Control of Reaction Temperature in Continuous Stirred Tank Reactor for Production of Ethyl Acetate

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B.Sc. (Honors) in Chemical Engineering Technology
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A Dissertation

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Chemical Engineering

Department of Chemical Engineering and Chemical Technology
Faculty of Engineering and Technology

November, 2018
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Mahasen Adam Issmail Abdallah

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Date: November, 2018
Control of Reaction Temperature in Continuous Stirred Tank Reactor for Production of Ethyl Acetate

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Date of Examination : 10 / 11 /2018
Dedication

To my beloved family, teachers and friends for their limitless support and encouragement,
I express my gratitude for the honest feelings; I dedicate this work to them.
Acknowledgements

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Control of Reaction Temperature in Continuous Stirred Tank Reactor for Production of Ethyl Acetate  
Mahasen Adam Issmail Abdallah  
M.S.c in Chemical Engineering (2018)  
Department of Chemical Engineering and Chemical Technology  
Faculty of Engineering and Technology  
University of Gezira  

Abstract  
Cascade control is commonly used to maintain the chemical processes conditions at their desired values by manipulating process variables of interest and to reduce the effect of the disturbances that have a rapid effect on a secondary measured variable, before the primary controlled variable is affected. A continuous stirred tank reactor (CSTR) surrounded by a jacket with specific dimensions is used for an exothermic reaction for the production of ethyl acetate from the reaction of acetic acid and ethanol. The objective of this research is to control the reaction temperature of the exothermic CSTR to obtain the optimum product using cascade control. The stability analysis and tuning of the developed control system applied for the reactor was studied using MATLAB software. Two control loops have been determined; the purpose of the Primary loop was to control the reactor temperature, while the secondary loop was used to control the coolant flow rate. The transfer functions for the two loops were identified from previous studies and references. The ultimate gains for the primary and secondary control loops were determined using different methods: Direct Substitution, Routh-Hurwitz, Bode and Root-locus methods. The controllers of the primary and secondary loops were tuned using Ziegler-Nichols techniques. The continuous stirred tank reactor stability was determined, analyzed and investigated using the same above techniques. The ultimate parameters for control loops showed that Root-Locus tuning method gave the highest gains: k=17.20 for the secondary control loop while direct substitution tuning method gave the highest gains: k=2.92 for the primary control loop. The highest gain was selected to obtain the best performance and high sensitivity. The proper controller mode selected according to the method was based on selecting one that gives the best performance with respect to minimum overshoot; its due to the fact that high overshoot may be dangerous, such as high temperature in a CSTR which may damage the reaction, thus it protects the reactor from temperature disturbances. The controller that gave minimum overshoot was selected it’s a PID-controller for the secondary loop (Slave loop) and a P-controller for the primary loop (Master loop). For further studies it is recommended that the same procedure of the analysis has to be applied from continuous time to discrete time (digital).
التحكم في درجة حرارة التفاعل في مفاعل خزان التحريك المستمر لإنجاز خلات الإيثل.

محاسن آدم إسماعيل عبد الله
ماجستير العلوم في الهندسة الكيميائية (2018م)
قسم الهندسة الكيميائية وتكنولوجيا الكيمياء
كلية الهندسة والتكنولوجيا
جامعة الجزيرة

مستخلص الدراسة

يستخدم التحكم المتتالي عادةً للحفاظ على أهداف التحكم عند القيم المرغوبة عن طريق متغيرات العملية ذات القيمة ووظائف تأثير الاضطرابات التي لها تأثير سريع على متغير تم قياسه ثانويًا، قبل أن يتم التبديل المتغير الأساسي (CSTR) المحاط بغلاف ذو أبعاد محددة لتفاعل الطارد للحرارة لإنجاز خلات الإيثل المنتج من تفاعل حمض الخليك والكحول الإيثل (الابتانول). الهدف من هذا البحث هو التحكم في درجة حرارة التفاعل الطارد للحرارة (CSTR) للحصول على المنتج الأمثل باستخدام التحكم المتتالي. تمت دراسة تحديد الاستقرار وضبط نظام التحكم المطبق على المفاعل باستخدام برنامج MATLAB. تم تحديد دائرة التحكم (تعقبية) امامية وعكسية. ان الغرض من دائرة التحكم الأولية (الحلقة الإيثلانية) هو التحكم في درجة حرارة المفاعل، في حين تم استخدام دائرة التحكم الثانوية للتحكم في معدل تدفق المبرد. تم تحديد دوال الانتقال (الدوال التحويلية) من الدوارات والمراجع السابقة. تم تحديد المكاسب الجهادية لدائري التحكم الأولية والثانية باستخدام طرق مختلفة وهي التعويض المباشر و Root-Locus. وتم ضبط المتغيرات لدائري التحكم الأولية والثانية باستخدام تقنية Ziegler-Nichols و Root-Locus. وتم تحديد استقرار مفاعل خزان التحريك المستمر و من ثم تحليلها والتحقق منها باستخدام الطرق المذكورة أعلاه، ومن خلال المقارنة للمكاسب النهائية لدوائر التحكم وجد أن طريقة Root-Locus النهائية لدائرة التحكم الثانوية أعطت أعلى مكسب هو: $k = 24.9$ لدائرة التحكم الأولية وبناءً على ذلك تم اختيار أعلى مكسب للحصول على أفضل أداء واعتو حساسية. ومن ثم تم اختيار التحكم المناسب التي تؤدي إلى احسن اداء مع توقع أقل بالنسبة لمقدار الحد الأدنى من التجاوز (overshoot) علماً بأن ارتفاع الحد الإلخى من التجاوز قد يؤدي إلى خطورة، مثل ارتفاع درجة الحرارة في مفاعل خزان التحريك المستمر (CSTR) قد يؤدي إلى ضرر في التفاعل، وبالتالي الحد الأدنى من التجاوز يحمي المفاعل من اضطرابات درجة الحرارة. من خلال الدراسة تم اختيار المحاكاة التي تعطى الحد الإلخى من التجاوز وهي المحاكاة P لدائرة التحكم الثانوية (slave loop) والمحاكاة PID لدائرة التحكم الأولية (Master loop).

توصي الدراسة باستخدام نفس الإجراء في التحليل بالتحويل من نظام التحكم المستمر إلى نظام التحكم الرقمي.
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Chapter One

1. Introduction

1.1: Background

The schemes used for reactor control depend on the process and the type of reactor. If an on-line analyzer is available, and the reactor dynamics are suitable, the product composition can be monitored continuously and the reactor conditions and feed flows controlled automatically to maintain the desired product composition and yield. More often, the operator is the final link in the control loop, adjusting the controller set points to maintain the product within specification, based on periodic laboratory analyses. Reactor temperature will normally be controlled by regulating the flow of the heating or cooling medium. Pressure is usually held constant. Material balance control will be necessary to maintain the correct flow of reactants to the reactor and the flow of products and unreacted materials from the reactor (Sinnott, 1998).

1.2: Background of Project

The control of chemical reactors is one of the most challenging problems in control processes. Considering that a CSTR is the heart of many processes, its stable and efficient operation is of paramount importance to the success of an entire process. Many reactors are inherently unstable. The instability appears when irreversible exothermic reactions are carried out in a CSTR. These reactions tend to produce a large increment in temperature, forcing the rupture of safety and reducing the lifetime of the reactor. The solution to this problem is a temperature control system capable of detecting the rising of the reactor temperature and quickly removing heat from the reactor. As the processes requirements tighten, or in processes with slow dynamics, or in processes with too many or frequently occurring upsets, the control performance provided by feedback control may become unacceptable. Cascade control is a strategy that in some applications significantly improves the performance provided by feedback control (Carlos, 2006).
With this arrangement, the output of one controller is used to adjust the set point of another. Cascade control can give smoother control in situations where direct control of the variable would lead to unstable operation. The “slave” controller can be used to compensate for any short-term variations in, say, a service stream flow, which would upset the controlled variable; the primary (master) controller controlling long-term variations (Sinnott, 1998).

1.1. Chemical Reactor
The chemical reactor must be regarded as the heart of a chemical process. It is the piece of equipment in which conversion of feed stock to the desired product takes place and is thus the single irreplaceable component of the process (Smith, 1982).

