control Valve

The calibration of FCV is tested using the LabVIEW program. The LabVIEW is programmed to inject a current signal with the range of 4 to 20mA to the FCV. The current signal will be converted into a percentage value to test valve opening stroke. The valve opening stroke is tested from 0% to 100% and from 100% to 0% to produce a hysteresis result. The first step is the signal was injected from the LabVIEW program to the FCV. The measurement of the temperatures inlet stream and the flow rate were recorded. The valve opening stroke was checked by measuring the stem travelling of FCV at the top to bottom. This whole process is repeated with a 40%, 60%, 80% and 100%. The other method that can be used to calibrate the FCV is using a measuring cylinder. When 20% signal was injected to FCV for 20 seconds, then the water from the reservoir tank was transferred to the level tank. The water in the level tank was drained out to the measuring cylinder, and the height of the water is recorded. The measurement of the flow will be respected to the time, and the unit is in litre per second (l/s). Then the process of calibration using the measuring cylinder was repeated with 40%, 60%, 80% and 100% opening of the valve.

5.1.2. Calibration of Temperature Sensor

The temperature sensor needs to calibrate due to the temperatures readings are the main objectives for this project. There will be four RTD in tubular and plate heat exchanger system, each of the RTD will undergo a calibration test according to the inlet and outlet of the stream. The additional instruments that needed for this calibration test is a thermometer that acts as the reference reading. The medium to calibrate the temperature sensor is the LabVIEW program, which uses the same concept as the FCV calibration test. The calibration is tested at the cold water stream first, which two RTD are located at the inlet and the outlet of the stream. When the cold water stream is tested the hot water stream valve need to be fully shut off. The thermometer was placed in the cold reservoir tank, and the reading is recorded. To check the outlet temperature of the cold stream, the thermometer will be placed in the water level tank that connected to the heat exchanger. Then the reading of inlet and outlet temperatures of the cold water stream is recorded. The reading of the thermometer and the reading from the LabVIEW is compared. If the comparison of these two reading is nearly accurate, it means that the temperature sensors are working. The same method of calibration also applies to the hot water stream. However, the cold water stream valve needs to be fully closed.
5.1.3. Tubular Heat Exchanger

The arrangement of the inlet and outlet water need to be clarified before any implementation of a controller or open loop is carried out to the system. The tubular heat exchanger undergoes different numbers of flow arrangement experiment to test the heat transferred to the system. Then the results of different arrangements are tabulated and compared (see Appendix A). Table 1 below shows four different of flow arrangement that being tested out to the system. The process of heat transfer is crucial where the absolute temperature of the hot and cold water should be produced beforehand. These criteria eventually lead to an excellent analysis of the difference in water temperature change. The two different water temperatures will be injected into the inlet of cold and hot water temperature. The outlet of the cold-water temperature will drain out from the system, which is due to the temperature difference of the outlet water. This will cause the temperature of water in the reservoir to increase. The outlet of the hot water temperature will be recycled back to the reservoir tank because of the inbuilt heater unable to heat up the water fast enough. It is important to note that the recycled hot water will have a temperature difference after the heat loss in the heat exchanger that affects the water temperature inside the reservoir.

Table 1: Arrangement flow of Tubular Heat Exchanger.

<table>
<thead>
<tr>
<th>Arrangement</th>
<th>Input and Output Connection of Tubular Heat Exchanger</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td><img src="image" alt="Diagram" /></td>
</tr>
</tbody>
</table>
Testing of the flow arrangement was conducted to detect the most reliable RTDs for further investigation of the performance of the heat exchanger. However, after the implementation of the flow arrangement to the tubular heat exchanger (see Appendix A), arrangement 1 will be used as the fixed arrangement for future investigation of the system. The reason for choosing this arrangement is due to the different capability of all RTD in the tubular heat exchanger. Based on the arrangement 1, the RTD for the Cold In and Hot Out show the most tallied value compared to the actual measurement taken from the temperature reference. These two RTDs can transmit any range of water temperature, while the remaining RTDs used Cold Out and Hot In to transmit a specific range of temperature after calibration process takes place. The result of calibration process will be explained more in-depth in the following section. As for the inlet of cold water, it plays an important role to transmit an actual measurement as to
know the temperature difference when a disturbance injected into the system. The hot outlet temperature sensor is considered vital as well because it is the sensing element for the feedback control loop. Hence, arrangement 1 is the best arrangement to adapt to the system.

5.1.4. Plate Heat Exchanger

Based on the instrument of plate heat exchanger that is available in the ICE Laboratory, the heat exchanger consists of two modes of operations which is operating either half of the plate heat exchanger or the full heat exchanger. The mode of operation for half of the plate exchanger is where the fluid is passed through only one side of the plate heat exchanger (see Figure 15). While in the full plate heat exchanger the fluid is passed through both sides of plate heat exchanger (see Figure 14). The mode of operation of the heat exchanger can be chosen by closing or opening of the manual valves which are located at the heat exchanger itself. Whenever the mode of half plate heat exchanger is selected, the user needs to close manual valves on the left side of the heat exchanger as shown in Figure 15 below. Based on Figure 14, the position of manual valves is fully open, and this condition depicts that the plate heat exchanger is in the full mode operation. The investigation and implementation of the feedback control loop to the system will be further discussed later in the next section.

Figure 14: Full Plate Heat Exchanger
The arrangement of the inlet and outlet of water also need to be clarified. As mentioned before, two arrangements can be implemented to the system, which are the co-current and the counter-current flow. Figure 16 shows the flow arrangement that is implemented to the system, where the parallel flow arrangement is implemented.

This flow arrangement is chosen because one out of the four RTDs is not in excellent condition. The temperature readings are necessary to show the real temperature to calculate the average temperature differences (LMTD) because if one of the RTDs is not working correctly, the temperature reading of the cold outlet will be wrong. The exact temperature of the cold inlet is necessary to ensure a constant temperature is injected into the heat exchanger as it plays an important role to measure the temperature drop when disturbance rejection is implemented. Inlet and outlet temperature of hot water temperature play important roles in the feedback of control loop. The outlet of hot water temperature is used as the
sensing element in the feedback control loop while the inlet of hot water temperature is used to ensure that a constant temperature is injected to the system. The same concept of the flow arrangement of the inlet and outlet of the tubular heat exchanger is also implemented to the plate heat exchanger. The outlet stream of the cold water will drain out from the system, and the outlet stream of the hot water will be recycled back to the reservoir tank.

5.2. Software to Monitor the Process

The LV software program is a useful tool to integrate the development of user interface (front panel) to control and monitor this project investigation [8]. The software is a development environment and system-design platform for a visual programming language. The LV software consists of two components, which are the front panel and block diagram. The implementation of controller methodology can be applied to the system by designing the program at the block diagram

The LV software can store data to excel file for the tabulation of data in the system. The block function, which is written to the spreadsheet, allows the collection of data into one spreadsheet. This block function was applied to the program which so that all data collection is recorded. The basic feature of each heat exchanger program will have an almost similar function. Below shows the front panel and block diagram of cooling/heating mixer, the other version of the front panel and block diagram for the tubular and plate heat exchangers are shown in Appendix B.

