ROBUST CASCADE CONTROL SYSTEM FOR A HEAT EXCHANGER PLANT

By

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FINAL PROJECT REPORT

Submitted to the Electrical & Electronics Engineering Programme
in Partial Fulfillment of the Requirements
for the Degree
Bachelor of Engineering (Hons)
(Electrical & Electronics Engineering)

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CERTIFICATION OF APPROVAL

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Approved:

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Project Supervisor

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December 2005

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD SYAFUDDIN BIN CHE ALI

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ABSTRACT

Cascade control system is one of the popular and widely used for the petrochemical or oil refinery plant. The obtained desired result from the system; the controller of cascade control system should be designed in such way that it will satisfy all the requirements needed. This project challenges the author to study the comparison in performance of two controllers; the classical and robust cascade control system for a heat exchanger plant. Two major efforts for this project are plant experimentation and computer simulation. Plant experimentation is conducted to identify the process model for temperature and flow plant model. These models are then used in the computer simulation to design and determine the performance for classical and robust cascade control system. The classical cascade control system does give the satisfy control performance compare to the robust cascade control system. However, the robust cascade control system is not suitable to use in the present condition of the plant and convenient to use for some cases only.

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LIST OF ABBREVIATIONS

PID	-	Proportional, Integral and Derivative
CV	-	Process, or Controlled Variable
MV	-	Manipulated Variable
FYP	-	Final Year Project
K_p	-	Process Gain
τ	-	Time Constant
θ	-	Dead / Delay Time
SP	-	Set Piont
DCS	-	Distributed Control System
K_u	-	Ultimate Gain
τ_u	-	Ultimate Period
K_c	-	Proportional Gain
τ_i	-	Integral Time
τ_p	-	Peak Time; the time required for the CV to reach the first or maximum peak
%OS	-	Percent Overshoot; the percentage amount of the CV that overshoots the steady-state value at Tp

CHAPTER 1
INTRODUCTION

1.1 Background of Study

In general, the project emphasizes on the performance of the controller in cascade control system and the design of the controller will be tested by proposed auto-tuning method. The configuration of cascade control system is shown in Figure 1 [1].

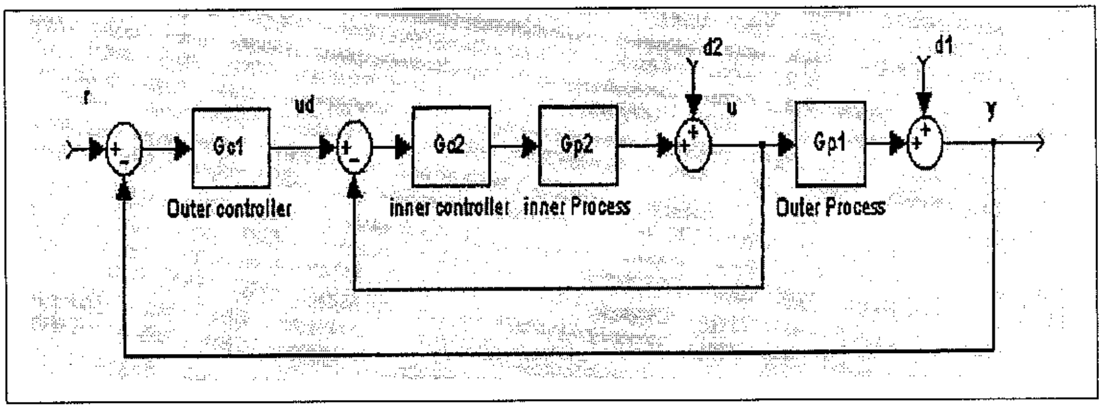

Figure 1: The configuration of cascade control system

The cascade control system basically consists of two loops; outer loop (primary loop) and inner loop (secondary loop). The control system consists of two processes and two controllers. The inner loop consists of the transfer function, G_{p2} and controller, G_{c2} and outer loop consists of transfer function, G_{p1} and controller, G_{c1}. Basically, the two controllers in the system are feedback controller using PID algorithm. Usually, a proportional controller is used for the inner loop, integral action is needed when the inner loop process contains essential time delays and outer process is such that the loop gain in the inner loop must be limited.

One of the aspects that need to understand is about the dynamic response both of the inner and outer loops. It is important to identify the dynamic response of both inner and outer loop because the disturbance that occurs in the system might affect the whole system. So, to serve the purpose of reducing or eliminating the inner loop disturbance d_2, it is essential to have the inner loop a faster dynamic response than the outer loop dynamic response in order to prevent the effect can spill over to the outer loop. If the inner loop does not have the faster dynamic response, there are no advantages in using the cascade design.

The project involves two major parts, which is plant experimentation and computer simulation. Plant experimentation is important in order to identify the process, to obtain the model parameters and to observe the control performance of the cascade controller. Besides, the plant experimentation also needs to verify the previous FYP [1]. The MATLAB will be use to simulate the design controller and the result from the plant experimentation is then compared with the simulation result.

The theoretical knowledge learnt from the subjects such as Control Systems 1 & 2 and Plant Process Control System will be applied effectively throughout the project. The simulation and programming software such as MATLAB also needs to emphasize while doing this project. The skills and understanding about the software need to improve in order to produce better simulation result.

1.2 Problem Statement

The cascade control system is used when single loop control does not provide satisfactory control performance. Cascade control system is applied which combines two feedback controllers and the outer controller's output serving as the inner controller's set point [2]. The design should fulfill the requirement in order to produce the satisfied output.

In this project, the SIM 305 Pilot Plant 6 which is the Heat Exchanger Process Pilot Plant will be use for the process identification experiment to obtain the process models for the primary and secondary loop.

However, there are several problems that need to be considered while designing cascade control system. One of the problem statements is *to define what type of controller to be designed and used.* Based on the project, the controller to be used is PID controller.

The design process model obtained from the UTP Pilot Plant is usually in low-order system with dead time (θ). The first-order-system is usually used because it is less complex and sufficiently feasible for this project. Other model parameters that need to be considered are Process Gain (K_p) and Time Constant (τ). It is important to identify and understand these parameters because these parameters are the critical part that affects the tuning method.

The next problem statement is *to define the type of tuning method that will be applied for the controller of cascade control system.* There are many types of tuning method used in the world and therefore essential and suitable methods need to be chosen to produce good performance.

Apart from that, the measure of robustness must be stated in order to determine the advantages of using a robust cascade control design compared to a classical scheme.

1.3 Objective and Scope of Study

The main objective of this project is to develop a process model of a system using cascade control system from Heat Exchanger Process Pilot Plant. Then, a controller is designed to use in cascade control system. It is then simulated and implemented by using the proposed tuning method for the controller. The model is to be obtained from Heat Exchanger Process Pilot Plant that located in the Plant Process Laboratory. The performances of classical and robust cascade control system are analyzed.

Besides, the study will emphasize on the fundamentals of cascade control systems and the best tuning method to be used in tuning the controller.

Below are the objectives throughout the project.

1. To understand and verify the model and its performance from the previous FYP. [1]
2. To obtain the process parameters for primary and secondary loop plant model.
3. To design control scheme in classical and robust cascade control system

4. To simulate both controller using MATLAB
5. To analyze and compare the performance of proposed robust design of cascade control over the classical model

CHAPTER 2
LITERATURE REVIEW / THEORY

2.1 Background of Tuning Methods

The ability of Proportional-integral-derivative (PID) controllers to compensate most practical industries has led to their wide acceptance in industrial application. It also is being used due to their relatively simple structure, which can be easily understood and implemented. The PID then usually integrates into complex control structure in order to attain a better control performance. From the various complex control structures, the cascade control system is commonly used because of easy implementation and also for the purpose of reducing the integral error of disturbance responses.