1.1.2 Non-Isothermal Operations
Chemical reactions are either exothermic (release energy) or endothermic (require energy) and therefore require that energy either be removed or added to the reactor for constant temperature to be maintained. (Smith, 1982).

1.1.3 Exothermic Reactions
An exothermic reaction is a chemical reaction that releases energy in the form of heat; it is the opposite of an endothermic reaction. Expressed in a chemical equation;
Reactants $\rightarrow$ Products $+$ Energy

An exothermic reaction is a chemical reaction that is accompanied by the release of heat, in other words, the energy needed for the reaction occurs is less than the total energy released. As a result, this extra energy is released in the form of heat. When using a calorimeter, the change in heat of the calorimeter is equal to the opposite of the change in heat of the system; this means that when the medium in which the reaction is taking place gains heat, the reaction is exothermic. The absolute amount of heat in a chemical system is extremely difficult to measure or calculate. The enthalpy change, $\Delta H$, of a chemical reaction is much easier to measure and calculate. A bomb calorimeter is very suitable for measuring the energy change, $\Delta H$ of a combustion reaction. Measured and calculated $\Delta H$ values are related to bond energies by $\Delta H = \text{energy used in bond breaking} - \text{energy released in bond making products}$.

Definition: the enthalpy has a negative value $\Delta H < 0$. For an exothermic reaction, this gives a negative value for $\Delta H$ since a large value (the energy released in the reaction) is subtracted from a smaller value (the energy used for the reaction) (Smith, 1982).

![Energy diagram](image)

**Figure (1-2): Energy used for the reaction (Smith, 1982).**

### 1.1.4 Reactor Temperature Control

The amount of heat generated by an exothermic reactor increases as the reaction temperature rises. If the operation without temperature controller (in an open loop configuration), an increase in the reaction temperature will also increase that removal, because of the increase in temperature difference between process and coolant temperature. If an increase in the reaction temperature results in a greater increase in the heat generation that in heat removal, the process is
said to display positive feedback as such it is considered to be unstable in the open loop. The positive feedback of the open process can be compensated by the negative feedback of a reactor temperature controller, which will increase the heat removal rate of the temperature rises. (Luyben, 1990).

1.2 Advanced control system

1.2.1 Control systems with multiple loops

The feedback control configuration involves one measurement (output) and one manipulated variable in a single loop. There are other simple control configurations which may be used. If there are more than one measurement and one manipulated variable or one measurement and more than one manipulated variables in such case the control systems with multiple loops may arise. Typical example is the cascade control (Gasmelseed, 2016).

1.2.2 Cascade control

Cascade control uses the output of the primary controller to manipulated the set point of the secondary controller as if it were the final control element. (Ramirez, 1997).

In a cascade control configuration we have one manipulated variable and more than one measurement (Gasmelseed, 2016).

1.2.3 The final control element

These are hard where components of the control loop that implement the control action. They receive the output of a controller (actuating signal) and adjust according the value of the manipulated variable. The most common final control element is the pneumatic (Ramirez, 1997).

1.2.4 Heat cooling system (jacket)

Product within the reactor usually liberate or absorb heat during processing, even the action of stirring caused liquid to generate heat in order to hold the reactor contents at the desired temperature, heat has to be added or removed by a cooling jacket or cooling pipe. Heat/cooling coil or external jackets are used for heating and cooling reactors. Heat transfer fluid passes through the jacket or coils to added or remove heat (Ramirez, 1997).

1.2.5 Temperature sensors

The most common are the thermocouples resistance bulb thermometer and thermostat. All provide measurements in terms of electrical signals the temperature sensing element is always inside the thermo well (Ramirez, 1997).
1.2.6 Digital control

**Z-Transforms**

The use of Z-Transforms offers a very simple and elegant method for solving linear difference equations that result from the conversion of continuous-to-discrete time models. Z-Transforms play the same role for discrete-time systems as that played by Laplace transforms for dynamic analysis and design of continuous open or closed loops systems (Gasmelseed, 2016) a.

1.3 The Problem Statement

Ethyl acetate is used as a solvent for many purposes and needs to be at a high purity. This high purity can’t be realized unless a robust cascade and digital control systems are applied.

1.4 Ethyl Acetate and it’s Applications

Production of ethyl acetate from ethanol and acetic acid. Ethyl acetate has high purity and this is required cascade and digital in analyzing this system we use Routh-Hurwitz, Direct substitution, Root-locu Bode, and Ziegler-Nichols methods for both the cascade and digital systems. Ethyl acetate is the organic compound with the formula CH\(_3\)COOC\(_2\)H\(_5\). This colourless liquid has a characteristic, pungent smell like certain glues or nail polish removers, in which it is used. Ethyl acetate is the ester from ethanol and acetic acid; it is manufactured on a large scale for use as a solvent. Ethyl acetate is a moderately polar solvent that has the advantages of being volatile, relatively non-toxic, and non-hygroscopic. It is a weak hydrogen bond acceptor, and is not a donor due to the lack of an acidic proton. Ethyl acetate can dissolve up to 3% water and has a solubility of 8% in water at room temperature. It is unstable in the presence of strong aqueous bases and acids. It is soluble in most organic solvents, such as alcohol, acetone, ether and chloroform.

1.4.1 Properties of Ethyl Acetate

Molecular formula CH\(_3\)COOC\(_2\)H\(_5\)
Molar mass 88.105 g/mol
Density 0.897 g/cm\(^3\)
Melting point -83.6 °C
Boiling point 77 °C
Viscosity 0.426 cp at 25°C.
1.5 Applications of Ethyl Acetate

1.5.1 Surface Coating and Thinners
Ethyl acetate is one of the most popular solvents and finds wide use in the manufacture of nitrocellulose lacquers, varnishes and thinners, to dissolve the pigments for nail varnishes. It exhibits high dilution ratios with both aromatic and aliphatic diluents and is the least toxic of industrial organic solvents. (Marek, 1956).

1.5.2 Pharmaceuticals
Ethyl acetate is an important component in extractants for the concentration and purification of antibiotics. It is also used as an intermediate in the manufacture of various drugs (Marek, 1956).

1.5.3 Flavours and Essences
Ethyl acetate finds extensive use in the preparation of synthetic fruit Essences, flavours and perfumes (Marek, 1956).

1.5.4 Flexible packaging
Substantial quantities of ethyl acetate are used in the manufacture of flexible Packaging and in the manufacture of polyester films and BOPP films. It is also used in the Treatment of aluminium foils (Marek, 1956).

1.5.5 Miscellaneous
Ethyl acetate is used in the manufacture of adhesives, cleaning fluids, inks, nail polish removers and silk, coated papers, explosives, artificial leather, photographic films & plates. In the field of entomology, ethyl acetate is an effective poison for use in insect collecting and study. In a killing jar charged with ethyl acetate, the vapours will kill the collected (usually adult) insect quickly without destroying it. Because it is not hygroscopic, ethyl acetate also keeps the insect soft enough to allow proper mounting suitable for a collection (Marek, 1956).

1.6 Objectives
- Development of conventional control system using cascade advance control.
- Stability analysis and tuning of the cascade control.
- Selection of the type of controller depending on minimum overshoot for the CSTR for production of ethyl acetate.
- Simulation of the CSTR at the optimum parameters.
Chapter Two

2. Literature Review

2.1 Production of Ethyl Acetate

Ethyl acetate is produced by the esterification reaction of ethyl alcohol and acetic acid using catalysts such as sulphuric acid, Para toluene euphonic acid or ion exchange resins. The reaction of ethanol (EtOH) with acetic acid (AcOH) towards ethyl acetate (EtAc) and water (H2O) is an equilibrium reaction.

\[
\text{CH}_3\text{COOH} + \text{C}_2\text{H}_5\text{OH} \rightarrow \text{H}_2\text{O} + \text{CH}_3\text{COOC}_2\text{H}_5 \]

.......................................................... (1)

(Suzuki et al., 1971).

