# DEVELOPMENT OF INTERACTIVE LEARNING SIMULATOR FOR PROCESS CONTROL USING MATLAB/SIMULINK

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# DEVELOPMENT OF INTERACTIVE LEARNING SIMULATOR FOR PROCESS CONTROL USING MATLAB/SIMULINK

**by**

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Mohamad Muhaimin Bin Md Yusof

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| | Symbol | Unit |
|---|---|---|
| $m_{uwsf}$ | Mass of the urea feed | kg |
| $m_{uwsp}$ | mass of the urea product | kg |
| $m_{vi}$ | mass of the separated vapor | kg |
| $m_{vo}$ | mass of the vapor outlet | kg |
| $P_v$ | Pressure inside the separator | bar |
| $P_w$ | Vapor pressure of water | mm Hg |
| $T_p$ | Temperature of Urea/water solution product | ˚C |
| $c_{uf}$ | Feed concentration of urea | % |
| $c_{up}$ | Product concentration of urea | % |
| $c_w$ | Water concentration of UWS product | % |
| $Q_s$ | Supplied energy steam | kW |
| $Q_{uwsf}$ | Heat energy of UWS feed | kW |
| $Q_{uwsp}$ | Heat energy of UWS product | kW |
| $\rho$ | density of the UWS | $kg/m^3$ |
| $c_p$ | Specific heat capacity of UWS | $kJ\ kg^{-1}\ ˚C^{-1}$ |
| $M_w$ | molecular weight of water | $g\ mol^{-1}$ |
| R | universal gas constant | $8314\ pa\ kmol^{-1}$ |
| $V_s$ | separator volume | $m^3$ |

**PEMBANGUNAN PEMBELAJARAN INTERAKTIF SIMULATOR UNTUK KAWALAN PROSES MENGGUNAKAN MATLAB / SIMULINK**

## ABSTRAK

Pembelajaran subjek kawalan proses untuk pelajar kejuruteraan kimia menjadi sangat mencabar kerana sukar untuk memahami teori kawalan proses dan menghubungkan kawalan kursus dengan aplikasi industri. Kajian ini menumpukan kepada bagaimana penyesuaian latihan simulator ini untuk tujuan pendidikan, penggunaan pra-simulasi dan kajian pasca simulasi untuk mengukur keberkesanan latihan simulator. Latihan simulator ini dilakukan untuk memotivasi para pelajar untuk mempelajari kawalan proses dan juga untuk meningkatkan pembelajaran interaktif dalam subjek kawalan proses. Kajian pra-simulasi digunakan untuk mendapatkan pendapat pelajar mengenai subjek kawalan proses. Dari analisis kaji selidik, ia memberikan idea tentang cara supaya pengajaran kawalan proses menjadi lebih menarik dengan membuat program simulasi menggunakan MATLAB Simulink yang berfungsi berdasarkan masa nyata. Dalam kerja ini, perkembangan simulasi penyejat vakum menggunakan MATLAB Simulink disahkan dengan membandingkan hasil simulati dengan kesusasteraan. Akhir sekali, tinjauan pasca simulasi telah dilakukan apabila simulator latihan telah selesai untuk menguji kecekapan latihan simulator. Hasil daripada tinjauan menunjukkan bahawa majoriti pelajar dapat meningkatkan pemahaman mereka mengenai subjek kawalan proses dengan menggunakan latihan simulator dan majoriti mereka dapat menjawab kuiz dengan betul dengan min 4.1 (SD = 12.88) dan 3.4 (SD = 8.98) untuk para peserta yang telah belajar kawalan proses dan peserta yang tidak belajar kawalan proses sebelum menggunakan simulator latihan.

**DEVELOPMENT OF INTERACTIVE LEARNING SIMULATOR FOR PROCESS CONTROL USING MATLAB / SIMULINK**


## ABSTRACT

Teaching process control course to undergraduate chemical engineering can be very challenging due to difficulty to understand the theory of process control and to relate the course with the industry application. This study focuses on how adaptation of training simulator for education purposes, use of pre-simulation and post-simulation survey to measure the effectiveness of the training simulator. The training simulator was done to motivate the students to learn the process control and also to enhance interactive learning in process control. Pre-simulation survey was used to obtain students' opinions regarding process control subject. From the analysis of survey, it give an idea on how to make the teaching of process control become interesting by creating a simulation program using MATLAB Simulink that works based on real-time. Also in this work, the developments of simulation of vacuum evaporator using MATLAB Simulink were validated by compare the result from simulation with literature. Lastly, post-simulation surveys were done when the training simulator has been finished to test the efficiency of training simulator. The result from the survey and quiz shows that majority of the students are able to enhance their understanding on process control subject by using the training simulator and majority of them able to answer the quiz correctly with mean 4.1 (Standard Deviation, SD = 12.88) and 3.4 (SD = 8.98) respectively for the participants that have learnt process control and participants that do not learnt process control.

# CHAPTER ONE

# INTRODUCTION

Chapter 1 outlines the overview of this research and the general information about process control, process control education, problem statement, objectives and scope work of this research.

## 1.1 Process Control

Process control in an engineering discipline that deals with mechanism and algorithm of a system to control the output of a specific process. Process Control is an application area of Chemical Engineering where it combines chemical process knowledge and an understanding of dynamic system (Dale E. Seborg, 2011). Process Control has become greater importance and critical in process industries due to global competition and faster product development. Also, modern plants have become more complicated and highly integrated processes make it difficult to operate. For these plants, it is very challenging to prevent disturbance from affecting the process from one unit to others. Therefore, the process industries need more reliable, error-free, robust, efficient and flexible control systems for the operation of process plant.