5.2.1. Front Panel

In the front panel, all the instruments that are used to control the system will be displayed. The control input allows the user to change the setting directly on this panel. Figure 17 is the front panel view after the modification made to the basic experiment template. The program was organising and modified to meet the other investigation requirement. Each of the heat exchanger front panels will have a slightly different version of the front panel as the different versions of instruments are used based on the system investigation.
5.2.1.1. Cooling/Heating Mixer Front Panel

There are two push buttons, and two toggle switches use as the control unit in this system. The Logging On push button is used to store the data in the spreadsheet while the Auto push button is to control the system by using the PI controller. The toggle switch is used as the digital input to turn on the pump and the heater. Next, the analogue turning knob was placed beside the data log switch, where the control part for the MV such as the heater and cold water control valve is located. The temperature indicator was placed at the top of the graph so that it can be easily monitored during the operation.
Figure 17: Front Panel of Cooling/Heating Mixer
5.2.2. Block Diagram

The block diagram is used for the development of graphical coding for the system of heat exchangers. This back panel supports all the connection of the instruments where how the arrangement should work and all the formula that used for the system to operate. The analogue input is connected to the indicator to display the result based on input that is given to the VI. The analogue output is connected to the control unit which allows the user to control the valve opening percentage and the heater power percentage at the hanging module rack.

5.2.2.1. Cooling/Heating Mixer Block Diagram

![Figure 18: Block Diagram of Cooling/Heating Mixer](image)
6. Control System Implementation

One of the objectives of this project is to design and implement the control system for the heat exchanger and finally for the integrated heat exchanger system. The implementation of the feedback control system will be discussed in more details in this chapter.

6.1. Designing the control loop program

To have a successful control system, the investigation of the manipulated and the process variables are essential for achieving the desired set point of the process. Therefore, the Table 2 below shows the list of the variables for the tubular and plate heat exchanger system.

Table 2: Selection of Elements for Feedback Control System

<table>
<thead>
<tr>
<th>Elements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulated Variables (MV)</td>
<td>Cold Water FCV.</td>
</tr>
<tr>
<td>Process Variables (PV)</td>
<td>Hot Outlet Temperature</td>
</tr>
<tr>
<td>Measuring Elements</td>
<td>Hot Outlet Temperature RTD</td>
</tr>
</tbody>
</table>

6.2. Feedback Control Strategy

The important elements that consist of the feedback control system are shown in Figure 19. In the feedback control system, the output of the system will be measured using the measuring element and sent to the comparator. The measured output value will be compared with the setpoint value (Yd) to obtain the value of the error signal. In this project, the Ym is the temperature of the hot outlet, while Yd is the set point temperatures of the output. This is called as the feedback error signal because it comes from the process measurement.

\[ \varepsilon = Yd - Ym \]  

(2)

Once the controller receives the error signal \( \varepsilon \), it calculates the value of the manipulated variable, which is issued to the final control element (FCE). In this project, the FCE is the cold FCV. Then this entire procedure will be repeated.
6.3. Classical Feedback Controller

There are several types of the controllers that can be used to achieve the process requirements. These include Proportional (P), Proportional Integral (PI) and Proportional Integral Derivative (PID) controllers. P controller is a proportional controller that makes the system response faster but produces an offset. The transfer function of the P controller is as below:

\[ g_c(s) = K_c \]  \[ (3) \]

Where the \( K_c \) is the gain of the P controller. The offset that P controller leaves can be eliminated by using the proportional integral action controller, which is the PI controller. However, the integral action gives an oscillatory response to the system. The transfer function of the PI controller is as below:

\[ g_c(s) = K_c \left(1 + \frac{1}{\tau_i(s)}\right) \]  \[ (4) \]

The \( \tau_i \) parameter is the integral time or the reset time of the process. For this thesis, the PI controller is used in the tubular heat exchanger and plate heat exchanger systems. Both heat exchangers desired is to maintain the outlet temperature within relatively tight tolerance. That alone prevents P controller from being an option that can be used in this system, as it produces an offset. Besides that, heat exchangers' dynamics response is sufficiently fast where they make the derivative term unnecessary [10]. Hence, PI controller is the best controller to applied for the heat exchangers as it provides corrective measures for offset.
7. Result and Discussion

This section will discuss in detail the outcomes of the comparison for each heat exchanger. The performance of heat exchangers is analysed based on the controller response criteria shown in Figure 20. Before the process begins, an investigation is carried out, and the functionality and connection between module instruments and LV program are also ready to check. The instruments’ wiring is connected to the I/O control panel. The connections of the LV program to the instrument are connected. Then, all value of the actual reading will be displayed at the front panel.

![Figure 20: Controller Response Criteria [11].](image)

7.1. Temperature Difference

A calibration procedure is carried out for temperature sensor of the mixer and heat exchangers. However, some of the temperatures that are displayed in the LV program are not tallied with temperature on the reference thermometer. The reference thermometer was placed directly into the water, and the measurement is recorded. For the inlet of the cold water, the reference point was measured inside the water reservoir tank while the outlet of the cold water stream is measured at the drain water point. These procedures are implemented on heat exchangers. The hot water stream also undergoes the same procedure; the only difference is that the measurement is located in another water reservoir tank. The comparison between these measurements of the tubular heat exchanger shows in Table 3 and Table 4 below. The reference temperature of these four RTD is 17°C. Figure 21 shows the arrangement of the inlet and the outlet temperature of heat exchanger.
Figure 21: Temperature inlet and outlet arrangement.

Table 3: Temperature inlet and outlet 1

<table>
<thead>
<tr>
<th>Valve Opening (%)</th>
<th>T1 In (°C)</th>
<th>T1 Out (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>17.35</td>
<td>12</td>
</tr>
<tr>
<td>40</td>
<td>17.2</td>
<td>11.975</td>
</tr>
<tr>
<td>60</td>
<td>17.125</td>
<td>11.925</td>
</tr>
<tr>
<td>80</td>
<td>17.11</td>
<td>11.9</td>
</tr>
<tr>
<td>100</td>
<td>17.1</td>
<td>11.9</td>
</tr>
<tr>
<td>80</td>
<td>17.11</td>
<td>11.91</td>
</tr>
<tr>
<td>60</td>
<td>17.125</td>
<td>11.925</td>
</tr>
<tr>
<td>40</td>
<td>17.15</td>
<td>11.925</td>
</tr>
<tr>
<td>20</td>
<td>17.225</td>
<td>11.975</td>
</tr>
</tbody>
</table>

Table 4: Temperature inlet and outlet 2

<table>
<thead>
<tr>
<th>Valve Opening (%)</th>
<th>T2 In (°C)</th>
<th>T2 Out (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>11.28</td>
<td>14.3</td>
</tr>
<tr>
<td>40</td>
<td>11.725</td>
<td>14.6</td>
</tr>
<tr>
<td>60</td>
<td>11.175</td>
<td>14.2</td>
</tr>
<tr>
<td>80</td>
<td>11.03</td>
<td>14.16</td>
</tr>
<tr>
<td>100</td>
<td>10.95</td>
<td>14.14</td>
</tr>
<tr>
<td>80</td>
<td>10.975</td>
<td>14.14</td>
</tr>
<tr>
<td>60</td>
<td>11</td>
<td>14.15</td>
</tr>
<tr>
<td>40</td>
<td>11.08</td>
<td>14.2</td>
</tr>
<tr>
<td>20</td>
<td>11.28</td>
<td>14.3</td>
</tr>
</tbody>
</table>

The heat exchanger is tested with cold water supply with a reference temperature of 17°C. The reading of $T_{1\text{ in}}$ is the only sensor that shows the same reading as the reference temperature. Apart from $T_{1\text{ in}}$, the other sensor is far from the actual thermometer reading. As can be seen, $T_{1\text{ out}}$ gives 5°C difference, while $T_{2\text{ in}}$ shows 6°C difference and $T_{2\text{ out}}$ is 3°C difference from the reference reading of the thermometer.