The Ziegler-Nichols is one of the well-known tuning methods used all over the world. The advantages of Ziegler-Nichols is it could be applied to process that are not well modeled by first order with dead time models and also it provides considerable insight into the effects of all loops elements (process, instrumentation and control algorithm) on stability and proper tuning constant values. Below is the opened-loop tuning correlations of Ziegler-Nichols method shown in Table 1 [3].

Controller	K_c	τ_i	τ_d
P	$(1/K_p)/(\tau/\theta)$	-	-
PI	$(0.9/K_p)/(\tau/\theta)$	3.3θ	-
PID	$(1.2/K_p)/(\tau/\theta)$	2.0θ	0.5θ

where K_p is the process gain, τ is the time constant and θ is the dead / delay time

Table 1: The Ziegler-Nichols opened-loop tuning correlations

Controller	K_c	τ_i	τ_d
P	$K_u / 2$	-	-
PI	$K_u / 2.2$	$P_u / 1.2$	-
PID	$K_u / 1.7$	$P_u / 2$	$P_u / 8$

Where K_u is the ultimate gain and P_u is ultimate period

Table 2: The Ziegler-Nichols closed-loop tuning correlations

The Cohen-Coon method is very similar to the Ziegler-Nichols step response method. It is based on the same principle of Ziegler-Nichols step response method to achieve quarter amplitude damping. The experiment is carried out in exactly the same way as for the Ziegler-Nichols step response method, based on a step response experiment.

The opened-loop tuning correlations are given in table below. The Cohen-Coon method was developed for the PID controller of the parallel type. However, the general expression for translating between parallel types to series type may be used to obtain the series type parameters [3].

Controller	K_c	τ_i	τ_d
P	$\frac{1}{K_p}(0.35+\frac{1}{\theta})$	-	-
PI	$\frac{1}{K_p}(0.083+\frac{0.9}{\theta})$	$\frac{3.3+0.31\theta}{1+2.2\theta}L$	-
PID	$\frac{1}{K_p}(0.25+\frac{1.35}{\theta})$	$\frac{2.5+0.46\theta}{1+0.61\theta}L$	$\frac{0.37}{1+0.19\theta}L$

where K_p is the process gain, L is the time constant and θ is the dead / delay time

Table 3: The Cohen-Coon opened-loop tuning correlations

The Cohen-Coon formulas are not as well-known as the Ziegler-Nichols rules. One reason could be that because they are more demanding on calculation. Comparing both method shown in Table 1 and 2, it may be seen that the methods are quite similar for small values of θ, i.e., when the process has a short dead time in relation to the time constant. The Ziegler-Nichols choose to connect the integral and derivative times completely to the dead time in process, while Cohen-Coon adjust the times according to the particular relationship between the dead time and time constant. This is the marked difference between the two methods.

In both methods, the controller gain is a function of this relationship. Because processes with large differences in the relationship between dead time and time constant have marked differences in dynamic behavior, it could be expected that the Cohen-Coon method would work better than Ziegler-Nichols method. For example, for very long dead times (large value of θ), the derivative time tends towards zero in the PID controller. This is correct, as the derivative part should not be used when the dead time is long.

A part from that, there are one method more that is quite similar to Ziegler-Nichols method, which is the Tyreus-Lueben method. For Tyreus-Lueben, it gives more conservative settings (higher order closed-loop damping coefficient) compared to Ziegler-Nichols. Below is the opened-loop tuning correlation of Tyreus-Lueben [3].

Controller	K_c	τ_i	τ_d
P	-	-	-
PI	$K_\pi / 3.2$	$2.2T_\pi$	-
PID	$K_\pi / 2.2$	$2.2T_\pi$	$T_\pi / 6.3$

Where K_π is the ultimate gain and P_π is ultimate period

Table 4: The Tyreus-Luyben opened-loop tuning correlations

2.2 The Heat Exchanger

A heat exchanger is a device for transferring heat from one fluid to another, where the fluids are separated by a solid wall so that they never mix. They are widely used in refrigeration, air conditioning, space heating, power production, and chemical processing. One common example of a heat exchanger is the radiator in a car, which the hot radiator fluid is cooled by the flow of air over the radiator surface.

In all the design of heat exchanger, focus is given to the one is avaialbe in UTP Pilot Plant, which is the shell-and tube-type. Figure 2 below shows the internal design of the shell-and-tube-type heat exchanger.

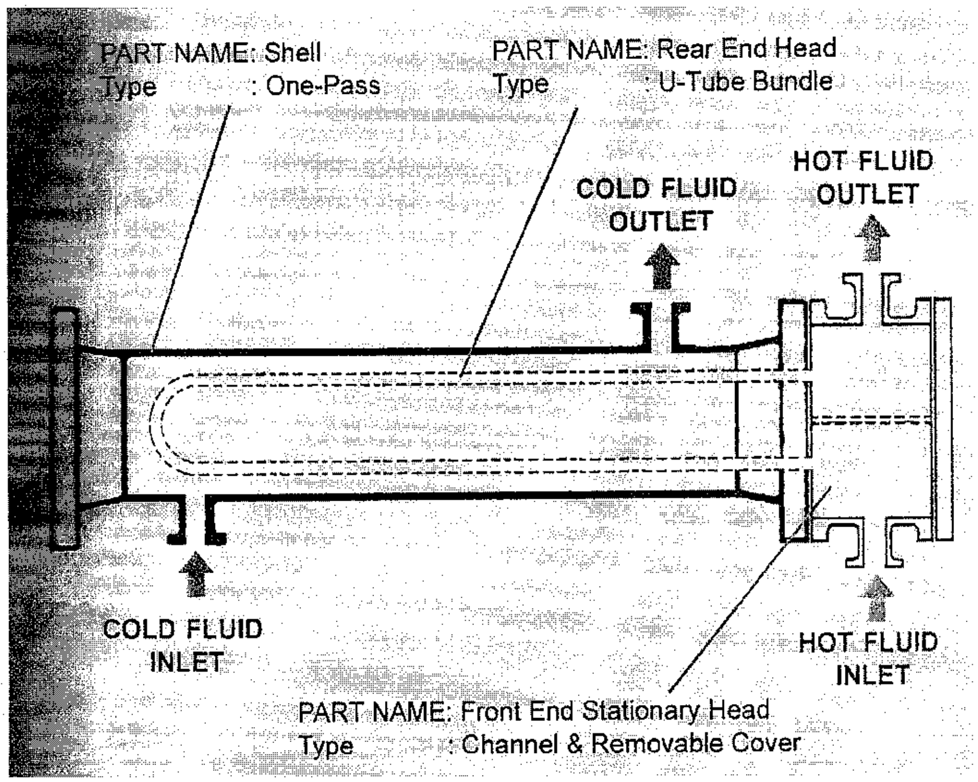

Figure 2: Shell-and-Tube-Type Heat Exchanger

A typical shell-and-tube-type heat exchanger consists of a series of finned tubes, through which one of the fluids runs. The second fluid runs over the finned tubes to be heated or cooled. The hot fluid is used to transfer heat to the cold fluid, which in this case is the process fluid and at certain temperature as it flows through the shell and made contact with the hot U-tube bundle. The heated process is them immediately cooled by a cooler after it leaves the shell via the cold fluid outlet pipe [1].

In order to control the amount of heat exchange, the temperature of cold fluid (controlled varible, CV) is measured at the cold fluid outlet pipe. Any deviation of the temperature measurement from its set point will result in control the valve at the hot fluid inlet pipe(manipulated varible, MV) being adjusted the valve opening in order to increase or decrease the flow of the hot fluid in the front end part of the heat exchanger. This action will bring the deviated temperature back to its set point, SP. The control strategy used in achieving this objective is called feedback control [1].