The subject of process control in engineering studies has become more and more important in recent years. The main objective of process control is to maintain the process at desired operating conditions, safely and efficiently, while meets the expectations of environment and product quality requirements (Lee, 2000). The second reason for control is to respond to changes at desired value. The study of process control in concerned on how to achieve this objective.

The benefits of controlling process in a distinct area of the chemical plant are to ensure the safety of workers and the community around a plant. Chemical plants have a great potential to do severe damage if something goes wrong and it is inherent the setup of process control to set boundaries on specific unit so that they don’t injure or kill workers or individuals in the community (Zhang et al.). For example, The Bhopal Gas Tragedy in Bhopal, India on December 3, 1984 was a large toxic gas leak that killed thousands of people in the surrounding area. This tragedy was largely due to the failure or lack of safety controls.

### 1.2 Process Control Education

In the field of engineering education, practical experience in engineering plays an important role to produce exceptional engineers (Golob and Bratina, 2013). Due to the practical and theoretical topics, teaching basic process control course is a challenging task. In the modern era with the increase used of technology and web-based distance experiments can play a vital role in supporting the learning process. In real course teaching, the theories described in the textbook are usually complex (Zhang et al., 2013). For example, the PID controller can either operate under direct or reverse modes, but without practical experience, students are usually confused on how to apply the theory that they learn in the class. In process control education, students must connect the pieces between theory and practice together to have good understanding in the subject (Sharma et al., 2016). Usually educators use virtual and remote laboratories which these two methods have become very popular in control education. Nowadays, in industrial process designs and academic purpose, process simulators are commonly used. For junior chemical engineers and students, these simulation tools are perfectly applicable for the process dynamics and control education (Zhang et al., 2013). These educational tools help students to have better understanding in the basic theories of process control, such as dead time, process capacity, control loops and multi-unit processes such as distillation columns, evaporators and etc. Also, this process simulator allows students to experience the experiment by using the theoretical principles from the lectures without having to participate in laboratory courses (Wagner et al., 2016). This process simulator will be used by educators during lectures to teach about process control. However, there are disadvantages of using this process simulator in education. It will only provide computer simulation and the improbable for the students to get real life experience.

## 1.3 Problem Statement

Teaching an undergraduate process control course for chemical engineering students can be very difficult due to advanced control mathematics content in the course syllabus. Conventional class room teaching of process control is known to cause fear and lack of motivation among students. Students can easily lose motivation and losing sight of the whole picture about process control. So, the first thing and foremost that need to be done is to motivate the students to learn the process control. This can be done by incorporate a new learning technique which is using educational virtual environment than conventional classroom. Educational virtual environment can be implementing by using Simulink Matlab. Basically, educational virtual environment is like game-based learning where students can have interaction with the training simulator

## 1.4 Research Objective

This research aims:

i. To obtain feedback of the USM student before and after using training simulator for process control education.
ii. To build a simulation of vacuum evaporator using mathematical model equation through Matlab/Simulink.

iii. To build real time simulation in training simulator.

### 1.5 Scope of Work

The scopes of the research were presented in order to achieve the three outlined objectives above:

i. In this research, pre-simulation survey and post-simulation survey were used as a method to obtain feedback of the USM student before and after using training simulator for process control education respectively. Pre-simulation survey was carried out to identify students' interest and perspective on process control/ control system subject. Meanwhile, post-simulation survey was carried out order to measure the effectiveness of interactive learning through training simulator when the participants had finished test the training simulator.

ii. In this part, Matlab/Simulink was used to develop the simulation of vacuum evaporator using the ODE equations based on the material balance, energy balance of the whole system and urea/water phase equilibrium relation. The simulation results obtained are then compared with those reported in the literature. If the simulation results obtained is comparable with the literature, the PID controller was implemented in the simulation to control the temperature of vacuum evaporator. Using the PID controller, setpoint tracking was carried out to test whether P, PI or PID controller able to reach the setpoint at temperature 130˚C.

iii. Lastly, a 'real-time sync' block is inserted to synchronize model execution to real time in normal mode of the vacuum evaporator.

# CHAPTER TWO

# LITERATURE REVIEW

Chapter 2 discusses literature review and compares the studies done by other researchers previously regarding the assessments on engineering education, simulation on evaporation of urea using vacuum evaporator and graphical user interfaces.

## 2.1 Assessments on Engineering Education

The purpose of this literature review is to determine how to collect the information whether this project are needed or not, and the means to run this project. It is for this reason the first methodological exploration in this series of literature reviews involves a mechanism known as the assessment. There are several data collection strategies and assessment methods that can be implemented in a research. These evaluation methods have an utmost importance to measure the outcome of a research study whether it is success or not.

A questionnaire in the area of ABET Engineering Criterion 3(a-k), comprehensive exam, and oral presentation are used to collect the information from the student (Wiesner and Lan, 2004). These methods were used to compare student who did not conduct computer-based experiments in 2001 and student who did physical experiments in 2002. Comparisons of performance of students were done at the four sub-level areas which are theory, safety, operation and analysis. Furthermore, an additional survey collected by the teacher observations whether the students are academically engaged during the learning process. Meanwhile, Kirkpatrick's Level 1 evaluation was used to evaluate the effectiveness of computer simulation tool in engineering education (Diefes-Dux et al., 2004). Kirkpatrick Model can be classified into 4 levels. In this literature, only Level 1 had been used to evaluate on how participants respond to the training. The students need to complete 6 online surveys which comprised of single-option variable, multi-options variable and unstructured response questions.