The three sensors did undergo the second part of calibration, which was by adjusting the zero, and span at the top of RTD mounting part until reaching the exact value according to the reference temperature. $T_{1\text{ in}}$, also can act as the reference point temperature because it works perfectly according to any temperature. After temperature alterations, it depicts that three RTDs did not work properly at any temperature. In Figure 22 shows, the cold water supply with a temperature of 17°C is transferred to the
temperature stream 1 and the data is recorded. Then the hot water supply is transferred to the temperature stream 1 with a temperature of 71°C, and it can be seen, $T_{1\text{ out}}$ (yellow line) did not show the same temperature as $T_{1\text{ in}}$ (red line). After that, cold water supply is transferred back to the temperature stream 1, and it proves the same value of lower temperature. The temperature stream 1 is tested with high temperature and low temperature to detect the most reliable RTDs. Therefore, $T_{1\text{ in}}$ and $T_{1\text{ out}}$, will use as a cold water stream as it shows the same temperature when a cold water supply is a transfer to these stream as shown in Figure 22.

![Temperature Calibration](image)

*Figure 22: Temperature Calibration for Temperature inlet and outlet 1*

Temperature stream 2 did undergo the second part of calibration, which was by adjusting the zero, and span at the top of RTD mounting part until reaching the exact value according to the reference temperature. Then it founds that the $T_{2\text{ out}}$ (yellow line) is working correctly and displays correctly for any range of temperature shown in Figure 23. However, this situation does not apply to the $T_{2\text{ in}}$ (red line), as it is only able to display high temperature correctly for this stream. In Figure 23 shows, the hot water supply with a temperature of 80°C is transferred to the temperature stream 2 and the data is recorded. Then the cold water supply is transferred to the temperature stream 2 with a temperature of 18°C, and it can be seen, $T_{2\text{ in}}$ (red line) did not show the same temperature as $T_{2\text{ out}}$ (yellow line). The temperature stream 1 is tested with high temperature and low temperature to detect the most reliable RTDs.
Therefore, $T_{2\text{ in}}$ and $T_{2\text{ out}}$, will use as a hot water stream as it shows the same temperature when a hot water supply is a transfer to these stream as shown in Figure 23.

![Temperature Calibration](image)

**Figure 23: Temperature Calibration Temperature inlet and outlet 2**

Whenever the calibration of the system is carried out at the temperature inlet and outlet 1, the other inlet and outlet will not have any flow of liquid inside it and vice versa. This is to avoid the heat transfer between two streams. Besides that, to prove the accuracy of temperature measurement over a full operating temperature range.
7.2. Cooling/Heating Mixer

The design of the system of the cooling/heating mixer follows the layout of the flow diagram in Figure 24. The decision of the arrangement of the instruments is based on the performance that could be achieved by feedback control loop. The goal of this system is to cool down the hot water in the mixer using the cold water supply that is connected to the stand-alone refrigerator. A constant flow rate of cold water supply is feed to the system from the reservoir tank. An FCV attached to a flow meter is used to monitor a constant flow rate into the system. The cold water supply is transported by using a pump that is connected to the reservoir tank via the FCV. The inbuilt heater is used to heat up the water inside of the mixer. This heater will be used in the feedback control loop to manipulate the temperature in the mixer according to the desired set point. The distinctive feature of the mixer is that two elements can be used for the control system profile. Where the heating coil inside the mixer can be used as the heating profile and the coil inside the mixer that can be used to transport coolant water for a cooling profile of the system. The cooling profile is the rate of the heat removed from the water using the coolant. The heating profile is when water inside the mixer is heated up from low temperature to high temperature.
Figure 24: Process of Cooling/Heating Mixer Flow Diagram
7.2.1. Heating Profile

The efficiency of the heating rate is investigated by implementing different stirrer speed. A 4L volume of water inside the mixer is heated up by using the inbuilt heating coil elements. The water is heated up from 18°C to 80°C with a different number of the speed of agitator. Figure 25 below shows the graph of five number of speed in rpm, which are 200rpm, 300rpm, 500rpm, 700rpm, and 800rpm. Based on the heating profile it can be concluded that the speed of stirrer does not have much impact on the heating profile. Therefore, the speed of 300rpm will be used as the constant speed for the agitator for the next investigation. This is because this speed is the optimum value for the system which is not too slow or too fast.

Figure 25: Efficiency based on stirrer speed
After the investigation of the speed of the stirrer, the mixer undergoes a different investigation. The next investigation is the effect of different heater percentages. The initial temperature in the mixer is set to 18°C, and then the heater is turned on with different power percentages. The heating rate is tested with 35%, 55%, 75% and 100% of power percentage. The temperature of water in the mixer is increased from 18°C to 80°C with these different power percentage and constant speed of 300rpm for the agitator. Each of the heater power percentages results in different heating rates. The heating profiles related to each power percentage is shown in Figure 26. The final temperature of 80°C is chosen to avoid the water from reaching boiling point, and production hot vapour. This will also avoid reduction of the mass/volume of water in the mixer.

Figure 26: Heating Rate based on Power Percentage
7.2.2. Cooling Profile

The cooling rate of the batch process in the mixer is investigated by cooling down the temperature of water in the mixer from 80°C to 20°C. The water inside of the mixer is heated up to 80°C by the in-built heater. Once the water temperature is constant at 80°C, then cold water is injected into the coil inside the mixer. The temperature in reservoir tank of the cold water is maintained at 18°C with the help of the stand-alone refrigerator. The mixer cooling profile is then tested with four different points of valve opening at 30%, 40%, 60% and 80%. Then the cooling rate for each valve opening is recorded as shown in Figure 27. The control valve is turned on until there is no heat transfer between water in the mixer and the coolant. Based on the result, the higher the flow rate, the faster the water in the mixer cools down. However, the differences between the highest and the slowest flowrate are not much, only by 2°C.

![Cooling Profile](image)

*Figure 27: Cooling Rate based on valve opening percentages*
7.2.3. Controller for Cooling

P controller is implemented for the mixer system. P controller is chosen because of the simplicity and the speed of response. The control parameter that is used for the controller is $K_c=10.5$. The parameter is obtained by using trial and error method. The feedback control loop is behaving as an on-off controller. This was because of the behaviour of the P controller reacts faster to the change of the process variables. Where the controller only able to fully open when then PV is less than the desired set point and fully closed when the PV more than the desired set point. The controller is implemented to the heater to reach the desired set point. A constant cold-water flowrate is injected to the system, which are 0.63 l/min to cool down the water in the mixer. The constant flowrate of 0.63 l/min is selected based on the numerous testing of flowrate that can maintained the temperature of 80°C in the mixer. However, from Figure 28 shows that the system unable to achieve the desired set point of 20°C due to the flowrate of 0.63 l/min is not enough to cool down the water temperature. Figure 28 shows how well the controller accommodates the set point change. Table 5 below show the elements of the feedback control for the cooling/heating mixer.