2.2 Reactors Types

There are two main basic vessel types:

-A tank

-A pipe

Both types can be used as continuous reactors or batch reactors. Most commonly, reactors are run at steady-state, but can also be operated in a transient state. When a reactor is first brought back into operation (after maintenance or in operation) it would be considered to be in a transient state, where key process variables change with time. Both types of reactors may also accommodate one or more solids (reagents, catalyst, or inner materials), but the reagents and products are typically liquid or gases. There are three main basic models used to estimate the most important process variable of different chemical reactors:

1. Batch reactor model (batch),
2. Continuous stirred-tank reactor model (CSTR),
3. Plug flow reactor model (PFR).

Furthermore, catalytic reactors require separate treatment, whether they are batch, CSTR, PF reactors, as the many assumption of the simpler models are key process variables include not valid. (Maumas, 2002).

-Residence time (t, lower case Greek tau).
- Volume (v).
- Temperature (T).
- Concentrations of chemical species (C₁, C₂, C₃, ⋯ Cₙ).
- Heat transfer coefficients (h, U).

2.1.1 CSTR (Continuous Stirred-Tank Reactor)

In a CSTR (Continuous Stirred-Tank Reactor), one or more fluid reagents are introduced into a tank reactor equipped with an impeller while the reactor effluent is removed. The impeller stirs the reagents to ensure proper spending inside the tank. Using chemical kinetics, the reaction’s expected percent completion can be calculated.

- Some important aspects of the CSTR:

  At steady-state, the flow rate at must equal the mass flow rate out, otherwise the tank will overflow or go empty (transient state). While the reactor is in a transient state, the model equation must be derived from the differential mass and energy balances.

  - The reaction proceeds at the reaction rate associated with the final (output) concentration.

  - Often, it is economically beneficial to operate several CSTRs in series. This allows, for example, the first CSTR to operate at a higher reagent concentration and therefore a higher reaction rate.

  - In these cases, the size of the reactors may be varied in order to minimize the total capital investment required to implement the process. It can be seen that an infinite number of infinite small CSTRs operating in series would be equivalent to a PFR.

  - The behavior of a CSTR is often approximated or modeled by that of a continuous ideally stirred-tank reactor (CSTR). All calculations performed with CSTRs assume perfect mixing. If the residence time is about 5-10 times the mixing time, this approximation is valid for engineering purposes.

  - The CSTR model is often used to simplify engineering calculations and can be used to describe research reactors.

  - In practice, it can only be approached, in particular in industrial size reactors.

Usage:
- When intense agitation is required
- Can either be used by itself or in a series or a battery of CSTRs

Advantages:
- Used primarily for liquid phase reactions

Disadvantages:

Very large CSTR reactors are necessary to obtain high conversion (Levenspiel, 1999)

2.1.2 PFR (plug Flow Reactor)

In a PFR, one or more fluid reagents are pumped through a pipe or tube. The chemical reaction proceeds as the reagents travel through the PFR. In this type of reactor, the changing reaction rate creates a gradient with respect to distance traversed, at the inlet to the PFR the rate is very high, but as the concentrations of the reagents decrease and the concentration of the product(s) increases the reaction rate slows. Some important aspects of the PFR:

All calculations performed with PFRs assume no upstream or downstream mixing, as implied by the term “plug flow”. Reagents may be introduced into the PFR at locations in the reactor other than the inlet. In this way, a higher efficiency may be obtained, or the size and cost of the PFR may be reduced.

A PFR typically has a higher efficiency than a CSTR of the same volume, that is, given the same space–time, a reaction will proceed to a higher percentage completion in a PFR than in a CSTR. For most chemical reactions, it is impossible for the reaction to proceed to 100% completion. The rate of reaction decreases as the percent completion increases until the point where the system reaches dynamic equilibrium (no net reaction, or change in chemical species occurs). The equilibrium point for most systems is less than 100% complete. For this reason a separation process, such as distillation, often follows a chemical reactor in order to separate any remaining reagents or byproducts from the desired product. These reagents may sometimes be reused at the beginning of the process, such as in the Haber process.

Continuous oscillatory baffled reactor (COBR) is a tubular plug flow reactor. The mixing in COBR is achieved by the combination of fluid oscillation and orifice baffles, allowing plug to be achieved under laminar with the net flow Reynolds number just about 100.

Usage:
Used most often for gas phase reactions
One long tube OR number of shorter tubes arranged in a tube bank

Advantages:
Easy to maintain (No moving parts)
The highest conversion per reactor volume of any of the flow reactors

Disadvantages:
Difficult to control temperature within the reactor
Hot spots can occur when the reaction is exothermic. Most homogeneous gas phase flow reactors are tubular PFRs, whereas most homogenous liquid phase flow reactors are CSTRs (Levenspiel, 1999).

### 2.1.3 Batch reactor

**Usage:**
- Small-scale operation
- Testing new processes
- Manufacture of expensive products
- Processes that are difficult to convert to continuous operations

**Advantages:**
- High Conversion

**Disadvantages:**
- High Labor Cost per batch cost
- Difficulty of Large Scale Production
- The variability of products from batch to batch
  
  (Levenspiel, 1999)

### Semi-Batch Reactor

A semi-batch reactor is operated with both continuous and batch inputs and outputs. A fermented, for example, is loaded with a batch, which constantly produces carbon dioxide, which has to be removed continuously, analogously, driving a reaction of gas with a liquid is usually difficult, since the gas bubbles off. Therefore, a continuous feed of gas is injected into the batch of a liquid. An example of such a reaction is chlorination.

**Disadvantages:**
- High Labor Cost per batch cost
- Difficulty of Large Scale Production

**Advantages:**
- Good temperature control
- Capability of minimizing unwanted side reaction

Used for two phase reactions (Levenspiel, 1999)
2.1.4: Catalytic Reactor

Although catalytic reactors are often implemented as plug reactors, their analysis requires more complicated treatment. The rate of a catalytic reaction is proportional to the amount of catalyst the reagents contact with a solid phase. Catalyst and fluid phase reagents, this is proportional to the exposed area, efficiency of diffusion of reagents in and products out, and turbulent mixing or lack thereof. Perfect mixing cannot be assumed. Furthermore, a catalytic reaction pathways is often multi-step with intermediates that are chemically bound to the catalyst; and as the chemical binding to the catalyst is also a chemical binding to the catalyst is also a chemical reaction, it may affect the kinetics. The behavior of the catalyst is also a consideration. Particularly in high temperature petrochemical processes, catalyst are deactivated by sintering, may affect the kinetics (Maumas, 2002).

Control System

There are a number of basic factors that have direct influence on the control of an operating process system. In a manual control system, these factors are normally performed by a human operator. Automatic systems achieve the same basic functions but through the manipulation of self-regulating controls. As a rule, automatic control operations are much more complex and difficult to achieve than those of a manual system control. The basic functions of system control include measurement, comparison, computation, and correction. Measurement is essentially an estimate or appraisal of the process being controlled by the system. Comparison is an examination of the likeness of measured values and desired values. Computation is a calculated judgment that indicates how much the measured value and desired operating value differs. Correction is the adjustments which are made in order to alter operating values to a desired level. These functions must all be achieved by an automatic system during the normal course of its operation (Patrick and Fardo, 2009).

1.3 Process Control

Control systems are tightly intertwined in our daily lives, so much that we take them for granted. They may be as low-tech and unglamorous as our flush toilet. Or they may be as high-tech as electronic injection in our cars. In fact, there are more than a handful of computer control systems in a typical car that we now drive. Everything from the engine to transmission, shock absorber, brakes, pollutant emission, temperature and so forth, there is an embedded microprocessor controller keeping an eye out for us. The more gadgetry, the more tiny
controllers pulling the trick behind our backs. At the lower end of consumer electronic devices, we can bet on finding at least one embedded microcontroller. In the processing industry, controllers play a crucial role in keeping our plants running—virtually everything from simply filling up a storage tank to complex separation processes, and to chemical reactors.