CHAPTER 3
METHODOLOGY

3.1 Major Activities Done

3.1.1 Desk study & Private communication

Desk study plays significant impact to strengthen the basic knowledge about anything related to the project. The books, journals, articles and report are the main important resources to the project. MATLAB need to be self-studied to improve on simulation skill; i.e. SIMULINK skills. In order to obtain more information related to the project, private communication also important and need to put under consideration. Besides the supervisor, the information also can be getting from the people that have the experience and some idea to improve the understanding about the project.

3.1.2 Pilot plant familiarization

The author has been familiarized with the pilot plant in terms of identifying which control loop that is of interest, obtaining the process reaction curve of a specific controlled variable, monitoring and controlling the plant via the control room. These activities were done in parallel with the PPCS laboratory sessions.

3.1.3 Parameter estimation

For this project, there are two process models that need to identify and obtain in order to design the process loop in cascade control system; temperature and flow process model. The temperature will be the primary loop and the flow will be the secondary loop. As the temperature is to be controlled, the primary loop should be the temperature and the secondary loop will be the flow. The secondary loop should have faster dynamic response than the primary loop so that it could prevent the effect of disturbance from spill over to the primary loop. Besides, the secondary loop also needs to do corrected work faster in order to control the primary variable such as the temperature that have the tight control condition. If the secondary loop does not have the faster dynamic response, there are no advantages in using the cascade control system design.

First, the temperature process model needs to obtain from the plant experiment. From the experiment, the temperature will be control through the opening of the control valve, FY631. Therefore, the manipulated variable will be the opening of the valve and the controlled variable is the temperature of heat exchanger. In order to get achieve the high accuracy in the experiment, there are some condition that needs to follow and the condition are as below:

1. The temperature in heating media tank, VE610 must be wait until reached 60°C
2. The level of water in the product water tank should be more that 50%
3. The perturbation that need to used is 20%

The process parameters for the secondary loops will be obtained through the experiment by controlling the valve, FY631 using flow controller, FIC 631. The opening of the control valve is taken as the manipulated variable, MV. In a cascade control system, the manipulated variable from temperature loop will be the set point to the flow loop. Then, the manipulated variable of the flow loop will adjust the control valve in order to maintain the control of the temperature.

Before this, for temperature process parameter, the step is conducted to verify the previous FYP work [1]. For flow process parameter, the Empirical modeling step is an option to use in order to obtain the parameters.

Empirical modeling is a very efficient modeling method that is specifically designed for process control. The flowchart for empirical modeling procedure is summarized in Figure 3 below: - [1]

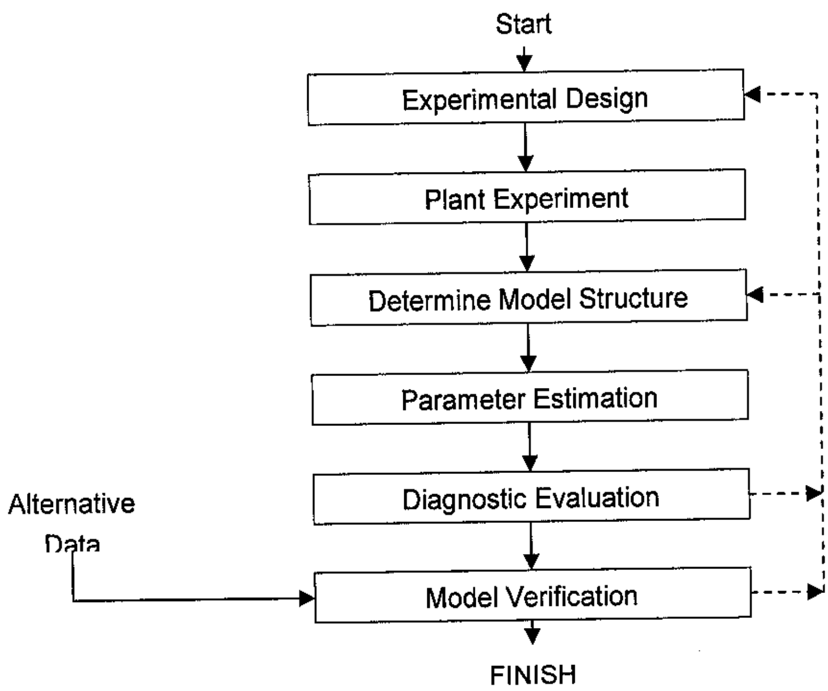

Figure 3: Procedure for Empirical Model Identification.

The desired result from plant experiment is a process reaction curve of a first-order-with-dead-time model, shown in Figure 4 below: -

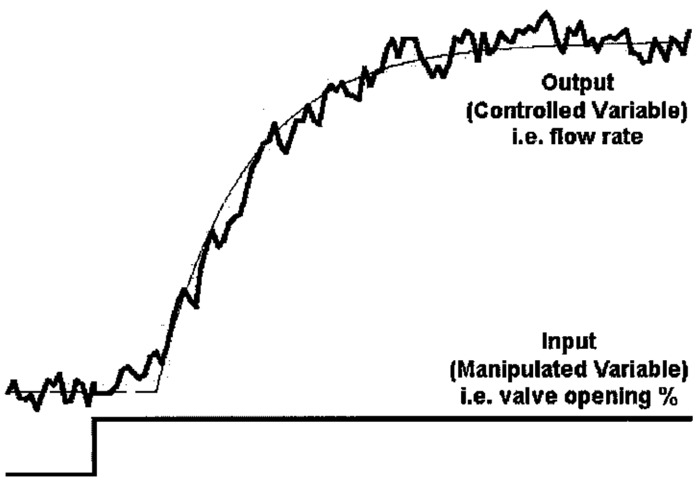

Figure 4: Process Reaction Curve.

Among the acceptance criteria for the process reaction curve obtained is that there should be no disturbance occurrence, which can be verified by returning the manipulated variable's value back to the initial value and ensuring that the controlled variable also returns to its initial value.

The next step is to determine the model parameters using Method I or Method II (the latter is preferred since it gives more accurate result). The model parameters are: - [1]

Parameter	**Description**	**Calculation (Method II)**
K_p	Process Gain	$K_p = \Delta / \delta$, where Δ = magnitude of change in MV
τ	Time Constant	$\tau = 1.5(t_{63\%} - t_{28\%})$
θ	Dead Time	$\theta = t_{63\%} - \tau$

TABLE 5: Calculating Model Parameters.

A part from that, in order to verify the accuracy of the data used, the diagnostic evaluation is done by returning the input variable back to the initial value. Naturally, the output variable will not return to exactly the same value due to the nonideality. However, if the difference between the output variable and input variable is too large (i.e. more that 50%), then the Empirical model is most likely corrupted by disturbance and the experiment should be repeated.

3.1.4 Tools and equipment used

MATLAB is the main software that is used in this simulation. Heat Exchanger Process Pilot Plant located in Plant Process Laboratory will be used for plant experimentation part through the project. All plant work are conducted using the Pilot Plant and its Distribution Control System (DCS).

CHAPTER 4
RESULT

4.1 Temperature Model Parameter

Four experiments are conducted to obtain the best model for the temperature loop. The results of the experiment are printed in order to calculate the model parameters for open loop method. Below are the results for all the experiments.