Table 5: Feedback Controller components for cooling/heating mixer

<table>
<thead>
<tr>
<th>Elements</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manipulated Variables (MV)</td>
<td>Heater</td>
</tr>
<tr>
<td>Process Variables (PV)</td>
<td>Temperature in Mixer</td>
</tr>
<tr>
<td>Measuring Elements</td>
<td>RTD in the Mixer</td>
</tr>
</tbody>
</table>

There are several methods to test out the performance of the controller. The first method is by manually change the set point by a 10°C temperature difference from 80°C to 20°C. The set point indicated by the black line is being changed manually whenever the process already achieved a stable response at the desired set point. Figure 28 below shows the response of the process indicated by red line based on the set point change.
Figure 28: Heater Controller based on set point change

The second method is to change the set point linearly by using the following formula.

$$ y = -Ax + B $$ (5)

Where $y$ is the setpoint value that is fed to the controller block in the LV program. The $x$ value is of time in seconds for the whole system to complete based on experimental data. $B$ is the initial value of temperature, which is $80^\circ C$, and $A$ is a constant value.

$$ y(^\circ C) = 20; \; x(second) = 6400 \; s; \; B(^\circ C) = 80 $$ (6)

$$ y = -Ax + B $$ (7)

$$ 20 = A(6400) + 80 $$ (8)

$$ A \left( \frac{^\circ C}{s} \right) = 1.883 $$ (9)

$\therefore$ $$ y (^\circ C) = -1.883x + 80 $$ (10)
Equation (10) is inserted in the formula node in LV program to calculate the value of set point automatically. Therefore, the MV (yellow line) reacts based on the change of set point (black line) as shown in Figure 29 and Figure 30. Figure 29 shows the result of constant cold water flow of 0.63 l/min injected to the coil while Figure 30 shows the result of constant cold water flow of 1.5l/min injected to the coil. Based on the result, the 1.5 l/min graph shows a better result where the temperature inside of mixer follows closely to the set point from 80°C to 20°C. However, the 1.5 l/min only suitable to use for the linear and exponential setpoint change only. This 1.5l/min is not suitable to use as the constant flow rate for the system shown in Figure 28. This is due to this flowrate unable to maintain a fixed set point at 80°C.

Figure 29: Controller based on linear setpoint change (0.63 l/min of cold water)
The third method, the set point is exponentially changed by using the formula below.

$$y = 81e^{-0.04x}$$  \hspace{1cm} (11)

The Equation (11) is obtained from the Microsoft Excel using the data shown in Figure 28. By using the Microsoft Excel feature of “Add Trendline” then with selection options of “exponential”, the above equation could be generated. This equation is implemented to the LV program as the set point formula and then fed to the set point in the PID controller block. This equation will automatically change the set point indicated by the black dotted line in Figure 31 from 80°C to 20°C. Then the MV indicated by the yellow line in Figure 31 will react to the change of the setpoint.
In comparison, exponential setpoint change is better than linear setpoint change. Both setpoint changes could be implemented at cooling crystallization process. In cooling crystallization, a solution that contains more dissolved material is formed by decrease in temperature. Based from the mixer system, the cooling crystallization could be implemented by injecting the coolant water to the coil inside the mixer. This will let the warm solution to cool down. In the beginning of the crystallization it produces the highest cooling rate, where a large temperature difference between solution and the coolant water [12]. However, towards the end of the cooling crystallization process the cooling rate will be lowest as the small temperature difference between solution and the coolant water. Thus, this reaction will produce an exponential response. Alternatively, the crystallization also can cool down the temperature linearly. However, this will produce the steepest cooling rate and create a risk of nucleation. Nucleation is a foreign substance that is produced during crystallization [13]. Therefore, the exponential setpoint change is better than the linear setpoint change.

**Figure 31: Exponential Setpoint Change**
7.3. Tubular Heat Exchanger

The design of the tubular heat exchanger systems follows the layout shown in Figure 32. The decision of the arrangement of the instruments is based on the performance that could be achieved by feedback control loop. The goal of this system is to manipulate the cold water valve to achieve the desired set point of the hot outlet temperature in the system. A constant flow rate of hot water supply is fed to the system from the reservoir tank. An FCV attached to a flow meter is used to monitor a constant flow rate into the system. The hot water supply is transported by using a pump that is connected to the reservoir tank via the FCV. The inbuilt heater is used to heat up the water inside the hot water reservoir tank.
Figure 32: Process Flow Diagram of Tubular Heat Exchanger
7.3.1. Implementation of Controller

The investigation and testing of the process in the tubular heat exchanger system were carried out by applying a conventional controller to the cold water inlet supply. The PI controller was chosen as the feedback control loop methodology. Tubular heat exchanger desired is to maintain the outlet temperature within relatively tight tolerance. That alone prevents P controller from being an option that can be used in this system, as it produces an offset. Besides that, heat exchangers’ dynamics response is sufficiently fast where they make the derivative term unnecessary [10]. Hence, PI controller is the best controller to applied for the heat exchangers as it provides corrective measures for offset. Before the PI controller is applied to the system, parameters of proportional gain, P and integral time $\tau_i$ need to be specified. These parameters can be obtained by using tuning methods. Several tuning methods can be implemented such as relay tuning and approximate process model tuning method. Both tuning methods can be used to obtain parameters for the PI controller in LV program. However, the tuning method that used for this thesis investigation is the approximate model. The approximate model was developed by using a MATLAB tool which is Ident. To obtain the approximate model, an open loop process needs to done first as shown in Figure 33.

7.3.1.1. Open Loop Tubular Heat Exchanger

A step is applied to the input without applying any controller yet, then the output responds to the step change, and the data is recorded in the Microsoft Excel. It must be taken into consideration that this approximation model is based on the response from the combined dynamics of the process, the final control element and the measuring device associated with the process setup. Figure 33 shows a simultaneous step change of input of cold water valve is stepped up from 0% to 20% (yellow line), and the input of hot water valve (purple line) is stepped up from 0% to 40%. After multiple tests of the open-loop process, these step-up values for both cold and hot water valves are the most optimum values to achieve a good performance of the controller. The performance of the controller is analysed using the controller performance response shown in Figure 20. It is the good way to see that the temperature of the hot outlet was cooled down by the action of the cold water stream. This is because the goal of this system is to maintain the hot outlet temperature at 70°C by varying the cold water flow rate. An inlet of hot water supply temperature is maintained at 80°C, and the inlet of cold water supply temperature is maintained at 20°C.
7.3.1.2. Approximate Model using MATLAB Identification Tools

From response curve of the hot outlet water temperature and the flow rate of the cold water supply, the data will be used as the output and input for the Identification Tools. The Identification method is shown in Figure 34 below. The first step is to import the input and output data from the open loop process to the MATLAB. Then the data from the MATLAB is imported to the Identification toolbox by using the import data window as shown in Figure 34. In the import data window, a time-domain signal was used for the data format signals. Once the data is stored in the Identification Tools, the input and output data can be viewed in the time plot window. Then the process model can be estimated by using the process model transfer function window. In this window, the process could be predetermined by clicking the delay, the number of zero and poles and the integrator function. Based on the approximate model method, the best fit for this process is 96.76%, which is close to the open loop data.