What are some of the issues when we design a control system? In the first place, we need to identify the role of various variables. We need to determine what we need to control, what we need to manipulate, what are the sources of disturbances, and so forth. We then need to state our design objective and specifications. It may make a difference whether we focus on the servo or the regulator problem, and we certainly want to make clear, quantitatively, the desired response of the system. To achieve these goals, we have to select the proper control strategy and controller. To implement the strategy, we also need to select the proper sensors, transmitters, and actuators. After all is done, we have to know how to tune the controller. Sounds like we are working with a musical instrument, but that's the jargon. The design procedures depend heavily on the dynamic model of the process to be controlled. In more advanced model-based control systems, the action taken by the controller actually depends on the model. Under circumstances where we do not have a precise model, we perform our analysis with approximate models. This is the basis of a field called "system identification and parameter estimation." Physical insight that we may acquire in the act of model building is invaluable in problem solving (Chau, 2001).

For further classification of the term into more workable divisions. Control is first classified as being either manual or automatic. This division generally refers to the amount of human effort needed to achieve a common function. Manual control is voluntarily initiated within the system with very little human effort. The terms open-loop and forward-feed are frequently used to describe manual control systems. Valve adjustments and switching functions are examples of manual control operations. In general, this type of control is achieved by some degree of physical effort on the part of a human operator. Automatic control, by comparison, applies to those things that are achieved, during normal operation, without human intervention. This type of control is used where continuous attention to system operation would be demanded for a long period without interruptions. Automatic control does not, however, necessarily duplicate the type of control achieved by a human operator. Equipment that employs automatic control is limited to
only those things that can be forecast by the input data. Terms such as closed-loop control and feedback are commonly used to describe automatic control functions (Chau, 2001).

2.3.1 Open-loop Control

Open-loop control is relatively easy to achieve because it does not employ any automatic equipment to compare the actual output with the desired output. In manufacturing, open-loop operations are achieved by adjustment of the system to some predetermined setting by a human operator.

The system then responds to this setting without any modification. Any changes made in operation are based entirely on some outside human judgment to correct the desired output. The open-loop system in Figure 2-1 is composed of a process energy source, a transmission path, a controller, and an actuator or final control element. The process energy source represents input variables such as time, temperature, speed, pressure, flow, displacement, acceleration, and force. The transmission path is responsible for transferring input energy to the remainder of the system. The controller provides intelligence for the system and governs the action of the actuator. The manual set point adjustment attached to the controller is used to alter the operating range of the controller. The actuator implements the response of the controller to the final controller element. The final control element can be a motor, pneumatic cylinder, solenoid, or hydraulic valve. The final control element is responsible for altering the process energy passing through the system. The output is considered to be the controlled process. Examples of controlled processes are water temperature, the pH of a chemical solution, the viscosity of crude oil, the temperature of molten aluminum in a furnace, or the path of a cutting tool on a milling machine.

![Diagram of Open-loop control system](image)

**Fig (2.1): Open-loop control system** (Chau, 2001).
A period of time is required before any corrective action takes place. If the amount of correction is too great or not enough, the process will need to be repeated. In manual systems of this type, control involves repeated steps of measurement, comparison, computing, and correction. This means that manual control usually demands continuous supervision by the operator, which is a decided disadvantage of this type of system. The primary advantage of open-loop or manual control is simplicity of operation and low-cost installation. The intended accuracy of the process being controlled determines its suitability for manual control. In a strict sense, the operator of a manual control system forms the feedback path from output to input that closes the loop of the control system (Patrick and Fardo, 2009).

2.3.2 Closed-loop Control

Closed-loop refers to a type of system that is self-regulating. In this type of system, the actual output is measured and compared with a predetermined output setting. A feedback signal generated by the output sensing component is used to regulate the control element so that the output conforms to the desired value. The term feedback refers to the direction in which the measured output signal is returned to the control element. In a sense, the output of this type of system serves as the input signal source for the feedback control element. Closed-loop control is so named because of the return path created by the feedback loop from the output (Patrick and Fardo, 2009).

Fig (2.2): automatic feedback system (Patrick and Fardo, 2009).

A brief explanation of some common terms associated with process control is presented here as a general review.
Process—Activities performed on raw materials or work pieces to convert them into a finished product are called processes. A process could also be described as an operation utilized to achieve an industrial manufacturing function, such as pressure, temperature, flow, liquid level, mechanical motion, numbers, weight, specific gravity, viscosity, and numerous analytical values.

Controlled Variable—Controlled variables are the basic process values being manipulated by a system. These values may vary with respect to time, as a function of other system variables, or both.

Controllers—A controller is a hardware piece of equipment that employs pneumatic, electronic, and/or mechanical energy to perform a system control operation. These units are designed to maintain a process variable at a predetermined value by comparing its existing value to that of a desired system value.

Set point—A set point is a prescribed or desired value to which the controlled variable of a process system is manually adjusted. It is indicated on the horizontal set point indicator.

Sensor—A sensor is a piece of equipment that is used to measure system variables. Sensors are normally transducers that change energy of one form into something different. Sensors serve as the signal source in automatic control systems.

Control Element—A control element is a part of the process control system that exerts direct influence on the controlled variable to bring it to the set point position. This element accepts output from the controller and performs some type of operation on the process. The term final control element is used interchangeably with control element (Patrick and Fardo, 2009).

2.3.3 Modes of Control

The operational response of a controller is often described as its mode of control. Several different types of control are available. In some cases, only a single mode of control is needed to accomplish an operation. This is described as a pure control operation. On-off, proportional, integral, and derivative are examples of pure control.

More sophisticated control is achieved by combining two or more pure modes of operation. This is described as a composite mode. Proportional plus integral, proportional plus derivative, and proportional plus integral plus derivative are examples of composite control modes (Patrick and Fardo, 2009).
2.3.3.1 On-off Operation

An on-off or two-state controller is the simplest of all process control operations. The actuator or final control element driven by the output of the controller is automatically switched on or off. It does not have any intermediate level of operation. Control of this type is popular and inexpensive to accomplish (Patrick and Fardo, 2009).

2.3.3.2 Proportional Control

In on-off control, the final control element was either on or off. If the control element were a valve, it would have been fully open or closed. There is no intermediate adjustment of the valve. In proportional control, the final control element can be adjusted to any value between fully open and fully closed. Its value is determined by a ratio of the setpoint input and the actual process value of the system. In a valve-controlled system, operation is arranged so that the valve is normally adjusted to some percentage of its operating range. Proportional control is defined mathematically as

\[ V_{\text{out}} = K_p \cdot V_e \]

Where:
- \( V_{\text{out}} \) = controller output
- \( K_p \) = proportional controller gain
- \( V_e \) = error signal, or \( V_{\text{sp}} - V_{pv} \)

As a rule, proportional control works well in systems where the process changes are quite small and slow.

As a rule \( G(c) = K_c \) (Gasmelseed, 2016) a., proportional control works well in systems where the process changes are quite small and slow. A disadvantage of proportional control is that it does not respond well to long-term or steady-state changes in the process being controlled. A change or disturbance will not let the process return exactly to its pre-disturbance value. This means that the process will have a difference in its new value. This is called an offset. It represents a new process value that is slightly less than the set point value. Offsets may or may not be acceptable for some industrial systems. The offset problem can be reduced by combining other modes of control with proportional controllers (Stephan, Opoulus, 1994).
2.3.3.3 Integral Control
The output of a controller is used to actuate the final control element to eliminate any difference between the set point and actual values of an operating system. This difference is commonly called the error signal. A controller is designed to eliminate system error. In proportional control, the output was adjusted proportionally to correct the system error. As a rule, this type of control produces an offset problem in the output.

An integral controller has an output whose rate of change is proportional to the system error signal. As long as there is an error, the output will continue to change to correct it. When the error is zero, the integral controller maintains the output at this value until a new error occurs. This means that an integral controller has inertia: It has a tendency to hold the output which was necessary to eliminate the error signal applied to its input.