Result

Comparison with simulation and all the plant experiments result:

Table 6					
Parameters	Simulation	Experiment 1	Experiment 2	Experiment 3	Experiment 4
K_P (process gain)	0.315	0.45	0.2465	0.2385	0.26
τ (time constant)	109.5s	40.5s	139.5s	108s	107.1s
θ (dead time)	36s	18s	39s	54s	48.5s

Table 6: Comparison between the simulation and plant experiment parameters

Ziegler-Nichols closed-loop tuning correlation [4]

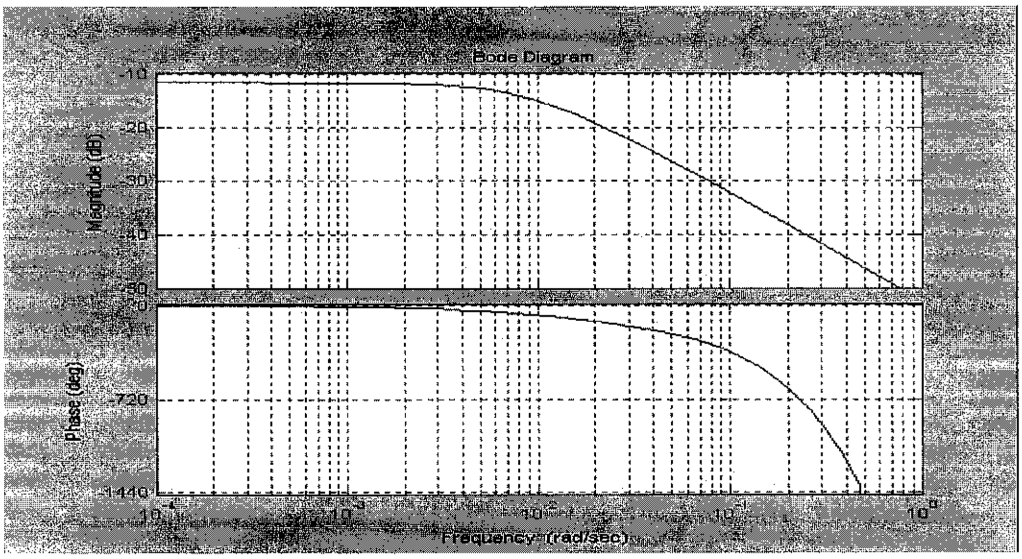

Figure 5: Bode Plot for temperature loop

Controller	Kc	Ti
PI	7.21	141.5

Table 7: Ziegler-Nichols Tuning Correlation for P+I mode

4.2 Flow Model Parameter

Four experiments are also conducted to obtain the flow model parameters. The results of the experiment are printed in order to calculate the model parameters for open loop method. Below are the results for all the experiments.

Comparison all the result of experiment.

Parameters	Experiment 1	Experiment 2	Experiment 3	Experiment 4
K_P (process gain)	0.077	0.078	0.078	0.062
τ (time constant)	1.5s	1.5s	1.5s	1.5s
θ (dead time)	4s	4s	4s	5s

Table 8: Comparison between the results of experiment

Ziegler-Nichols closed-loop tuning correlation [4]

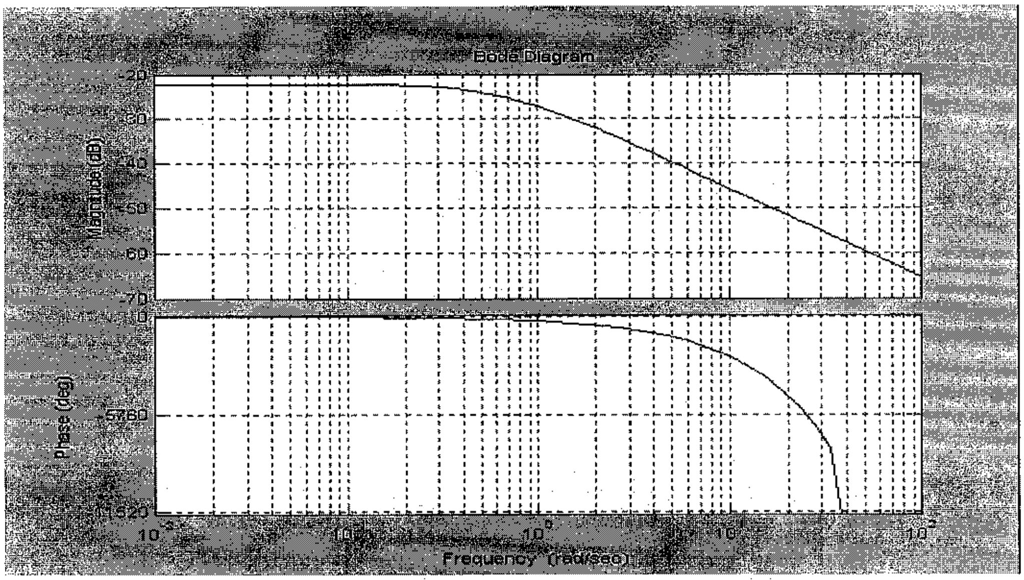

Figure 6: Bode Plot for flow loop

Controller	Kc
P	8.62

Table 9: Ziegler-Nichols tuning correlation for P mode

CHAPTER 5
DISCUSSION

For the early stage of the project, a significant amount of reading and literature review had been done in order to understand and see the whole view of the project. All the theories behind the project need to be identified and the problem statement of the project needs to be determined. That was the first phase of the project.

The previous similar project [1] had been given in order to verify the temperature process model. After the experiment completed all the process parameters need to calculate and all the parameters value will be using again to run the simulation in MATLAB. Besides, the flow model is also obtained. Below are the models for temperature and flow model that obtained.

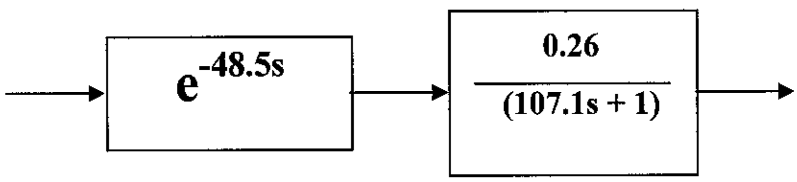

Figure 7: Process Model Block Diagram for Primary Loop

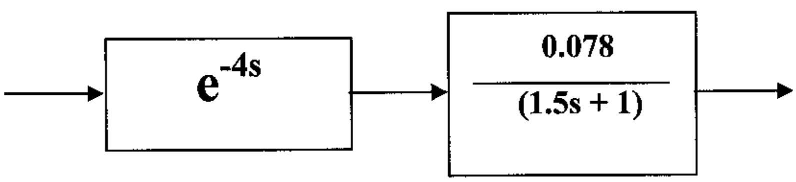

Figure 8: Process Model Block Diagram for Secondary Loop

In designing the PID controller for cascade control system, the correct mode of controller needs to use. In this case, the secondary loop (flow) must have the proportional mode to get enough response and rapid action and that the objective of the secondary is to maintain the primary variable to the set point and it does not require the integral mode. In some case, it still requires the integral mode but for this case, the integral mode is excluded. For the primary loop or temperature, the mode that should be use is P+I. The integral mode is very important in order to reduce the offset to zero. If no integral mode, the process variable is impossible to keep to the set point.

So, in the simulation each of the loop is evaluate separately first and in cascade design. The purpose of evaluating the loop individually because the responses of each loop need to identify first. Then, both loops will be combining to classical cascade structure.