Figure 33: Open Loop of Tubular Heat Exchanger
Figure 34: Implementation of Ident Tools to Tubular Heat Exchanger
The approximate model parameter of K, τ and α is obtained from the Identification toolbox as shown in Figure 34 above in the Data/model Info window. The value of parameter K is 5.4654, τ is 11.632 and α is 10.754. These values will be used for the calculation of controller parameter using Ziegler-Nichols Approximate Model PID Tuning Rules as shown in Table 6. However, to use these tuning rules, the model needs to meet the criteria of $0.1 < \frac{\alpha}{\tau} < 1$ [9]. As mentioned before, a PI controller had been decided to be the chosen controller therefore the controller parameter is $Kc = 0.9609$ and $\tau i = 0.173$. Initially, the system is tested by the positive value of $Kc$; however, a large oscillatory response of the process variable is produced (see Appendix F). Therefore, a modification was made to obtain a good response of process variables. The new parameter value is $Kc = -0.9609$ and $\tau i = 0.173$.

**Table 6: Ziegler-Nichols Approximate Model PID Tuning Rules [9]**

<table>
<thead>
<tr>
<th>Controller Type</th>
<th>$Kc$</th>
<th>$\tau i$</th>
<th>$\tau d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$\frac{1}{K} \left( \frac{\tau}{\alpha} \right)$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>$\frac{0.9}{K} \left( \frac{\tau}{\alpha} \right)$</td>
<td>3.33$\alpha$</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>$\frac{1.2}{K} \left( \frac{\tau}{\alpha} \right)$</td>
<td>2.0$\alpha$</td>
<td>0.5$\alpha$</td>
</tr>
</tbody>
</table>

The implementation of PI controller is tested through setpoint tracking and disturbance rejection. Setpoint tracking is a process that when a change of the value of current setpoint either step up or step down. Disturbance rejection was implemented by adding a bucket of ice to the cold water reservoir temperature tank. Setpoint tracking is implemented to the outlet of the hot temperature, which is the PV of the heat exchanger.

**7.3.1.3. Setpoint Tracking**

In Figure 35, the implementation of the set point tracking is indicated by the black line of the set point. The red line shows the PV of the process, while the green line indicates the MV of the system. The process is tested with an initial set point of 70°C; the MV will react to this set point until the hot outlet temperature (the PV) reaches a steady state. When the steady state process is achieved the setpoint is stepped down to 50°C and then stepped up to 60°C. According to Figure 35, when the setpoint changes are implemented, the MV will react by changing the inlet cold water flow rate. The implementation of setpoint tracking also tested with a different value of step up and step down that shown in Appendix C.
Table 7: Tubular Heat Exchanger Performance Response Analysis

<table>
<thead>
<tr>
<th></th>
<th>Fall Time (s)</th>
<th>Settling Time (s)</th>
<th>Undershoot</th>
<th>Decay Ratio</th>
<th>Offset (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular Heat Exchanger</td>
<td>173.5</td>
<td>78</td>
<td>0.032</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Rise Time (s)</th>
<th>Settling Time (s)</th>
<th>Overshoot</th>
<th>Decay Ratio</th>
<th>Offset (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubular Heat Exchanger</td>
<td>33.5</td>
<td>70.5</td>
<td>0.0819</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 7 shows the analysis of setpoint tracking for the tubular heat exchanger. Both setpoint change test produces zero offsets.
7.3.1.4. Disturbance Rejection

Based on Figure 36, the implementation of the disturbance rejection is by adding two buckets of ice to the cold water temperature reservoir. This response is shown in the red box in Figure 36; this is where a sudden drop of temperature of inlet cold water (orange line) from 20°C to 15°C. Hence, by adding the disturbance, the MV which is the valve of cold water indicated by the green line is decreased. The effect of disturbance on the hot outlet temperature is shown in the blue box in Figure 36. When the disturbance rejection and the setpoint tracking are tested, a constant flow rate of hot water is used, which is 7 l/min.

![Disturbance Rejection of Tubular Heat Exchanger](image1)

*Figure 36: Disturbance Rejection of Tubular Heat Exchanger*
7.4. Plate Heat Exchanger

The configuration of the plate heat exchanger is almost the same as the tubular heat exchanger. The only differences are the type and the performance of the heat exchanger. The design of the system of the plate heat exchanger follows the layout shown in the flow diagram in Figure 37. The arrangement of the instruments is decided considering the performance that is expected to be achieved by feedback control loop. The goal of this system is to manipulate the cold water valve to achieve the desired set point of the hot outlet temperature. A constant flow rate of hot water supply is fed to the system from the reservoir tank. An FCV attached to a flow meter is used to monitor a constant flow rate is injected into the system. The hot water supply is transported from the reservoir tank by using a pump to the FCV. The inbuilt heater is used to heat up the water inside the hot water reservoir tank.
Figure 37: Process Flow Diagram of Plate Heat Exchanger
7.4.1. Implementation of Controller

The investigation and testing of the process in the plate heat exchanger system were carried out by applying the conventional controller to the cold water inlet supply. The process of implementation of PI controller to the tubular heat exchanger is adapted and applied it to the plate heat exchanger. Tubular heat exchanger desired is to maintain the outlet temperature within relatively tight tolerance. That alone prevents P controller from being an option that can be used in this system, as it produces an offset. Besides that, heat exchangers’ dynamics response is sufficiently fast where they make the derivative term unnecessary [10]. Hence, PI controller is the best controller to applied for the heat exchangers as it provides corrective measures for offset. Before the PI controller is applied to the system, parameters of proportional gain, P and integral time $\tau_i$ need to be specified. These parameters can be obtained by applying tuning methods of the approximate model to the system. To obtain the approximate model. An open loop process needs to done first as shown in Figure 38 and Figure 39.