A qualitative survey form was used at the beginning and the end of the semester to obtain the feedback using the tablet PC in teaching Process Control. The usage of tablet PC was to increase the motivation of students and making it more interactive during teaching in class. Also, multiple choice questions and tutorial sessions were introduced for each chapter at the end of the class (Kalavally, 2012). Table 2.1 shows a sample survey to evaluate self-reflection of students toward process control. Meanwhile Table 2.2 shows a sample survey at the end of semester to evaluate the effectiveness of tablet PC.

**Table 2.1 : Sample Survey to Evaluate Self-reflection od Students towards Process Control (Kalavally, 2012)**

| No | Questions |
|---|---|
| 1 | Do you find process control unit to be highly mathematical? |
| 2 | Are you afraid of this unit? |
| 3 | Do you understand the importance of learning process control as an engineer? |
| 4 | Do the tutorial class help you understand the applications further? |
| 5 | Do you think you will do well in this unit? |
| 6 | What are the good aspects of this unit at this stage? |
| 7 | How do you think we can make the unit more interesting? |

**Table 2.2 : Sample survey at the end of the semester (Kalavally, 2012)**

| No | Questions |
|---|---|
| 1 | Do you feel more confident with the unit now compared to the first weeks of the semester? |
| 2 | Have you learned a lot from the process control lectures and tutorials? |
| 3 | What are the topics that you are confident with in this course? Name a few |
| 4 | What are the topics that you think need more revision? |
| 5 | What are the good aspects of this unit? |
| 6 | How do you think this unit can be made more interesting in future? |

In this work, it give a detailed account on how qualitative data collection strategies used in engineering education, addresses methods for creating trustworthiness, and the strategies for analysing qualitative data (Leydens Jon et al., 2013). For qualitative data collection, there are several strategies that can be implementing such as observation, interviews focus groups and using documents like open-ended questionnaires. Specific data analysis methods can be separates into observational protocol, interviews/focus groups, and documents analysis.

Cognitive interviews can be employed to improve the quality of the survey. The goal of analysing cognitive interview data was to reveal problems respondents have with the survey context, understanding questions, retrieving and integrating information used to answer questions, and communicating answers in order to revise or repair questions. Cognitive interviews are complement with questionnaire testing methods and other information to provide multiple sources of evidence for discerning survey question quality (Ryan et al., 2012).

## 2.2 Simulation on Unit Operation

Simulink is a software and commercial tool for modelling, simulating and analysing dynamic systems. Simulink mostly used in control theory and digital signal processing for simulation and design (Chaturvedi, 2010). Implementation of Simulink software package can create virtual scenarios from real-world situations (Durán et al., 2007). Simulations are interactive, so you can change parameters on the fly and immediately see what happens.

Simulation based on mathematical modelling can be used for investigation, prediction and control of industrial processes and systems, and for educational purposes. In this paper, heat exchanger in series model was developed. The model was simulated and interfaced using MATLAB/Simulink and Citect. Citect allows the user to grab and moves the pointer on the slider allowing the changes in parameter value. This model was used as training simulator to teach students in aspects of heat transfer and process control (Murphy et al., 2002).

LabVIEW software can be used to create realistic interactive control room interfaces. The interfaces consist of mathematical model of unit operations. These computer-simulated experiments will be used on student in unit operations laboratory (Wiesner and Lan, 2004). Interfaces of laboratory equipment of heat exchanger, mass transfer and humidification are created using LabVIEW by applying mathematical model of the equipment. From this interfaces, the student can conduct the virtual experiments similar with the physical experiments.

FOODS-LIB is a multi-level steady-state food process design tool for food engineers, food scientists, and food technologists. The MATLAB computational software package and its SIMULINK dynamic system simulation toolbox were used to develop the computational algorithms and the graphical user interface (GUI), respectively. This software was used by student to run the simulation of unit operation that already exists in the software. For example, the simulation of ice-cream manufacturing process are shown in diagram below (Diefes-Dux et al., 2004).

### 2.3 Simulation on Evaporation of Urea Using Vacuum Evaporator

An evaporator is an equipment process that is used to change the liquid form of a chemical substance such as water into vapor. Evaporator is a common operational process in the chemical, pharmaceutical, food, and wastewater treatment industries, etc (Li et al., 2018). It usually used to remove the water content in the process to get desired concentration. Evaporation is a process involving high energy consumption which the evaporated solution must have a significant amount of heat to evaporate the water.

According to Chen and Jebson (1997), factor that affected the evaporator such as temperature difference between the liquid evaporating and the steam condensing temperatures, evaporating temperature, and the heating tube length. Firstly, by decreasing the temperature difference between the liquid and the steam condensing temperatures, overall heat transfer coefficient was observed to increase. Second, the heat transfer coefficient increased as the evaporating temperature increased. Lastly, with increasing the heating tube length of evaporator, overall heat transfer coefficient decreases.

Evaporation processes of the syrup are used as model in Mathlab/Simulink in order to gain understanding about different aspects of the process and assess different control strategies (Emil Davidson, 2015). The modelling was based on the mathematical equations of mass balance of evaporator. Its assumption is syrup at its boiling point when it reaches each evaporator. Thus, the model was independent of the pressure and temperature. In this work, different control strategies have been implementing and test in the model and the result has been compared. The figure below shows the Simulink model of multiple effect evaporator effect.