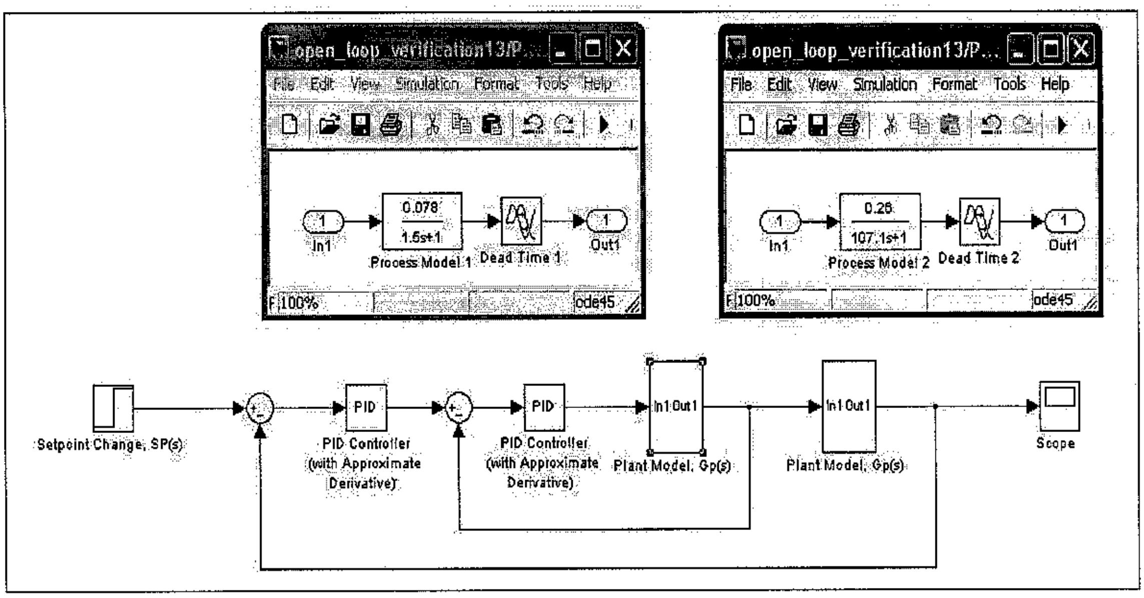

Figure 9: The simulation of classical cascade control loop in MATLAB

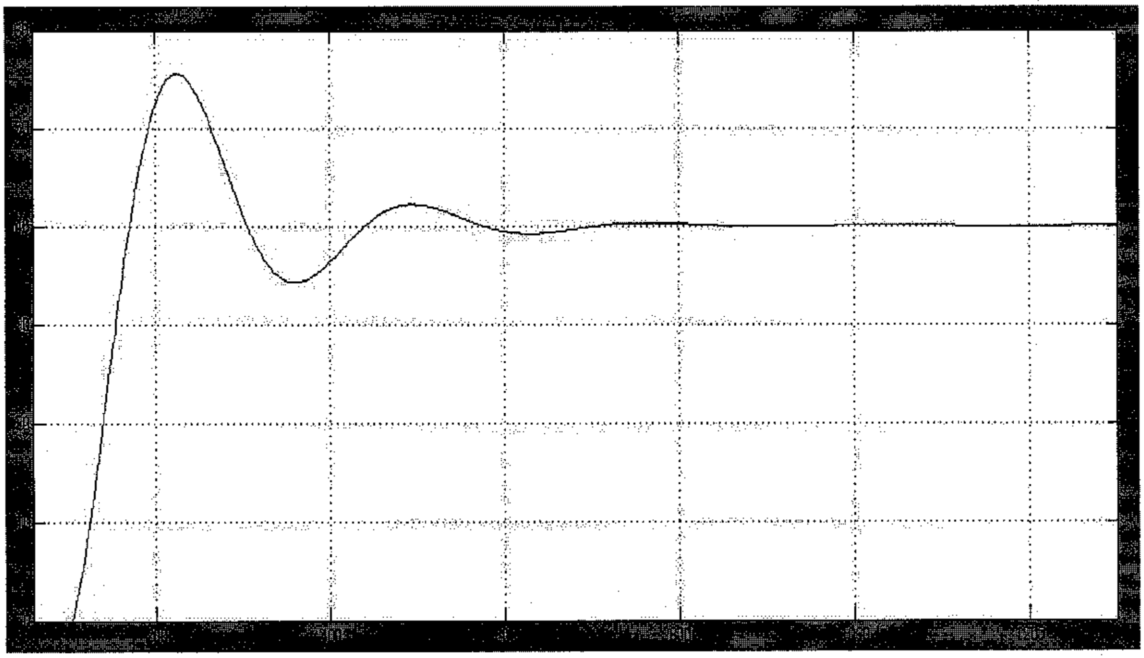

Figure 10: The result of simulation for classical cascade control system

From the result of simulation, the graph shows that the temperature, which is the controlled variable, CV successfully control and return back to its set point, SP. The secondary loop (flow) control the temperature by adjusting the opening of the control valve, then regulating the flow of hot fluid in the front end part of the heat exchanger so that any deviation of temperature will be brought back to its set point.

Besides, the percentage of overshoot, %OS is about 40% and according to this project, the %OS is acceptable. The response reach the peak time at 223.15s and at this time the process have the highest amont of %OS.

In designing the robust cascade control structure, there are two methods to be used; closed-loop transfer function and combining the block diagram. For the first part which is using the closed-loop transfer funtion, all the transfer funtion need to obtain first in order to simulate the robust cascade control system. [5]

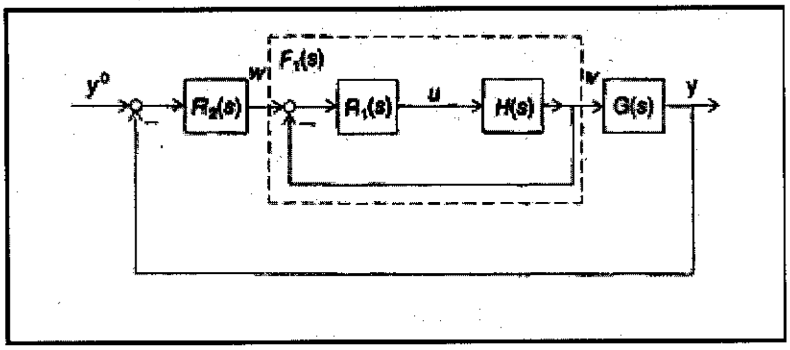

Figure 11: The block diagram of classical cascade control system

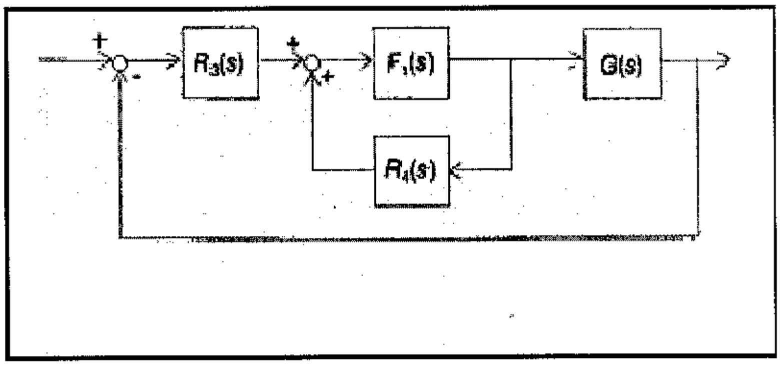

Figure 12: The block diagram of robust cascade control system

From Figure 10, there are the main block diagram for determine the classical cascade control system. The transfer function for $R_1(s)$, $R_2(s)$, G(s) and H(s) are as below: [5]

$R_1(s) = 8.62$

$$R_2(s) = \frac{1020s + 7.21}{141.5s}$$

$$G(s) = \frac{0.26e^{-48.5s}}{107.1s + 1}$$

$$H(s) = \frac{0.078e^{-4s}}{1.5s + 1}$$

Then, refer to Figure 11, the transfer function for $R_3(s)$, $R_4(s)$ and $F_1(s)$ need to be identified in order to simulate the robust cascade control system and these transfer function can be refer in Attachment 3 in Appendix section [5,6].