7.4.1.1. Open Loop Plate Heat Exchanger

Based on the experiment layout section, the plate heat exchanger could have two modes of operation which is half and a full plate of the heat exchanger. Both modes of operation will be undergoing an open-loop step response. Then the output responds to the step change, and the data is recorded in the Microsoft Excel. For the half of the plate heat exchanger, an input of cold water valve is stepped up from 0% to 20%, while the input of hot water valve is stepped up from 0% to 40% (see Figure 38).
The full plate of heat exchanger an input of cold water valve is step up from 0% to 15%, while the input of hot water valve is step up from 0% to 40% (see Figure 39). Both modes of operation an open loop step response then will be used to find the approximate model of the process. Similar to the tubular heat exchanger case, the goal of this system is also to maintain the hot outlet temperature at 70°C by varying the cold water flow rate. An inlet of hot water supply temperature is maintained at 80°C, and the inlet of cold water supply temperature is maintained at 20°C. The performance of both types of heat exchangers will be later analysed and compared.
Figure 39: Open Loop Full-Plate Heat Exchanger

The data from response curve of the hot outlet water temperature and the flow rate of the cold water supply will be used as the output and input in the Identification Toolbox. The method of Identification for the half and full plate heat exchanger is shown in Appendix D. Based on the approximate model method, the best fit of half plate heat exchanger process is 95.15% while for full plate heat exchanger it is 94.02%. The approximate model parameters, of $K$, $\tau$ and $\alpha$ are obtained from the Identification toolbox and shown in Equation (12). For the half plate heat exchanger, the value of parameter is shown Equation (13), (14) and (14).
\[ G(s) = \frac{K_p}{1 + T_p s} * \exp(-T_d * s) \]  
(12)

\[ K_p = 5.48 \]  
(13)

\[ T_p = 22.006 \]  
(14)

\[ T_d = 15 \]  
(15)

While for the full plate heat exchanger parameter value shown in Equation (16);

\[ G(s) = \frac{K_p}{1 + T_p s} * \exp(-T_d * s) \]  
(16)

\[ K_p = 6.1026 \]  
(17)

\[ T_p = 21.896 \]  
(18)

\[ T_d = 15 \]  
(19)

These values will be used for the calculation of controller parameters using Ziegler-Nichols Approximate Model PID Tuning Rules as shown in Table 6. However, to use these tuning rules, the model needs to meet the criteria of 0.1 < \( \frac{\alpha}{\tau} < 1 \) [9]. As mentioned before, it has been decided that a PI controller is to be the working controller, therefore, the controller parameters for the half plate heat exchanger are \( K_c = 0.241 \) and \( \tau_i = 0.8325 \), while the full plate heat exchanger is \( K_c = 0.215 \) and \( \tau_i = 0.8325 \). These parameter values for both modes of operations are implemented in the system. However, with these parameters, the controller is unable to achieve the desired set point of the feedback control loop (see Appendix E).

Appendix E, the response of the hot outlet temperature does not meet the desired set point. These circumstances occur at both modes of operation. Therefore, a trial and error method is implemented in this system. Based on the parameter values of the approximate model, these value use as the references value to make a guess of the new parameter. The curve of the hot outlet temperature is a slow response process (see Appendix E). Therefore, a new parameter is tested by increasing the parameter value of proportional gain that will also increase the speed of control system response. Besides that, decrease the integral time value to increases the settling time and eliminates the offset. Table 8 shows the new parameter that are tested to the plate heat exchanger. The proportional gain value is modified to a negative value, as it also produces a large oscillatory response of process variables (see Appendix F).
Table 8: New Controller Parameter Values for Plate Heat Exchanger

<table>
<thead>
<tr>
<th>Mode Operation</th>
<th>Proportional Gain (Kc)</th>
<th>Integral Time (τi)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Half Plate Heat Exchanger</td>
<td>-0.7</td>
<td>0.3</td>
</tr>
<tr>
<td>Full Plate Heat Exchanger</td>
<td>-0.7</td>
<td>0.35</td>
</tr>
</tbody>
</table>

The same step of implementation the PI controller is tested by adding disturbances to the process control. The methods that used for the tubular heat exchanger also implemented to this system which is set point tracking and disturbance rejection. This process necessary to test the efficiency and accuracy of our process control performance of plate heat exchanger. Setpoint tracking is implemented to the outlet of the hot temperature, which is the PV of the plate heat exchanger. The setpoint tracking and disturbance rejection capabilities are tested.

7.4.1.2. Setpoint Tracking

The setpoint tracking capability is tested as shown in Figure 40 and Figure 41 indicates by the black dotted line of the set point. The process is tested with an initial set point of 70°C; the MV indicates by the green line reacts to this set point change until the hot outlet temperature which is the PV (red line) reaches a steady state. When the steady state is achieved, the set point is stepped down to 60°C as the new set point. When the setpoint tracking is implemented, the MV will have reacted by trying to control the inlet of cold water flowrate to achieve a new set point of the system. Therefore, after implementing the setpoint tracking, it can be concluded that the trial and error parameter value implemented to the system is a useful parameter value to achieve a good performance of the system. The difference of the mode operation for the plate heat exchanger shows the different capabilities of the system reaching the desired set point. The half plate heat exchanger reaches the desired setpoint faster than to the full plate heat exchanger.
Figure 40: Set Point Tracking Half-Plate Heat Exchanger

Figure 41: Set Point Tracking Full-Plate Heat Exchanger
Figure 42: Comparison of Half and Full Plate Heat Exchanger

Table 9: Performance Response of Plate Heat Exchanger

<table>
<thead>
<tr>
<th></th>
<th>Fall Time (s)</th>
<th>Settling Time (s)</th>
<th>Undershoot</th>
<th>Decay Ratio</th>
<th>Offset (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full Plate</td>
<td>158.5</td>
<td>417</td>
<td>0.095</td>
<td>N/A</td>
<td>0</td>
</tr>
<tr>
<td>Half Plate</td>
<td>129</td>
<td>398</td>
<td>0.105</td>
<td>N/A</td>
<td>0</td>
</tr>
</tbody>
</table>

Figure 42 shows the performance setpoint tracking of the half and full plate of heat exchangers. The same procedures of set-point tracking from 70°C to 60°C is tested to each heat exchangers. Based on the result of analysis shown in Table 9, half plate heat exchanger has a faster falling time and settling time compared to the full plate heat exchanger. Regarding the undershoot criteria, the full plate heat exchanger has a smaller undershoot compared to the half plate exchanger. Besides that, both modes of operation produce a zero offset.
7.4.1.3. Disturbance Rejection

The disturbance rejection capability is tested as shown in Figure 43 and Figure 44 by adding two buckets of ice to the cold water reservoir. This response is shown in the red box of Figure 43; this is where a sudden drop of temperature of inlet cold water from 20°C to 15°C. Hence, by adding the disturbance, the MV which is the valve of cold water indicated by the green line is decreased. The disturbance affects the system where a slight temperature drops to the hot outlet temperature as shown in the blue box in Figure 43 and Figure 44 below. During the disturbance rejection and the setpoint tracking testing a constant flow rate of hot water is maintained in the system, which was 7 l/min.