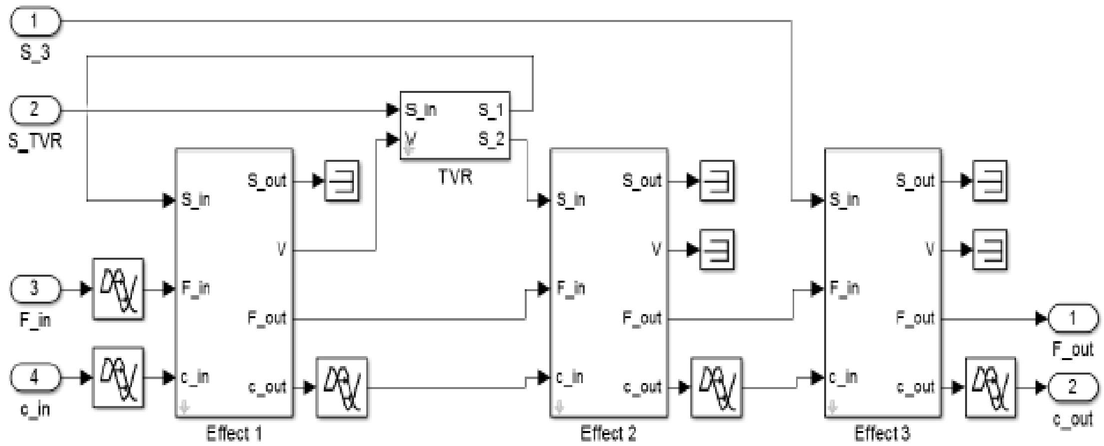



**Figure 2.1 : Simulink model of multiple effect evaporator effect (Emil Davidson, 2015)**

Usually, the methods of continuous evaporation are used for a solution conditioning in the technologies of spent nuclear fuel reprocessing. Thus, the effective continuous process will depend on the operation of the evaporation equipment. In this paper, the method of mathematic simulation was applied for the investigation of one-effect evaporator. MATLAB / Simulink was used to develop approach and mathematical description of the evaporator as a computer model (Kozin et al., 2016).

In sugar production process, evaporation is the most energy consuming. Development of control is needed to control product quality and the used of energy in evaporation process. The simulator of the evaporation process has been developed to meet the requirements of test facilities for different control strategies a real time simulator (Nielsen et al., 1996). Using the real-time simulator, a control strategies scheme has been designed and implemented. It is possible to investigate plant variations due to different input sequences, and in addition a number of measured disturbance sequences can be applied.

Two stages evaporation or crystallization processes were used to purify Bis(2-hydroxyethyl) Terephthalate (BHET) produced from Polyethylene Terephthalate (PET) waste glycolysis process. By using ASPEN PLUS simulator, two stages evaporator and crystallizer were modelled. The models were used to examine the performance of both methods at various operating temperatures and pressures on the efficiency of evaporator and product quality. (H.W. Goh, 2012).

In patent Granelli (1993), the evaporation of urea was carried out under vacuum conditions such as pressure at 0.25-0.5 absolute bar. In order to counter the formation and deposition of high-melting, evaporator was injected with overheated water vapor in the overhead portion of the concentrator. For energy saving process, evaporation of urea was carried out under two-stages of evaporator. In the first stages, urea is concentrated until 90% weight percent and the second stages, urea is further concentrated to 99.5-99.8% weight percent.

For the evaporation of urea, the evaporation process was used to increase the concentration of urea/water solution by vaporizing the water under certain conditions of pressure and temperature (Fahmy et al., 2015). Vacuum evaporator was used to concentrate the urea/water solution until desired concentration. Urea will crystallize and formation of undesired substance will form if the conditions are not met. A dynamic model of urea evaporation process was developed using MATLAB/Simulink. In this paper, controller strategies of multi-loop PI controller and model predictive controller were used to compare which controller were faster and better performance during plant variation.

There are two possible scenarios for urea crystallization based on water evaporation rate. Firstly, the solid particle of urea will formed when the concentration of urea increases uniformly as the water evaporation rate is low (Ebrahimian et al., 2012). Furthermore, when water vaporizes at a high rate, urea concentration increases at the droplet surface which urea shell formed around the droplet. This may lead to the boiling of the water inside the urea shell and explosion.

## 2.4 Interactive Learning

Interactive learning (IL) is a learning process that can enable students to interact with the study materials. Educational usages of interactive learning environments such as e-books, streaming videos, podcasts, social networking, cloud computing, and many other mobile applications have been adopted by individual innovative educators and institutions around the world. The concept of interactive learning will be able to boost students' motivation and enthusiasm of the students by placing the student at the centre of learning process.

Inverted classroom approach has been reported to be generally beneficial for engineering courses. The aim of this paper is to measure the effectiveness of the inverted-classroom approach in developing MATLAB/Simulink skills in chemical engineering education (Li and Huang, 2017). The user-friendly interface of MATLAB Simulink enables easier simulations of mathematical models into a pallet of Simulink block diagrams. Solving ODE models, performing Laplace transform, and designing PID controllers were included in the teaching modules. Students' overall feedback on the inverted-classroom format was positive as they gradually adapted to inverted-classroom learning format.

(Kumar et al., 2012) reported that, the MATLAB-GUI had been developed in 2012 but on the first phase it is only work on virtual laboratory environment that including for teaching induction generators. Graphical user interface (GUI) is a human-computer interface that enables the end-user to graphically interact with the system through the application and which can be manipulated by a mouse or keyboard (Johnsson and Magnusson, 2017).