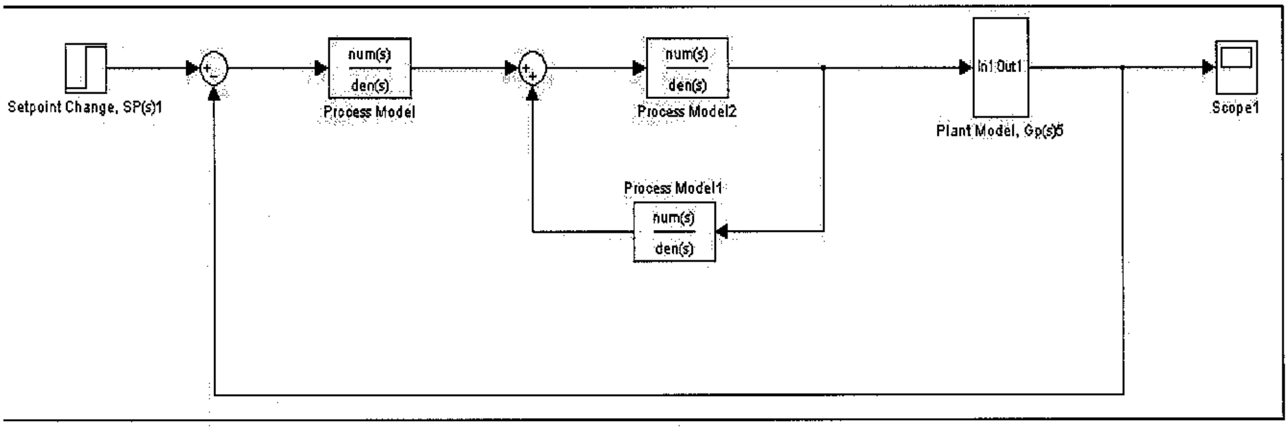

Figure 13: The simulation of robust cascade control loop using closed-loop transfer function

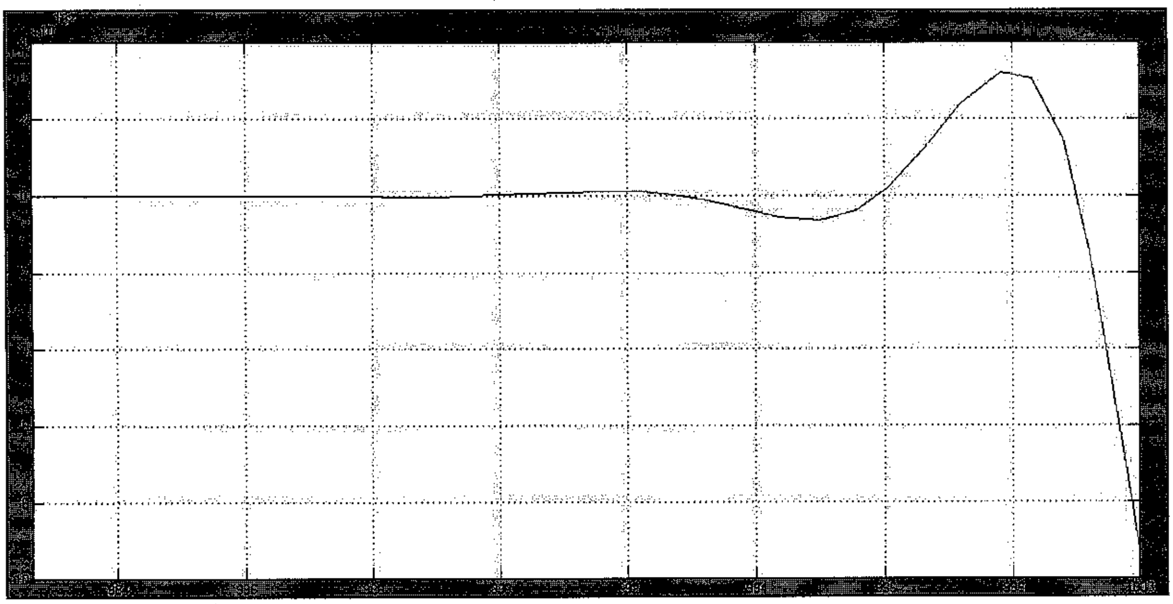

Figure 14: The result of simulation for robust cascade control system using closed-loop transfer function

From the simulation of robust cascade control system using closed-loop transfer function, the result that obtained is out of control and not acceptable. The control variable, CV can not be control based on the result obtained and besides the flow loop doesn't have any control on the temperature. Moreover, this problem may occur due of a large time delay inherent in process model. This may lead the response to be out-bounded from the system and thus unstable.

In order to overcome this problem, the second method, which is combining the block diagram of the process, is used. By doing this method, it is easier compared to the first method. Below is the block diagram for second method:

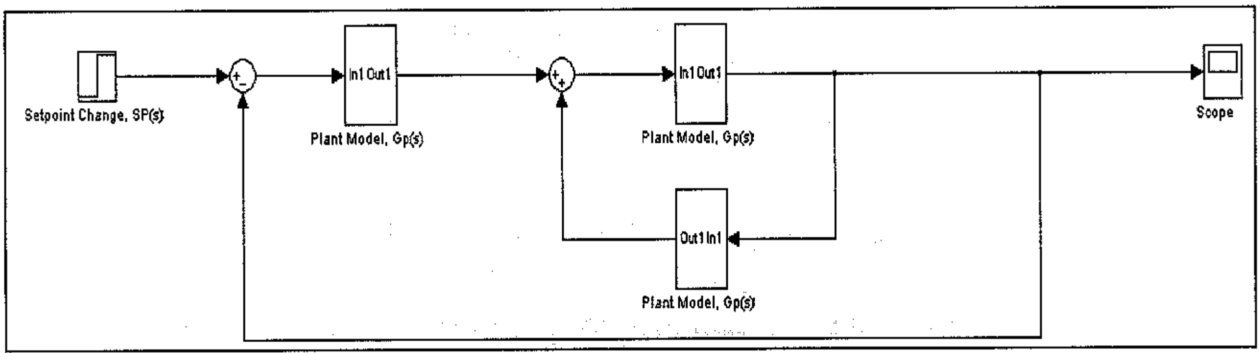

Figure 15: The simulation of robust cascade control loop using combining block diagram

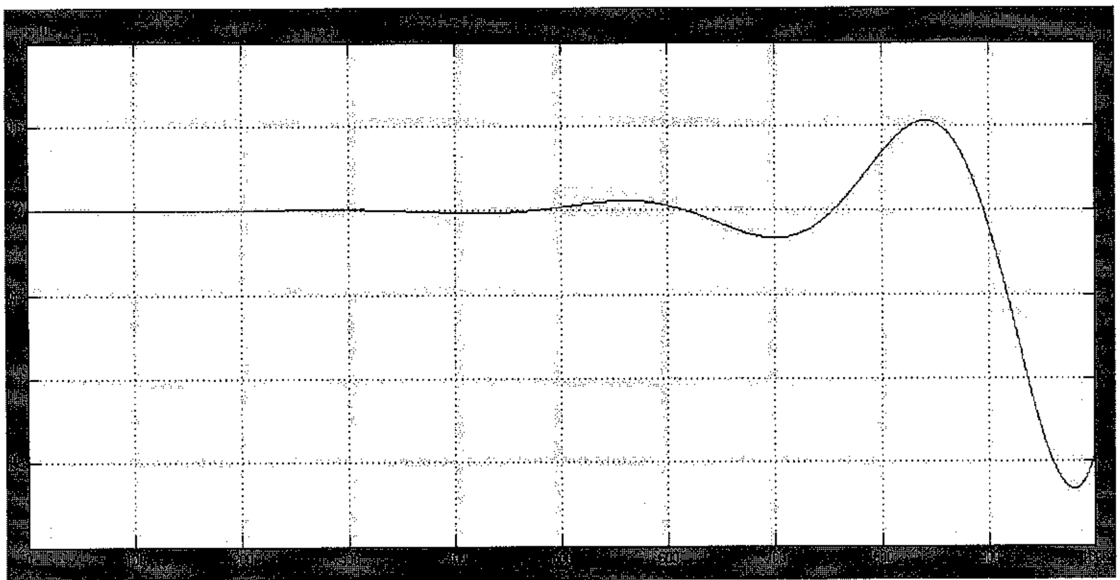

Figure 16: The result of simulation for robust cascade control system using combining block diagram without delay time