Integral control is continuous, and the output changes at a rate proportional to the magnitude and duration of the error signal. When there is a large error signal, the output changes rapidly to correct the error. As the error gets smaller, the output changes more slowly. This action is done to minimize the possibility of overcorrection. As long as there is an error, the output will continue to change. Mathematically, this is expressed

\[ \frac{\Delta V_{out}}{\Delta t} = K_i \cdot V_e \]

or \[ \Delta V_{out} = K_i \cdot V_e \cdot \Delta t \]

where \( \Delta V_{out} \) = controller output voltage
\( \Delta t \) = time rate of change
\( K_i \) = integration constant
\( V_e \) = error voltage

2.3.3.4 Derivative Control
Many controllers have an inertia or hysteresis problem. In the water temperature control system for example in it takes some time for steam to increase the temperature of the water. This means that there is a delay between the application of steam and the water temperature rising to a new value. The significance of this is that an error will not cause an immediate deviation from the set point value. When an error is detected by the system, it responds just as slowly to the corrective action. To overcome this sluggish characteristic, some exaggerated corrective action must be taken. If a controller produces a large corrective signal in response to a minute error, the system
will be brought into control more quickly. This occurs even if the system has a large amount of inertia. However, if the corrective action remains large, the controller will overcompensate for the error. This could cause the unit to break into oscillation. A more desirable corrective action is one that is initially large but drops off with time. This is a characteristic of the derivative controller.

A basic element of the derivative controller is a differentiator circuit. A differentiator works in proportion to the rate of change of its input. Electronically, this is determined by the product of circuit resistance and capacitance. Mathematically, the output of a derivative controller is expressed as

\[ V_{out} = K_p \cdot \Delta V_e / \Delta t \]

Where:

- \( K_d \) = derivative gain
- \( \Delta V_e \) = change in error voltage
- \( \Delta t \) = change in time rate (Stephan, 1994).

\[ G(c) = K_c (1 + \frac{1}{t_d S}) \]

(Gasmelseed, 2016) a.

**2.3.3.5 Proportional plus Integral plus Derivative Control**

When proportional, integral, and derivative control operations are The PID controller is a unique instrument that is widely used to control a number of difficult processes with a great deal of precision. This type of controller is generally more expensive than other units, and it is more difficult to prepare for operation. In some instruments, each mode of operation can be selected for independent use by programming in the desired operation. Each mode of control must be individually adjusted or tuned to make it functional. PT and PD control can also be accomplished by instrument programming. PID controllers are generally not used for all controller applications today. Controller selection is determined by such things as the amount of precision control needed, the difficulty of the process being controlled, the initial set-up and tuning procedure, the characteristics of the process being controlled, and the initial cost of the controller

\[ G(c) = K_c (1 + \frac{1}{t_d S}) \]

(Gasmelseed, 2016) a.
2.3.4 Pressure Control
Pressure control refers to those functions that alter the pressure level of an operating system. Such operations include relieving, reducing, bypassing, sequencing, and counterbalance. As a general rule, control devices of this type are named according to the function they achieve.

2.3.5 Flow Control
The sensing elements of a flow meter are either of the inferential type or they deduce an output by direct displacement of quantities. The output signal of the sensing element may be either mechanical or electrical, depending on the type of sensor employed.

2.3.6 Sensors Control
Sensor-element operation is an extremely important consideration when selecting a thermal system controller for a specific application. Such things as response time, temperature operating range, resolution sensitivity, and repeatability are dependent on the sensor element. In addition, the physical size of the sensor has a great deal to do with component location and installation design procedures.

2.3.7 Temperature Controllers
Are used in heat systems to achieve the control function. A controller senses system temperature and decides on the amount of heat needed to meet the demands of the operating set point. Controller accuracy is determined by temperature gradients, thermal lag, component location, and controller selection.

2.3.8 Level Control
Equipment used to determine the level of a storage tank is based on the operating principle of the sensing element. This element is responsible for detecting a change in level and generating a signal that is used to correct the problem. In general, level systems will respond to either mechanical, pneumatic, electrical, radiation, or ultrasonic information (Patrick and Fardo, 2009).

Production Controls
The nature of the production control logic differs greatly between continuous and batch plants. A good example of production control in a continuous process is refinery optimization. From the assay of the incoming crude oil, the values of the various possible refined products, the contractual commitments to deliver certain products, the performance measures of the various units within a refinery, and the like, it is possible to determine the mix of products that optimizes
the economic return from processing this crude. The solution of this problem involves many relationships and constraints and is solved with techniques such as linear programming. In a batch plant, production control often takes the form of routing or short-term scheduling. For a multi-product batch plant, determining the long term schedule is basically a manufacturing resource planning (MRP) problem, where the specific products to be manufactured and the amounts to be manufactured are determined from the outstanding orders, the raw materials available for production, the production capacities of the process equipment, and other factors. The goal of the MRP effort is the long-term schedule, which is a list of the products to be manufactured over a specified period of time (often one week). For each product on the list, a target amount is also specified. To manufacture this amount usually involves several batches. The term “production run” often refers to the sequence of batches required to make the target amount of product, so in effect the long term schedule is a list of production runs. Most multiproduct batch plants have more than one piece of equipment of each type. Routing refers to determining the specific pieces of equipment that will be used to manufacture each run on the long term production schedule. For example, the plant might have five reactors, eight neutralization tanks, three grinders, and four packing machines. For a given run, a rather large number of possible routes are possible. Furthermore, rarely is only one run in progress at a given time. The objective of routing is to determine the specific pieces of production equipment to be used for each run on the long-term production schedule. Given the dynamic nature of the production process (equipment failures, insertion/deletion of runs into the long term schedule, etc.), the solution of the routing problem continues to be quite challenging (Robert, et.al., 1997)
Chapter Three

3. Materials and Methods

This chapter contains information about the methods for tuning controllers, stability test and the system responses, also information about MATLAB software.

3.1 System Stability and Tuning

Mathematical models of a system have been obtained in transfer function form, and then these models can be analyzed to predict how the system will respond in both the time and frequency domains.

3.1.1 Stability

Systems have several properties such as controllability, stability and invariability that play a very decisive role in their behavior. From these characteristics, stability plays the most important role. The most basic practical control problem is the design of a closed-loop system such that its output follows its input as closely as possible, unstable systems cannot guarantee such behavior and therefore are not useful in practice. Another serious disadvantage of unstable systems is that the amplitude of at least one of their state and/or output variables tends to infinity as time increases, even though the input of the system is bounded. This usually results in driving the system to saturation and in certain cases the consequences may be even more undesirable: the system may suffer serious damage, such as burn out, break down, explosion, etc. For these and other reasons, in designing an automatic control system, our primary goal is to guarantee stability. As soon as stability is guaranteed, then one seeks to satisfy other design requirements, such as speed of response, settling, time, bandwidth, and steady-state error. The concept of stability has been studied in depth, and various criteria for testing the stability of a system have been proposed. Among the most celebrated stability criteria are those of Routh, Hurwitz, and Bode [. Mathematically, the stability of a linear system can be determined by an analysis of the roots of the characteristic equation from the differential equation describing the Process (which corresponds to the roots of the denominator of the transfer function). Here the roots of the characteristic equation for given K are on the imaginary axis, and the system is oscillating.
3.1.1.2 Routh-Hurwitz Criterion

The Routh-Hurwitz stability criterion provides a simple algorithm to decide whether or not the zeros of a polynomial are all in the left half of the complex plane (such a polynomial is called at times "Hurwitz"). A Hurwitz polynomial is a key requirement for a linear continuous-time invariant to be stable (all bounded inputs produce bounded outputs).

Necessary stability conditions: Conditions that must hold for a polynomial to be Hurwitz. If any of them fails, the polynomial is not stable. However, they may all hold without implying stability. Sufficient stability: Conditions that if met imply that the polynomial is stable. However, a polynomial may best able without implying some or any of them.

The Routh criteria provides condition that are both necessary and sufficient for a polynomial to be Hurwitz. The Routh-Hurwitz criteria is comprised of three separate tests that must be satisfied. If any single test fails, the system is not stable and further tests need not be performed. For this reason, the tests are arranged in order from the easiest to determine to the hardest.

The Routh Hurwitz test is performed on the denominator of the transfer function, the characteristic equation. For instance, in a closed-loop transfer function with G(s) in the forward path, and H(s) in the feedback loop, we have:

\[ T(s) = \frac{G(s)}{1+G(s)H(s)} \]

If we simplify this equation, we will have an equation with a numerator N(s), and a denominator D(s):

\[ T(s) = \frac{N(s)}{D(s)} \]

The Routh-Hurwitz criteria will focus on the denominator polynomial D(s).

Rowth Herwitz Tests:

Here are the three tests of the Routh-Hurwitz Criteria. For convenience, we will use N as the order of the polynomial (the value of the highest exponent of s in D(s)).