*Figure 43: Disturbance Rejection Testing Half-Plate Heat Exchanger*
Figure 44: Disturbance Rejection Testing Full-Plate Heat Exchanger

Figure 45 shows the comparison disturbance rejection of full and half plate heat exchangers. Both modes of operation produce a zero offset. When the disturbance is injected to both modes of operation, there a slight decreasing of temperature. The temperature drop at half plate operation is 0.656°C and 0.644°C for the full plate operation.
Figure 45: Comparison Disturbance Rejection of Full and Half Heat Exchangers
7.5. Integrated Heat Exchanger

The design of the integrated heat exchanger system follows the layout of the process flow diagram shown in Figure 46. The integrated heat exchanger consists of two types of heat exchangers, which are tubular heat exchanger and cooling/heating mixer. The arrangement of the instruments was decided based on the performance expected to be achieved by two feedback control loops. For the integrated system is where the hot outlet of the tubular heat exchanger is fed to the inlet of the coil inside the cooling/heating mixer. The hot stream that feeds on the tubular heat exchanger to the coil in the mixer used to heat up the water temperature according to the desired set point. Both systems are designed to achieve two goals. The first goal of the integrated system is to manipulate the cold water valve to achieve the desired set point of the temperature hot outlet tubular heat exchanger system. The second goal is to manipulate the hot water valve to achieved desired set point of the temperature inside the cooling/heating mixer. FCVs attached to a flow meter are used to monitor the flow rate that is injected into the system. The hot and cold water supplies are transported from reservoir tank by using two pumps to the FCVs. The inbuilt heater is used to heat up the water inside of the hot water reservoir tank.
Figure 46: Process Flow Diagram of Integrated Heat Exchanger System

- Hot water stream supplied by the hot water reservoir with inbuilt heating element.
- Inlet of hot water stream with temperature range of 75-80 degree Celsius.
- The controller section which controls the temperature of batch mixer by manipulating the hot water valve.
- Hot Outlet Stream feed to the inlet of coil inside the cooling/heating mixer.
- Inlet of cold water stream with temperature range of 17-20 degree Celsius.
- The controller section which controls the outlet of hot water stream by manipulating the cold water valve.
- Cold out to drain.

<table>
<thead>
<tr>
<th>Displayed Text</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>E-1</td>
<td>Stand-Alone Refrigerator</td>
</tr>
<tr>
<td>E-2</td>
<td>Cold Water Reservoir</td>
</tr>
<tr>
<td>E-4</td>
<td>Cold Water Pump</td>
</tr>
<tr>
<td>E-5</td>
<td>Hot Water Pump</td>
</tr>
<tr>
<td>E-6</td>
<td>Hot Water Reservoir</td>
</tr>
<tr>
<td>E-11</td>
<td>Cooling/Heating Mixer</td>
</tr>
<tr>
<td>E-13</td>
<td>Tubular Heat Exchanger</td>
</tr>
<tr>
<td>I-1</td>
<td>Cold Water Flowrate</td>
</tr>
<tr>
<td>I-2</td>
<td>Hot Water Flowrate</td>
</tr>
<tr>
<td>I-3</td>
<td>Temperature Sensor of Hot Outlet Stream</td>
</tr>
<tr>
<td>I-4</td>
<td>Temperature Controller of Hot Outlet Stream</td>
</tr>
<tr>
<td>I-6</td>
<td>Temperature Sensor of Mixer</td>
</tr>
<tr>
<td>I-7</td>
<td>Temperature Controller of Mixer</td>
</tr>
<tr>
<td>V-1</td>
<td>Cold Water Valve</td>
</tr>
<tr>
<td>V-2</td>
<td>Hot Water Valve</td>
</tr>
</tbody>
</table>
7.5.1. Implementation of Controller

The investigation and testing of the process in the integrated heat exchanger system were carried out by applying the conventional controller to the cold and hot water valve. The process of implementation of PI controller to the tubular heat exchanger is adapted to this system. There will be two controllers in the system; the first PI controller is used to control the cold water valve to achieve the desired set point of the hot outlet temperature in the tubular heat exchanger. Controller parameter found in chapter 7.3.1.2 is implemented again to the tubular heat exchanger. The second PI controller is used to control the hot water valve to achieve desired set point of the temperature inside the cooling/heating mixer. For the second PI controller, the parameters of proportional gain, $P$ and integral time $\tau_i$ need to be specified. These parameters can be obtained by applying tuning methods of the approximate model to the system. The open loop of the integrated heat exchanger is carried out to obtain the approximate model for the cooling/heating mixer.

7.5.1.1. Open Loop Integrated Heat Exchanger

For the integrated heat exchanger, an open loop testing is implemented to this system. The open loop step response is conducted to get the approximate model for the cooling/heating mixer system. A step change is applied to the hot water valve in the presence of a PI controller in the tubular heat exchanger system. Then the output responds to the step change, and the data is recorded in the Microsoft Excel. The reason for applying a controller to this system is to obtain the steady state of the temperature inside the mixer. Based on the steady state data of the temperature mixer, an implementation of second PI controller adapted to the system. Based on Figure 47 the input of hot water valve is step up from 0% to 40% along with PI controller. An inlet of hot water supply temperature is maintained at 75°C, and the inlet of cold water supply temperature is maintained at 20°C. In Figure 47, the hot outlet was maintained at 70°C, then fed it the coil inside the mixer to heat up the water from 18°C to 67°C.
From response curve of the water temperature inside the mixer (green line) and the flow rate of the hot water supply (orange line), the data will be used as the output and input for the Identification Tools. The method of Identification tools shows in Figure 48 below. Based on the approximate model method, the best fit for this process is 97.06% which is close to the open loop data.

The approximate model parameters $K$, $\tau$ and $\alpha$ are obtained from the Identification toolbox are shown in Equation (20) Therefore the controller parameter is for the mixer is $Kc = 4.124$ and $\tau i = 0.8325$.

$$G(s) = \frac{Kp}{1+Tp1+s} \exp(-Td * s) \quad (20)$$

$$Kp = 2.0161 \quad (21)$$

$$Tp1 = 138.57 \quad (22)$$

$$Td = 15 \quad (23)$$
Figure 48: Approximate Model of Integrated Heat Exchanger using Identification Tools.
For the first PI controller for the tubular heat exchanger using the same value parameter which is $K_c = -0.9609$ and $\tau_i = 0.173$. While for the second PI controller use values that obtained from the approximate model of mixer. Then both controller is tested to the integrated system, the result show in Figure 49 below.

![Integrated System Controller](image)

*Figure 49: Integrated Heat Exchanger Controller*

Table 10 shows the abbreviation that used for the integrated heat exchanger.

**Table 10: Abbreviations for Integrated Heat Exchanger System**

<table>
<thead>
<tr>
<th>Abbreviations</th>
<th>Explanation</th>
<th>Colour in Graph</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP1</td>
<td>Set Point of Hot Outlet Tubular Heat Exchanger</td>
<td>Black Dotted Line</td>
</tr>
<tr>
<td>SP2</td>
<td>Set Point of Cooling/Heating Mixer</td>
<td>Purple Dotted Line</td>
</tr>
<tr>
<td>MV1</td>
<td>Manipulated Variable of Tubular Heat Exchanger.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Cold Water Flowrate</td>
<td>Blue Line</td>
</tr>
<tr>
<td>MV2</td>
<td>Manipulated Variable of Cooling/Heating Mixer.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Hot Water Flowrate</td>
<td>Orange Line</td>
</tr>
</tbody>
</table>
The system first is tested with the fully automated system, where the first set point (SP1) is the hot outlet of the tubular exchanger and the second setpoint (SP2) is the temperature inside the mixer. The SP1 is set to 70 and the SP2 set to 67. Therefore, based on the result both of PV able to reach the desired set point of the system. Later, this system is tested with setpoint tracking at the second controller, where the set point of the mixer is either step up or step down while the SP1 will always have a constant set point in the integrated system (see Figure 50).