The Figure 16 shows the response from the simulation using combining block diagram. The controlled variable, CV does not give satisfy performance because it doesn't reach set point at 40°C. Besides, the response also shows that it is difficult to be controlled and doesn't reach the steady state. This problem might cause by the large delay time in the plant model for both loops. When there is large delay time in the system, it is hard and difficult to control the whole system. Therefore, to overcome this problem, the time delay in the plant model is taken out and the response of the simulation shows in Figure 17.

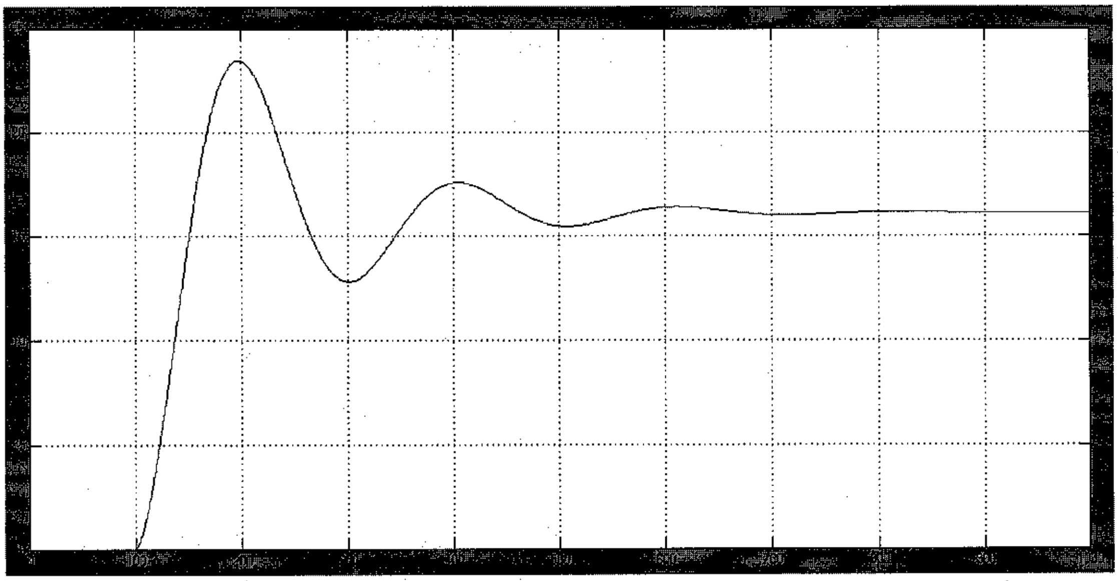

Figure 17: The result of simulation for robust cascade control system using combining block diagram without delay time

From the figure above, it shows that the controlled variable, CV manages to reach steady state. Unfortunately, the controller variable does not able to return back to set point which is at 40 °C. The CV only manages to reach at temperature almost 16 °C. The graph of the simulation shows that it has some overshoot and it reach the maximum overshoot at 200s, which is its Tp.

A part from that, after all the simulation work had been done, it somehow shows that this method is not suitable to use in all condition. In this project, it is not convenient to compare the classical and robust cascade control system because the robust system is not technically suit the condition that used in the project. Therefore, the other method should be used in order to get better performance result for the robust cascade control system.

CHAPTER 6
CONCLUSION

The main objective is to design a process controller using classical and robust cascade control system. The design also included the controller of the cascade control system and simulates it in order to determine the performance of each design. The plant implementation will be used and the performance analysis of the proposed auto-tuning method will be tested on the pilot plant. The process parameters for both primary and secondary loop need to be identified first in order to design the PID controller for both loops.

The aim of this project is to control the temperature. So, the temperature will be the primary loop and the flow is selected as the secondary loop because it has faster dynamics response, essential in designing the cascade control system.

The classical cascade control system has shown that when a certain input perturbed, the system can control the controlled variable, CV which is the cold fluid that being measured at the cold fluid outlet pipe of the heat exchanger to maintain at its set point by controlling the flow of hot fluid inlet pipe, MV in the front end part of the heat exchanger. This action continuously takes place in order to maintain the temperature at its set point.

For the robust system, there are two methods that been conducted; the closed-loop transfer function and combining block diagram. In closed-loop transfer function, the result obtained is not a bounded response and somehow shows that the system is unstable. This problems cause by the large delay time in the process model. Therefore, to overcome this problem, the combining block diagram is used and this method is much easier. Unfortunately, there is still a problem occurs and the response that obtained from the simulation is still out of control. The problems that may be cause the response to be in such that way is reset windup. It conclude that, these method that been introduced is not suitable to use in the present condition of plant. There may be only convenient to use these methods to some cases only such as the process model with no dead time or small dead time.

For recommendation, this project can be extended to cover more aspects of case study. Further analysis can be done including the following issues:-

- *Applying other types of controllers in the category of intelligent controller* such *as* Fuzzy Logic or Genetic Algorithm in order to seek for any improvement in the intelligent process control.
- *Applying other method in designing the robust cascade control system* which is more convenient and suitable for any process in the plant.