Based on (Andreatos and Zagorianos, 2009) study, some teaching tool had been developed by using specified software. From that study too, GUI was a tool that very useful in order to solve the problem in teaching control system as MATLAB as the source of the develop software. Automatic Control Systems Teaching Assistant also known as ACTA-II was a very user friendly tool that many of trainers used it in their teaching progress. This tool can overcome the complex calculations and graphs in term of Automatic Control Systems as user friendly tool. The purpose of the ACTA-II tool was to display the classic control theory system stability criteria in graph. By using this tool, the graph can be shown quickly, easily and accurately. The ACTA-II actually can be created using MATLAB itself by using some powerful computational and graphical functions.

As GUI is very useful to solve teaching problems, this software actually can be performed under several types of generator such as Self Excited Induction Generator (SEIG) and Grid Connected Induction Generator (GCIG). In order to overcome the limitation of GUI capabilities, some researcher had been developed a tool which was front end tool. This tool can embedded the coding in MATLAB such as mathematical model operation. Other study stated that MATLAB GUI only a tool that only used in small scale of teaching (Jamehbozorg and Radman, 2013). Energy Capacitor Systems (ECSs) one of the study field that used MATLAB GUI as the education tool because it can save a lots of time unlike for the hybrid systems. In this work, the development of interactive educational software for communication engineering subjects is needed to increase the understanding of the subject matters especially among the students.

# CHAPTER THREE

# MATERIALS AND METHODS

This chapter covers the overview of research methodology and research methodology flowchart. It includes the survey methods used to assess the students and method used to analyse the results obtained. It also includes the steps to develop simulation of vacuum evaporator using Matlab/Simulink followed by implementation of graphical user interfaces.

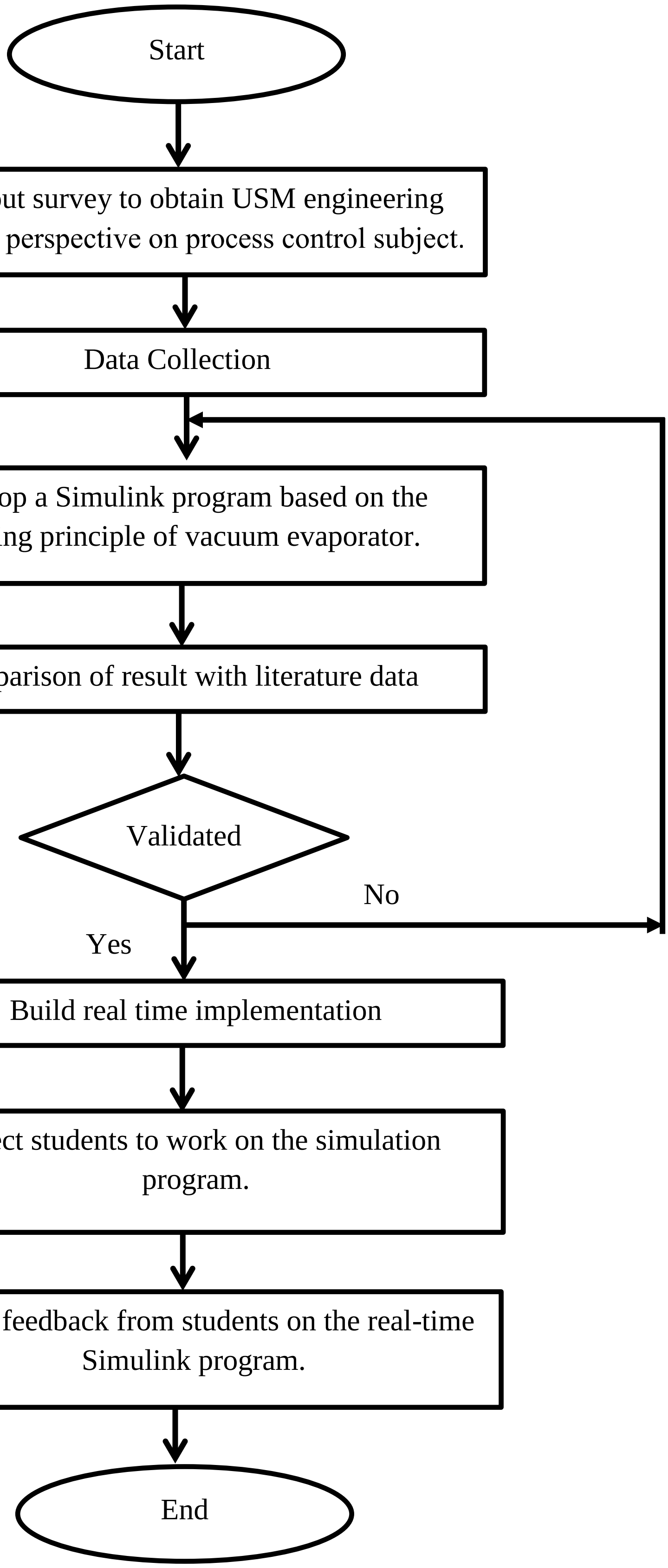
## 3.1 Overview of Research Methodology

In order to achieve the research objectives as mentioned in Chapter One, a process model based on the working principle of vacuum evaporator was developed using the real-time Matlab-Simulink software. Basically, it integrates the Simulink files that have been developed using MATLAB. This educational program created is used to study the effectiveness of interactive learning of process control using Matlab-Simulink program.

Firstly, the perspective of USM engineering students on the process control subject is identified. The subjects are chosen based on the feedback from the students regarding the tough subjects in the school of chemical engineering. The results of the survey were analysed and a real-time Simulink program is developed with an added user-friendly interface. Finally, the simulation program is test by students to allow the students to understand the subject more effectively and another feedback survey is carried out to identify the effectiveness of the simulation program.