![Setpoint Tracking of Integrated Heat Exchanger](image)

*Figure 50: Setpoint Tracking of Integrated Heat Exchanger*

From the result, it is clear that this system is unable to run smoothly due to some limitations. The major limitation is that once the temperature inside mixer (PV2) is above the setpoint value, no other external or internal influence can cool down the water. Eventually, this will lead to closing the hot water valve.
From the controller behaviour in Figure 50 above, MV2 will completely shut off when the PV2 is above the desired setpoint (SP2). However, because of this action the first goal that to maintain the 70°C hot outlet of the water in the tubular heat exchanger to be achieved due to no inlet of the hot water stream.

To overcome this problem, an experiment to cool down the water inside the mixer was conducted. The cooling/heating mixer was wrapped with ice as shown in Figure 51 to cool down the temperature inside the mixer. This was to test the controller performance.

Figure 51: Ice is wrapped around the outer surface of the mixer.

Figure 52 shows the result of the investigation of wrapping ice on the outside surface of the mixer. A modification to the behaviour of the MV2 is implemented which the MV2 will supply a constant flow rate of 0.7 l/min if the opening of the hot water valve is below 10%. This is to ensure a continuous flow of hot outlet stream for the system. However, the modification producing an offset in the tubular heat exchanger system. From the graph, it is obvious that the water temperature inside the mixer can cool down due to the influence of the ice. This process of cooling down takes a long period, indicating that ice does not provide a solution to the problem. The suggestion that can be made to overcome this problem is to add another coil inside the mixer that will transport cold water into the cooling/heating system. Other suggestion would have a jacketed layer at the outer surface of mixer that can control the cold water inlet to cool down the water temperature. However, these solutions will take a longer time to construct.
8. Conclusion

In conclusion, the outcomes of the modelling and controlling of a bench-scale integrated heat exchanger system. Since the commencement of this thesis project, the research on the different type of heat exchanger has been conducted. The research provided an understanding of the working principle to run the instruments that available in the ICE lab. The purpose of understanding and constructing the heat exchangers system is to understand the concept of heat transfer theory. Before, constructing a full system of the heat exchanger, the functionality of all instruments need to be checked. This will help the flow of project investigation system run smoothly.

The performance of different types of heat exchangers was modelled according to the methodologies that suit the heat exchanger behaviours. The batch process which is the cooling/heating mixer can be modelled by using the mathematical modelling method. The cooling and heating mixer controller was tested with a different method of a set point change to see the performance of the mixer. The setpoint was changed exponentially, linearly or manually, and the PV will always react to these SP changes. It proves that any method to test the controller can be conducted to this system. However, due to the limitation of the batch
process, none of the tuning methods is applied to this system. The controller of the system is an on-off controller that will either fully open or fully close the MV.

However, plate and tubular heat exchanger cannot be modelled by using the mathematical model because of the influence of the length of the heat exchanger. Therefore, rather than using mathematical method for the continuous process, the approximate model method is used to find the model with the help of utilising the MATLAB Identification toolbox. The process of investigation of the plate and tubular heat exchanger that was carried out throughout this research project undergoes almost the same steps process. An open loop step response needs to be done first to get all the parameter values for the controller. The only difference of this step is where the plate heat exchanger had to undergo a trial and error tuning method. This is because of the parameter values that obtained from the approximate model did not give a good performance for the system. Then when implementation of the controller, the system is testing out with two methods of adding disturbances. The methods were the setpoint tracking and disturbance rejection. Based on the result of the plate and tubular heat exchanger, it can be concluded that the tubular heat exchanger gave a better performance compared to the plate heat exchanger. To support this statement, where the tubular heat exchanger is easier to model because the parameter that was obtained from the approximate model can be used directly to the system. Besides, the response curve of the tubular heat exchanger was much smoother than the plate heat exchanger. The tubular heat exchanger system is also able to achieve the desired setpoint faster than the plat heat exchanger.

The last investigation is where the integrated heat exchanger was tested to the system. This system is a combining of tubular heat exchanger and cooling/heating mixer. However, this system unable to run smoothly due to some limitations. The limitation is where once the temperature inside mixer is above the setpoint value, no other external or internal influence can cool down the water. Therefore, a further investigation of this system was unable to be carried out.

The learning for utilisation of the programming software LabVIEW was developed to monitor the behaviours of the heat exchangers system. Besides that, programming skills of LabVIEW are enhanced successfully and will improve the collecting of the experimental process data. The development of LabVIEW program helped the user to monitor and understand the behaviour of each heat exchangers. A MATLAB software feature was useful for the development of the approximate model by using Ident Toolbox.
9. Future Work

In this section, the explanation of the future development that needs to do to improve the Instrumentation Control facility. Besides that, some ideas that can be implemented to the ICE lab facility where a solution to overcome the problem that has been faced when completing the thesis.

9.1. Replace the temperature sensor

The temperature that attached to the tubular heat exchangers had been used for a specified period. Even after calibration process is executed, still some of the RTD not working according to the operating temperature. The only solution to this problem is to change to a new RTD in the heat exchanger. A new RTD will show the accurate measurement of the temperature. Hence a better performance of the system can be achieved.

9.2. Advanced control scheme

This project research only able to implement a PI controller to the heat exchanger system. Therefore, to test the performance of heat exchanger a different type of controller can be implemented to the system. The control methodologies that can be applied shortly is the advanced control scheme which is GMC control and IMC control.

9.3. Suggestion for future

Based on the research of the integrated heat exchanger system, there was a limitation that made it hard for the system to achieve a good performance. Therefore, there is room for this integrated system to improve. The next integrated system could combine the plate heat exchanger and the cooling/heating mixer. Another possible development is combining two continuous processes (the plate heat exchanger and the tubular heat exchanger) into one system.
10. References


11. Appendices

Appendix A
Arrangement of Tubular Heat Exchanger

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<thead>
<tr>
<th>Arrangement</th>
<th>Open loop graph</th>
<th>Measurement of inlet and outlet arrangement</th>
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<td></td>
<td>AT STEADY STATE</td>
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<tr>
<td></td>
<td></td>
<td>LV Reading (°C)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cold In</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cold Out</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hot In</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hot Out</td>
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</table>

*Different from actual measurement
AT STEADY STATE

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<td>19.1*</td>
<td>21.1</td>
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<td>35.6</td>
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<tr>
<td>Hot In</td>
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<td>58*</td>
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*different from actual measurement
AT STEADY STATE

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<tr>
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<td>51.2</td>
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</table>

*different from actual measurement
Appendix B
Front Panel and Block Diagram for Tubular and Plate Heat Exchanger
Front Panel and Block Diagram for Tubular and Plate Heat Exchanger
Appendix C

Setpoint Tracking of Tubular Heat Exchanger. Initial set point is 70; then step down to 60 and step up back to 70.
Appendix D

Approximate Model of half-plate heat exchanger using Identification Tools

Approximate Model of full-plate heat exchanger using Identification Tools
Appendix E
Plate Heat Exchanger Controller using the parameter that was obtained from the approximate model Ident tools
Heat Exchanger Controller using the parameter that was obtained from the approximate model
Ident toolbox with positive $K_c$.

$$K_c = 0.969$$

$$\tau_i = 0.173$$