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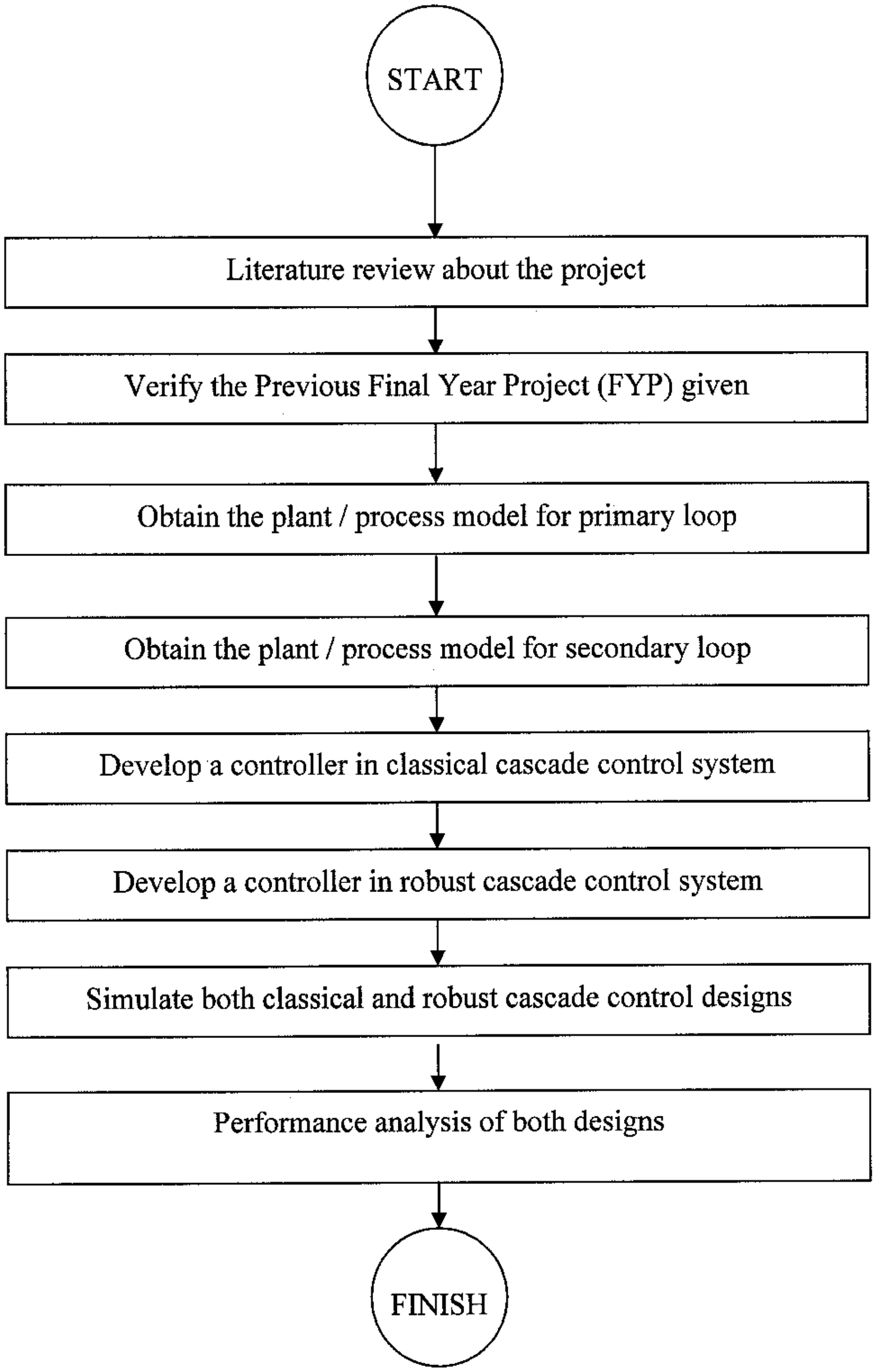
APPENDICES

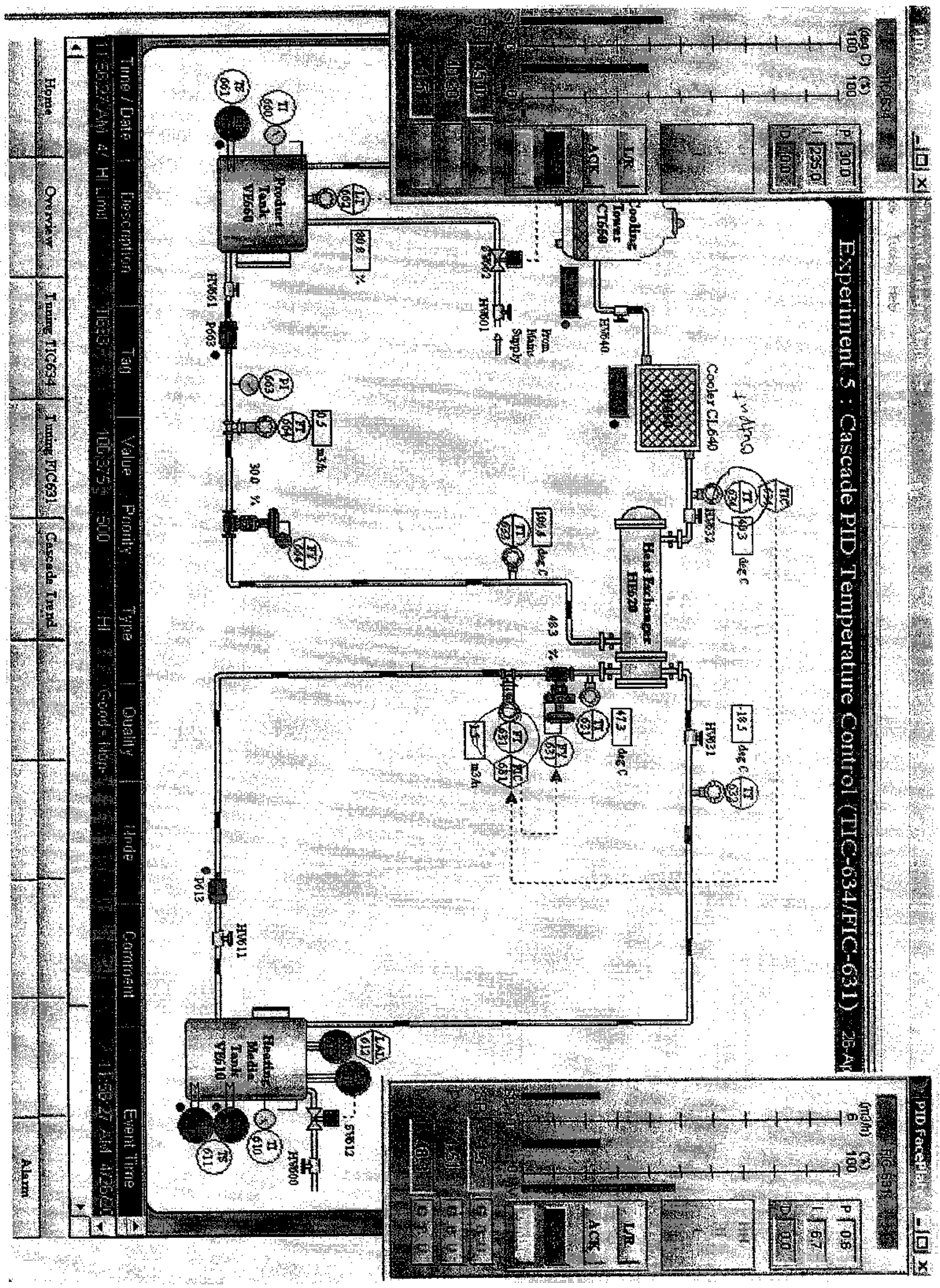
ATTACHMENT 1

Project Flow Chart



ATTACHMENT 2

Heat Exchanger Process Pilot Plant



ATTACHMENT 3

Transfer function for $R_3(s)$, $R_4(s)$ and $F_1(s)$

$R_3(s) =$

$$\frac{-3319870s^{12} - 1707698s^{11} - 3268108s^{10} + 592834s^{9} + 976848s^{8} + 906544s^{7} + 162259s^{6} - 30257s^{5} - 14076s^{4} - 3711s^{3} - 538s^{2} - 178.3s}{1468812s^{13} + 3194225s^{12} + 1243493s^{11} + 3908722s^{10} + 2071822s^{9} + 632651s^{8} + 336251s^{7} + 141388s^{6} - 16263s^{5} - 4033s^{4} - 1044s^{3} + 105s^{2} - 46.37s}$$

$R_4(s) =$

$$\frac{63656s^{10} + 117753s^{9} + 56674s^{8} - 52589s^{7} - 66307s^{6} - 14018s^{5} - 1525s^{4} + 1132s^{3} + 247s^{2} + 178.3s}{593404s^{12} + 508775s^{11} + 738830s^{10} + 643711s^{9} + 1292273s^{8} + 418768s^{7} + 257040s^{6} + 60793s^{5} + 24175s^{4} + 1294s^{3} + 429s^{2} + 178.3s}$$

$$F_1(s) = \frac{-4.034s^3 - 2.689s^2 + 1.009s + 0.6724}{916.97s^3 + 15.56s^2 + 8.009s + 1.672}$$