## 3.2 Research Methodology Steps

Figure 3.1 shows the summary of methodology steps involved in this research work.



### 3.3 Carry out pre-simulation survey of USM Student's perspective on Process Control subject.

A survey was carried out to identify students' interest and perspective on process control/ control system subject. The targeted group was undergraduate students from Universiti Sains Malaysia(USM). The pre-simulation survey was created by using the goole form and posted online via Facebook and WhatsApp. Students from different engineering background were allowed to respond to this survey to obtain a general view on process control/control system subject and not just limit to students from School of Chemical Engineering. The information about the survey is summarised below:

#### 3.3.1 Summary of survey questions

**Table 3.1 : Pre-Simulation Survey Questions**

| Number | Questions |
|---|---|
| 1 | Which school are you from? |
| 2 | Which year are you right now? |
| 3 | Have you learned process control/control system before this? |
| 4 | If yes, what do you feel about Process Control/Control System? |
| 5 | If no, do you want to learn Process Control/Control System in the future, if given a chance? |
| 6 | What are the problems you faced in understanding Process Control/Control System? |
| 7 | What do you feel about Process Control/Control System teaching in your institution? |
| 8 | In your opinion, how to make learning process control/control system interesting? |

### 3.4 Data collection of Vacuum Evaporator

In research of Fahmy et al. (2015), the mathematical model development of vacuum evaporator is based on the material balance, energy balance of the whole system and urea/water phase equilibrium relation. By using these mathematical models, evaporator model was implemented using MATLAB/SIMULINK.

a) Material Balance:

Mass flow rates of UWS product ($m_{uwsp}$) and separated vapor($m_{vi}$) can be obtained by perform material balance of the system.

$$m_{uwsp} = m_{uwsf} \frac{C_{uf}}{C_{up}} \quad \textbf{(3.1)}$$

$$m_{vi} = m_{uwsf} - m_{uwsp} \quad \textbf{(3.2)}$$

b) Energy Balance:

UWS product temperature, Tp can be obtained by perform energy balance of the system and expressed by the following differential equation below:

$$\frac{dT_p}{dt} = \frac{(Q_s+Q_f)_{in}-(Q_p)_{out}}{\rho . C_p . V} \quad \textbf{(3.3)}$$

$$Q_{uws|x} = m_{uws|x} Cp_{uws|x} T_{uws|x} \quad \textbf{(3.4)}$$

c) Approximation of urea/water phase equilibrium

The approximations of mathematical representation for urea/water phase equilibrium relation are shown below:

$$P_w = e^{(18.2886 - \frac{3186.44}{T_p+227.02})} \quad \textbf{(3.5)}$$

$$X_w = 1.06425 e^{(0.92498 * \ln(\frac{0.95*100*P_v}{P_w})} \quad \textbf{(3.6)}$$

$$C_w = 1.00\left(\frac{M_w x_w}{M_u(1-x_w) + M_w x_w}\right) \quad \textbf{(3.7)}$$

$$C_p = 100 - C_w \quad \textbf{(3.8)}$$

**Table 3.2 : Feed specifications of urea**

| | |
|---|---|
| Temperature | 99˚C |
| Concentration | 80% |

**Table 3.3 : Control parameter of vacuum evaporator**

| | |
|---|---|
| Temperature | 130˚C |
| Pressure | -0.67 bar |
| Concentration | 95% |

Assumptions made in the simulation of vacuum evaporator of urea are stated below:

1) Heat capacity and density is constant.
2) Heat transfer coefficient is constant.
3) No heat loss to the surrounding.
4) Only water will be evaporated.
5) The outlet temperature of urea in the heat exchanger is equal to the temperature of separator.

### 3.5 Simulation Steps of Vacuum Evaporator

The vacuum evaporator of urea process simulation model was simulated using the following steps as shown below:

1. A Simulink block diagram is simulated using the ODE equations listed above with their respective values.

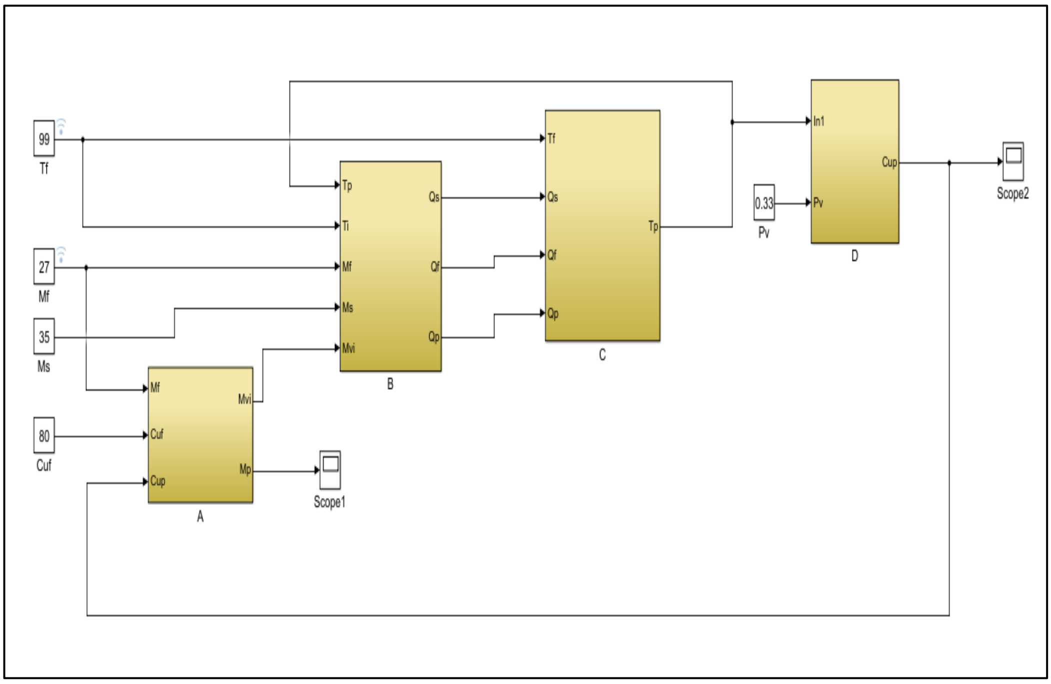



**Figure 3.1: Simulink Block Diagrams using ODE Equations**

2. Subsystem A, B, C and D in Figure 3.1 were used for simulation of vacuum evaporator using material balance, energy balance, temperature of product and urea/water phase equilibrium equation respectively.
3. Feed specifications such as inlet temperature, total feed flowrate, flow rate of the steam and feed concentration are inserted into simulink model. A critical step here is to consider the assumptions made while simulating the process. An example step of feed specifications for Simulink block diagram is shown in Figure 3.2 below.

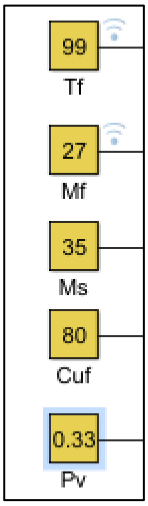



**Figure 3.2: Feed Specifications**

4. A complete simulink block diagram for vacuum evaporator is created.

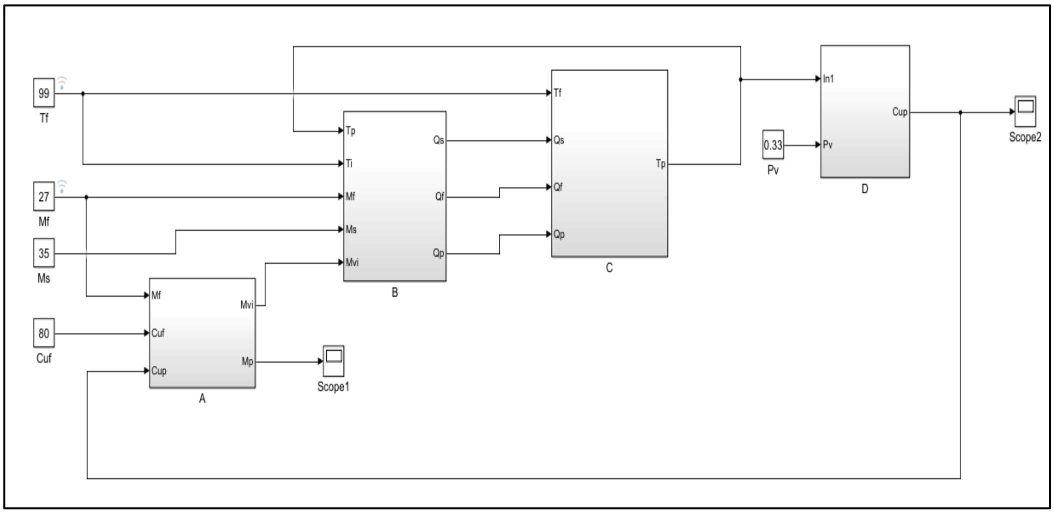



**Figure 3. 3: Complete Simulink Block Diagram**

5. The result obtained is observed and analysed.

6. A 'real-time sync' block is inserted to synchronize model execution to real time in normal mode of the vacuum evaporator.

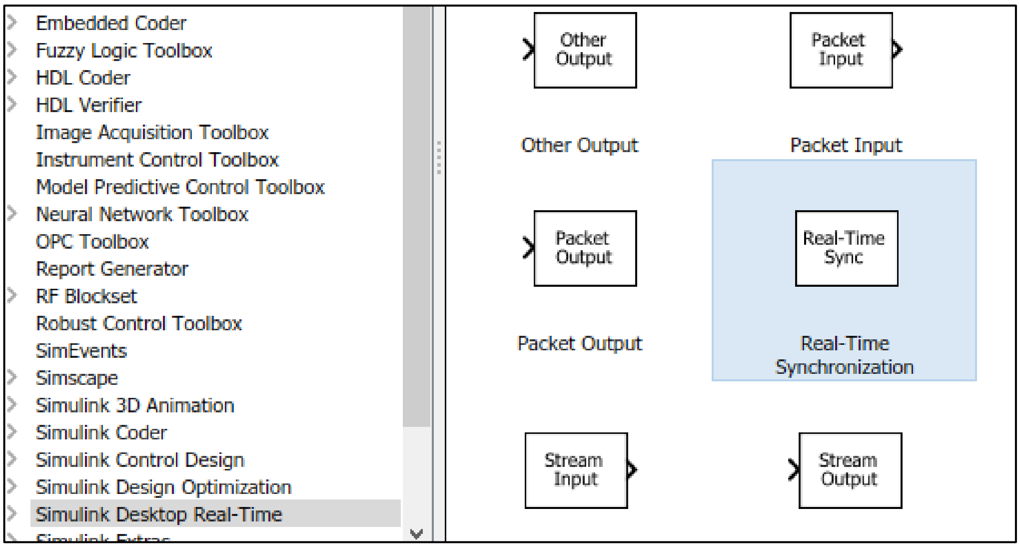



**Figure 3.4: Real-Time Synchronization Block**

### 3.4 Comparison Simulation Results with Literature

1. The output of the simulation model is used to validate the model accuracy. The simulation model should be able to replicate the real world scenario of the process as closely as possible.
2. The simulation model are run at different vacuum pressure which are -0.55, -0.60, -0.65, -0.70, -0.75, -0.80, -0.85 and -0.90 bar to be compared with the results from literature shown in figure below.