The equation D(s) can be represented generally as follows:

\[ D(s) = a_0 + a_1s + a_2s^2 + \cdots + aNs^N \]

Rule 1

All the coefficients ai must be present (non-zero)

Rule 2

All the coefficients ai must be positive (equivalently all of them must
Rule 3

If Rule 1 and Rule 2 are both satisfied, then form a Routh array from the coefficients $a_i$. There is one pole in the right-hand s-plane for every sign change of the members in the first column of the Routh array (any sign changes, therefore, mean the system is unstable).

We will explain the Routh array below.

The Routh Array

The Routh array is formed by taking all the coefficients $a_i$ of $D(s)$, and staggering them in array form. The final columns for each row should contain zeros:

\[
\begin{array}{cccc}
S^N & a^N & a^N - 2 & \ldots & 0 \\
S^{N-1} & a^{N-1} & a^N - 3 & \ldots & 0 \\
\end{array}
\]

Therefore, if $N$ is odd, the top row will be all the odd coefficients. If $N$ is even, the top row will be all the even coefficients. We can fill in the remainder of the Routh Array as follows:

\[
\begin{array}{cccc}
S^N & aN & aN - 2 & 0 \\
S^{N-1} & aN - 1 & aN - 3 & 0 \\
S^{N-2} & bN - 1 & bN - 3 & \ldots \\
S^{N-3} & cN - 1 & cN - 3 & \ldots \\
\end{array}
\]

Now, we can define all our $b$, $c$, and other coefficients, until we reach row $S^0$. To fill them in, we use the following formulae:

\[
bN - 1 = \frac{-1}{a_{N-1}} \begin{vmatrix} aN & aN - 2 \\ aN - 1 & aN - 3 \end{vmatrix}
\]

And

\[
bN - 3 = \frac{-1}{a_{N-1}} \begin{vmatrix} aN & aN - 4 \\ aN - 1 & aN - 5 \end{vmatrix}
\]
For each row that we are computing, we call the left-most element in the row directly above it the pivot element. For instance, in row b, the pivot element is \(a_{N-1}\), and in row c, the pivot element is \(b_{N-1}\) and so on and so forth until we reach the bottom of the array.

To obtain any element, we negate the determinant of the following matrix, and divide by the pivot element:

\[
\begin{vmatrix}
  k & m \\
  l & n
\end{vmatrix}
\]

Where:

- \(k\) is the left-most element two rows above the current row.
- \(l\) is the pivot element.
- \(m\) is the element two rows up, and one column to the right of the current element.
- \(n\) is the element one row up, and one column to the right of the current element (Hurwitz A., 1964).

In terms of \(k l m n\), our equation is:

\[
v = \frac{(lm) - (kn)}{l}
\]

**The procedure**

1. The characteristic equation is put in Routh array.
2. Taken row number \(n\) and the first value in the first column is equated to zero with is solve to give the ultimate \(K_u\).

**3.1.1.2 Direct Substitution Method**

The closed-loop poles may lie on the imaginary axis at the moment a system becomes unstable. We can substitute \(s = i \omega\) in the closed-loop characteristic equation to find the proportional gain that corresponds to this stability limit (which may be called marginal unstable). The value of this specific proportional gain is called the critical or ultimate gain. The corresponding frequency is called the crossover or ultimate frequency. The ultimate gain and ultimate period that can be used in Z-N continuous cycling relations, and the result on ultimate gain is consistent with Routh array analysis and limited to relatively simple systems (Gasmelseed, 2016) b.
3.1.1.3 Root locus Analysis

The root locus is a graphical representation in s-domain and it is symmetrical about the real axis. Because the open loop poles and zeros exist in the s-domain having the values either as real or as complex conjugate pairs. In this chapter, let us discuss how to construct (draw) the root locus. In control theory and stability theory, root locus analysis is a graphical method for examining how the roots of a system change with variation of a certain system parameter, commonly a gain within a feedback system. This is a technique used as a stability criterion in the field of classical control theory developed by Walter R. Evans which can determine stability of the system. The root locus plots the poles of the closed loop transfer function in the complex s-plane as a function of a gain parameter. In addition to determining the stability of the system, the root locus can be used to design the damping ratio (ζ) and natural frequency (ωn) of a feedback system. Lines of constant natural frequency can be drawn radially from the origin and lines of constant damping ratio can be drawn as arccosine whose center points coincide with the origin. By selecting a point along the root locus that coincides with a desired damping ratio and natural frequency, a gain K can be calculated and implemented in the controller. More elaborate techniques of controller design using the root locus are available in most control textbooks: for instance, lag, lead, PI, PD and PID controllers can be designed approximately with this technique. The definition of the damping ratio and natural frequency presumes that the overall feedback system is well approximated by a second order system; i.e. the system has a dominant pair of poles. This is often not the case, so it is good practice to simulate the final design to check if the project goals are satisfied.

Plotting Root locus using Mat lab:
Mat lab format:
>>num=[ ];
>>den=[ ];
>>sys=tf(num ,den );
>>rlocus(sys)
Where:
rlocus(sys): calculate and plots the root locus of the open-loop SISO model sys.
Tf: computers the transfer function
num: The numerator of the transfer function
den: the denominator of the transfer function. Plot in the complex plane the value of the roots of the characteristic equation as the controller parameter change.

These root locus plots can be useful to determine characteristic of the response of the system.

**The procedure is as follows**

1- Using MATLAB the root of the open loop is plotted against the frequency \( \omega \).
2- By double clicking on the curve with imaginary axis Ku and Pu are obtained.

![Root Locus Diagram](image)

**Figure (3.1): Root locus plot**

**3.1.1.4 Bode Diagram**

Some of the important properties of the bode stability criterion are: It provides a necessary and sufficient condition for closed – loop stability based on the properties of the open – loop transfer function. Consider an open – loop transfer function \( G(OL)= Gc Gv Gm \) that is strictly proper (more poles than zeros) and has no poles located on or to the right of the imaginary axis, with the possible exception of a single pole at the origin. Assume that the open – loop frequency response has only a single critical frequency and a single gain crossover frequency. Then the closed – loop system is stable if \( AR < 1 \). Otherwise it is unstable. Bode stability criterion is applicable to system that contain time delay. Gain physical insight into why a sustained oscillation occurs at the stability limit. Thus the desired “sustained oscillation “places requirements on both timing (phase) and applied force (amplitude). The bode stability criterion is very useful for a wide range of process control problems (Gasmelseed, 2016) b.
The procedure is as follows

1- The open-loop transfer function is obtained.
2- Using MATLAB the phase angle, the amplitude ratio are plotted against the frequency \( \omega \).
3- A horizontal line from -180 degree is extended the cute phase angle carve and by duple clicking and the period the inter section \( \omega_c \) is obtained.
4- From this point in part three the vertical line extended to meet AR amplitude ratio curve, and from the horizontal line we read the amplitude ratio db.

This can be converted the normal scale by the flowing equation:

\[
20 \log_{10} AR = \text{db}.
\]

The bode Magnitude plot measures the system Input/Output ratio in special units called decibels. The Bode phase plot measures the phase shift in degrees (typically, but radians are also used) (www.mstarlabs.com/control/znrule.html).

Plotting Bode plot with Matlab:

MATLAB format:

\[
\text{>>num=[ ];}
\]

\[
\text{>>den=[ ];}
\]

\[
\text{>>sys=tf(num,den);}
\]

\[
\text{>>bode(sys),grid}
\]

Where: Bode(sys): plots the Bode diagram of the OLTFT and then \( \text{Ku} = \frac{1}{AR} \)

![Figure (3.2): bode plot](image-url)
3.1.2 Method of Tuning

Controller tuning must be chosen to ensure that the response of the controller variable remains stable and returns to its steady-state value, or move to a new desired value, quickly. However the action of controller tends to introduced oscillations.

3.1.2.1 Continuous Cycling Method (Ziegler - Nichols tuning)

The system is brought to the edge of instability under proportional control only. Suitable values of parameter can then be determined from proportional gain ($K_c$) found at that condition.

It is a heuristic method of tuning a PID controller. It was developed by John G. Ziegler and Nathaniel B. Nichols. It is performed by setting the $I$ (integral) and $D$ (derivative) gains to zero. The "P" (proportional) gain, $K_p$ is then increased (from zero) until it reaches the ultimate gain $K_u$, at which the output of the control loop has stable and consistent oscillations. $K_u$ and the oscillation period $T_u$ are used to set the $P$, $I$, and $D$ gains depending on the type of controller used:

1. First, note whether the required proportional control gain is positive or negative. To do so, step the input $u$ up (increased) a little, under manual control, to see if the resulting steady state value of the process output has also moved up (increased). If so, then the steady-state process gain is positive and the required Proportional control gain, $K_c$, has to be positive as well.

2. Turn the controller to P-only mode, i.e. turn both the Integral and Derivative modes off.

3. Turn the controller gain, $K_c$, up slowly (more positive if $K_c$ was decided to be so in step 1, otherwise more negative if $K_c$ was found to be negative in step 1) and observe the output response. Note that this requires changing $K_c$ in step increments and waiting for a steady state in the output, before another change in $K_c$ is implemented.

4. When a value of $K_c$ results in a sustained periodic oscillation in the output (or close to it), mark this critical value of $K_c$ as $K_u$, the ultimate gain. Also, measure the period of oscillation, $P_u$, referred to as the ultimate period. (Hint: for the system A in the PID simulator, $K_u$ should be around 0.7 and 0.8)

5. Using the values of the ultimate gain, $K_u$, and the ultimate period, $P_u$, Ziegler and Nichols prescribes the following values for $K_c$, $t_I$ and $t_D$, depending on which type of controller is desired: (www.mstarlabs.com/control/znrule.html)
**The procedure is as follows**

Close the feedback loops; Turn on proportional gain only; Increase the controller gain until the process starts to oscillate. Continuous and slowly increase the gain until the cycles constant amplitude; Note the period of these cycles $P_u$ (distance in time between tow peaks) and the value of $K_c$ at which they were obtained (called $K_u$).

Determine the controller settings according to the tuning Ziegler – Nichols rules.

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>$K_c$</th>
<th>$\tau_{ls}$</th>
<th>$\tau_{ds}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>$0.5K_u$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>$0.45K_u$</td>
<td>$Pu$</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>$0.6K_u$</td>
<td>$Pu$</td>
<td>$Pu$</td>
</tr>
</tbody>
</table>

**3.1.3 Time Response**

Speed of response is an important measure of how quickly a system responds. When you evaluate how well a system is performing you need to measure speed of response with some metric. When you are designing a system you need to be able to predict speed of response. The time response represents how the state of dynamic system changes time we subjected to particular input. Since the models has been derived consist of different equations, some integration must be performed in order to determine the time response of the system. Fortunately, MATLAB provides many useful resources for calculate the time response for many types of inputs. MATLAB provides tools for automatically choosing optimal PID gains.

**The procedure is as follows**

1- The overall transfer function is put in MATLAB format.

2- Either step or impulse forced function may be introduced to see the simulation and response of the system.

3- From to the plot the flowing can be obtained:
   - The rise time.
   - Peak time.
   - The over shoot.
   - The decay ratio.
   - The recovery or settling time.
3.1.4 P, I, D controllers

Proportional-Integral-Derivative (PID) control is the most common control algorithm used in industry and has been universally accepted in industrial control. The popularity of PID controllers can be attributed partly to their robust performance in a wide range of operating conditions and partly to their functional simplicity, which allows engineers to operate them in a simple, straightforward manner. As the name suggests, PID algorithm consists of three basic coefficients; proportional, integral and derivative which are varied to get optimal response. Closed loop systems, the theory of classical PID and the effects of tuning a closed loop control system are discussed in this paper. The PID toolset in Lab VIEW and the ease of use of these VIs is also discussed.

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3.1.5 Control System

The basic idea behind a PID controller is to read a sensor, then compute the desired actuator output by calculating proportional, integral, and derivative responses and summing those three components to compute the output. Before we start to define the parameters of a PID controller, we shall see what a closed loop system is and some of the terminologies associated with it.

3.1.5.1 PID Theory

3.1.5.1.1 Proportional Response

The proportional component depends only on the difference between the set point and the process variable. This difference is referred to as the Error term. The proportional gain \( K_c \) determines the ratio of output response to the error signal. For instance, if the error term has a magnitude of 10, a proportional gain of 5 would produce a proportional response of 50. In general, increasing the proportional gain will increase the speed of the control system response. However, if the proportional gain is too large, the process variable will begin to oscillate. If \( K_c \) is increased further, the oscillations will become larger and the system will become unstable and may even oscillate out of control.

3.1.5.1.2 Integral Response

The integral component sums the error term over time. The result is that even a small error term will cause the integral component to increase slowly. The integral response will continually increase over time unless the error is zero, so the effect is to drive the Steady-State error to zero. Steady-State error is the final difference between the process variable and set point. A phenomenon called integral windup results when integral action saturates a controller without the controller driving the error signal toward zero.
3.1.5.1.3 Derivative Response

The derivative component causes the output to decrease if the process variable is increasing rapidly. The derivative response is proportional to the rate of change of the process variable. Increasing the derivative time ($T_d$) parameter will cause the control system to react more strongly to changes in the error term and will increase the speed of the overall control system response. Most practical control systems use very small derivative time ($T_d$), because the Derivative Response is highly sensitive to noise in the process variable signal. If the sensor feedback signal is noisy or if the control loop rate is too slow, the derivative response can make the control system unstable.

3.2 Tuning

The process of setting the optimal gains for P, I and D to get an ideal response from a control system is called tuning. There are different methods of tuning of which the “guess and check” method and the Ziegler Nichols method will be discussed. The gains of a PID controller can be obtained by trial and error method. Once an engineer understands the significance of each gain parameter, this method becomes relatively easy. In this method, the I and D terms are set to zero first and the proportional gain is increased until the output of the loop oscillates. As one increases the proportional gain, the system becomes faster, but care must be taken not make the system unstable. Once P has been set to obtain a desired fast response, the integral term is increased to stop the oscillations. The integral term reduces the steady state error, but increases overshoot. Some amount of overshoot is always necessary for a fast system so that it could respond to changes immediately. The integral term is tweaked to achieve a minimal steady state error. Once the P and I have been set to get the desired fast control system with minimal steady state error, the derivative term is increased until the loop is acceptably quick to its set point. Increasing derivative term decreases overshoot and yields higher gain with stability but would cause the system to be highly sensitive to noise. Often times, engineers need to trade off one characteristic of a control system for another to better meet their requirements.

3.3 MATLAB Software

MATLAB is an interactive system whose basic data element is an array that does not require dimensioning. This allows you to solve many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar
non interactive language such as C or FORTRAN. The name MATLAB stands for matrix laboratory. MATLAB was originally written to provide easy access to matrix software developed by the LINPACK and EISPACK projects, which together represent the state-of-the-art in software for matrix computation. MATLAB has evolved over a period of years with input from many users. In university environments, it is the standard instructional tool for introductory and advanced courses in mathematics, engineering, and science. In industry, MATLAB is the tool of choice for high-productivity research, development, and analysis. MATLAB features a family of application-specific solutions called toolboxes. Very important to most users of MATLAB, toolboxes allow you to learn and apply specialized technology. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems. Areas in which toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation, and many others. MATLAB is the graphics system. It includes high-level commands for two-dimensional and three-dimensional data visualization, image processing, animation, and presentation graphics. It also includes low-level commands that allow you to fully customize the appearance of graphics as well as to build complete Graphical User Interfaces on your MATLAB applications, (Gasmelseed, 2016-2017).

3.4 Selection of Controller

From the simulation of each loops, the controller that gives minimum overshoot is to be selected, this is due to the fact that overshoot may be dangerous, such as high temperature in a CSTR which may damage the products of the reaction
Chapter Four

4. Results and Discussion

4.1 Control Strategy

Control reaction temperature in a continuous stirred tank reactor (CSTR) using advance control.

![Diagram of control system](image)

Fig (1.1): Cascade Control for a Jacket and Reaction Temperatures for Exothermic Reaction.