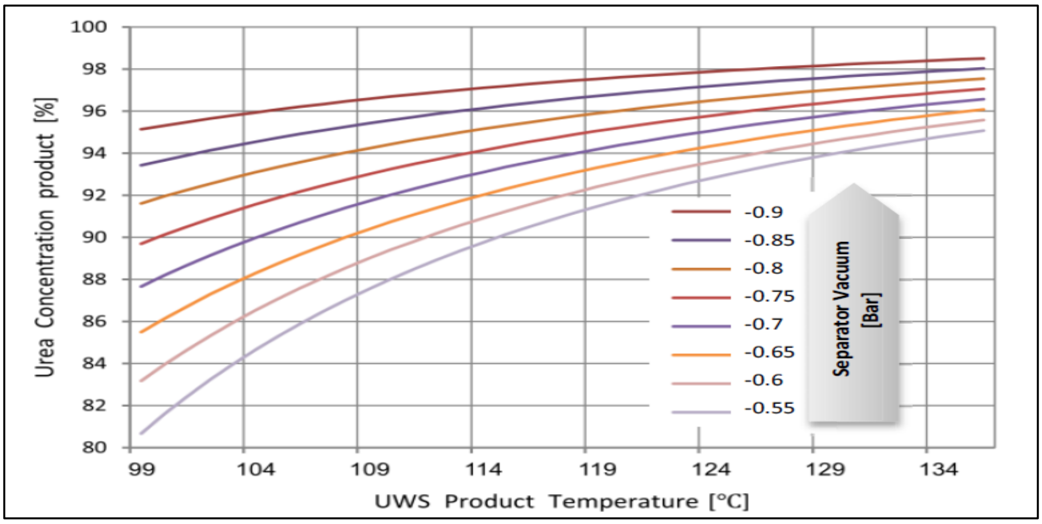



**Figure 3.5: Urea/Water Equilibrium Phase Relation from Literature (Fahmy et al., 2015)**

## 3.5 Implementation of PID Controller and Tuning of PID Controller

1. A PID controller block is built in the Simulink program as shown in Figure 3.6 below.

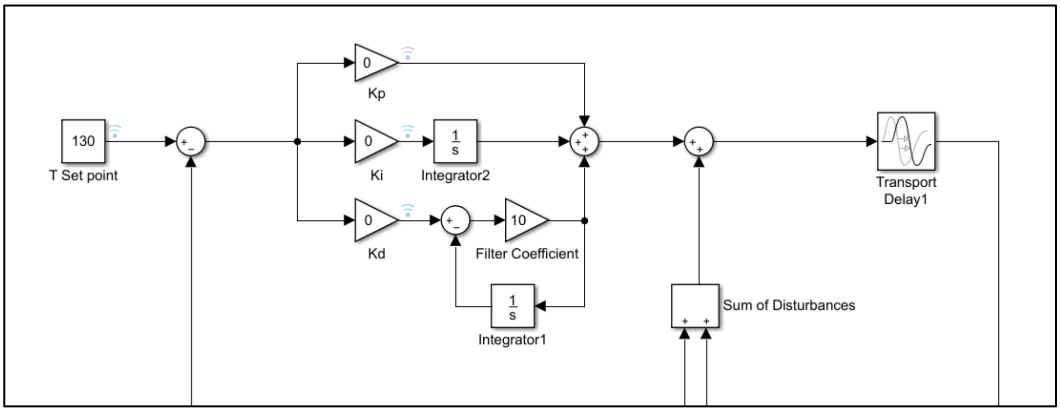



**Figure 3.6: PID Controller Block**

2. Few disturbances were introduced to the vacuum evaporator simulation such as flow variation of input fluid and inlet temperature of process stream.
3. A step change was performed on the manipulated variable and the values of time constant, time delay and process gain are obtained from the resulting process reaction curve.

4. Cohen-Coon tuning method is used to obtain the values of the tuning parameters. The Cohen-Coon tuning method is shown in table below:

**Table 3.4: Cohen-Coon tuning method**

| Controller | Kc | $\tau_I$ | $\tau_D$ |
|---|---|---|---|
| P | $\frac{1}{K_p}\frac{\tau}{\tau_d}(1 + \frac{\tau_d}{3\tau})$ | - | - |
| PI | $\frac{1}{K_p}\frac{\tau}{\tau_d}(\frac{9}{10} + \frac{\tau_d}{12\tau}$ | $\tau_d\frac{30 + 30\tau_d/\tau}{9 + 20\tau_d/\tau}$ | - |
| PID | $\frac{1}{K_p}\frac{\tau}{\tau_d}(\frac{4}{3} + \frac{\tau_d}{4\tau})$ | $\tau_d\frac{32 + 6\tau_d/\tau}{13 + 8\tau_d/\tau}$ | $\tau_d\frac{4}{11 + 82/\tau}$ |

5. Tuning parameters of PID controller are inserted in PID blocks in Simulink block diagram to manipulate the flow rate of supplied steam in order to maintain the UWS product temperature.
6. Run the simulation.
7. Observe the result whether P, PI or PID controller able to reach the setpoint at temperature 130˚C.