4.2 Identification of transfer functions:

4.2.1 The Secondary loop (Slave loop):

\[ G_{c2} = K_{c2} \] ................................................................. (4-1)

\[ G_{v(s)} = \frac{3}{(0.2s+1)} \] ................................................................. (4-2)

\[ G_{m1} = 0.5 \] ................................................................. (4-3)

\[ G_{p2} = \frac{1}{(3s+1)(s+1)} \] ................................................................. (4-4)
4.2.2 The Primary loop (Master loop)

\[ G_{c1} = K_{c1} \] ................................................................. (4-5)
\[ G_{p1} = \frac{0.8}{(4s+1)} \] ................................................................. (4-6)
\[ G_{m1} = 0.5 \] ................................................................................. (4-7)

Where:

\( G_{m1} \) = Measuring Element for primary loop.
\( G_{m2} \) = Measuring Element for secondary loop.
\( G_{c2} \) = proportional controller for secondary loop.
\( G_{c1} \) = proportional controller for primary loop.
\( G_v \) = control valve.
\( G_{p1} \) = process controller for primary loop.
\( G_{p2} \) = process controller for secondary loop.
\( \pi F \) = Multiplication of the forward transfer functions.
\( \pi L \) = Multiplication of the loop transfer functions.
\( \pm \) = Positive for – ve feedback and –ve for positive feedback.
\( G(S) \) = Overall transfer function.
\( OLT F \) = open loop transfer functions.
\( R(s) \) = forcing function or set point.
\( C(s) \) or \( U(t) \) = controller output.
\( K_{c1} \) = controller gain for primary loop.
\( K_{c2} \) = controller gain for secondary loop.

Fig (4.1): block diagram of cascade process control.
4.3 The Transfer functions of secondary loop

\[
\pi F = \frac{3 + Kc_2}{(0.2S+1)(3S+1)(S+1)} 
\]

\[
\pi l = \frac{1.5 + Kc_2}{(0.2S+1)(3S+1)(S+1)} 
\]

\[
G(s) = \frac{C(s)}{R(s)} = \frac{\pi F}{1 + \pi l} = \frac{3 Kc_2}{(0.2S+1)(3S+1)(S+1)+1.5Kc_2} 
\]

\[
\text{OLT}F = \frac{3 + 0.5 Kc_2}{(0.2S+1)(3S+1)(S+1)} 
\]

4.4 The ultimate gain \( K_u \) and the ultimate period \( P_u \)

4.4.1 Direct substitution

The Characteristic equation:

\[
1 + \text{OLT}F = 0 \tag{4-12} 
\]

\[
1 + \frac{3 + 0.5 Kc_2}{(0.2S+1)(3S+1)(S+1)} = 0 \tag{4-13} 
\]

\[
(0.2S+1)(S+1)(3S+1)+1.5Kc_2 = 0 \tag{4-14} 
\]

\[
0.6S^3 + 3.8S^2 + 4.2S^1 + (1 + 1.5Kc_2) = 0 \tag{4-15} 
\]

Set \( S = i\omega \)

\[
0.6(i\omega)^3 + 3.8(i\omega)^2 + 4.2(i\omega) + (1 + 1.5Kc_2) = 0 \tag{4-16} 
\]

\[
-0.6(i)(\omega^3) - 3.8(\omega)^2 + 4.2(i\omega) + (1 + 1.5Kc_2) = 0 \tag{4-17} 
\]

By taking the imaginary part

\[
-0.6(i\omega)^3 i + 4.2(i\omega) = 0 \tag{4-18} 
\]

\[
\omega = \sqrt{\frac{4.2}{0.6}} = \sqrt{7} = 2.65 \text{rad/sec} \tag{4-19} 
\]

Ultimate period \( P_u \)

\[
P_u = \frac{2\pi}{\omega} = \frac{2\pi}{2.65} = 2.371 \text{sec} \tag{4-20} 
\]
By taking the real part

\[-3.8(\omega^2) + (1+1.5Ku_2)=0\]

\[\omega = 2.65\text{rad/sec}\]

\[Ku_2 = 17.12\]

The ultimate gain \(Ku_2 = 17.12\)

### 4.4.2 Root Locus Criteria

\[\text{OLT} = \frac{3+0.5Kc_2}{(0.2s+1)(3s+1)(s+1)}\]

MATLAB format:

```matlab
>> num = [1.5];
>> a = conv([0.2 1],[1 1]);
>> den = conv(a,[3 1]);
>> sys = tf(num,den);
>> rlocus(sys) inter
```

The Root Locus plot appears like this:

![Root Locus Plot](image)

**Fig (4.2): Root Locus plot of the cascade system (Secondary loop)**

From the figure (4.2): the system is stable since the root of the characteristic equation is not have positive real parts (i.e., root locus plot does not cross the imaginary access)

The ultimate gain \(Ku_2 = 17.20\)
Cross over frequency $\omega = 2.65$ rad/sec

Ultimate period $P_u = \frac{2\pi}{\omega} = 2.371$ sec, Overshoot (%) : 100

### 4.4.3 Bode Criteria

$$\text{OLTTF} = \frac{3 + 0.5 K_c}{(0.2 S + 1)(3S + 1)(S + 1)}$$

MATLAB format:

```matlab
>> num = [1.5];
>> a = conv([0.2 1],[1 1]);
>> den = conv(a,[3 1]);
>> sys = tf(num,den);
>> bode(sys)
```

Then the plot appears like this:

![Bode Diagram](image)

**Fig (4.3) Bode plot of the cascade system (Secondary loop)**

From figure (4.3) system stability the system was stable up to -180 not reach -180 at the cross over frequency and would be unstable under -180

At phase = -180 deg

Amplitude Ratio $AR = 0.0606$ abs

The ultimate gain $K_u = \frac{1}{AR} = \frac{1}{0.0606} = 16.5$

Cross over frequency $\omega = 2.62$ rad/sec

Ultimate period $P_u = \frac{2\pi}{\omega} = \frac{2\pi}{2.62} = 2.398$ sec
4.4.4 Routh Array Criteria

From Characteristic equation =1+OLTF=0

\[
\begin{align*}
1 + \frac{3 + 0.5 Kc2}{(0.2 S + 1)(3S + 1)(S + 1)} &= 0 \\
(0.2S+1)(S+1)(3S+1)+1.5 Kc2 &= 0 \\
0.6S^3 + 3.8S^2 + 4.2S + (1+1.5Kc2) &= 0
\end{align*}
\]

Routh array:
Number of rows=4

\[
\begin{bmatrix}
0.6 & 4.2 \\
3.8 & 1 + 1.5Kc2 \\
4.0421 - 0.23685Kc2 & 0 \\
1 + 1.5Kc2 & 0
\end{bmatrix}
\]

The ultimate gain \(K_{u2}\)

\[
4.0421 - 0.23685Ku2 = 0
\]

\(K_{u2} = 17.069\)

\(K_{u2} = 17.1\)

From direct sub \(\omega = \sqrt{\frac{4.2}{0.6}} = \sqrt{7} = 2.65\text{rad/sec}\)

4.4.5 The average of Ultimate gains \(K_u\) and Ultimate periods \(P_u\)

\[
K_{u2}(\text{average}) = \frac{Ku(R)+Ku(R-L)+Ku(B)+Ku(D,S)}{4} = \frac{17.12+17.20+17.10+16.5}{4} = 16.98
\]

\[
P_{u2} (\text{average}) = \frac{Ku(R)+Ku(R-L)+Ku(B)+Ku(D,S)}{4} = \frac{2.371+2.371+2.371+2.398}{4} = 2.378 \text{ sec}
\]

Table (4.1) Ziegler Nichols tuning parameters (for the Secondary loop)

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>(Kc)</th>
<th>(\bar{T}(\text{min}))</th>
<th>(\bar{T}_d(\text{min}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional controller</td>
<td>8.490</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral controller</td>
<td>7.641</td>
<td>1.983</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral derivative controller</td>
<td>10.188</td>
<td>1.190</td>
<td>0.2975</td>
</tr>
</tbody>
</table>

4.5 Simulation of the System

4.5.1 The secondary loop

\[
G(s) \frac{C(s)}{R(s)} = \frac{\pi F}{1 + \pi L} = \frac{3 Kc2}{(0.2 S + 1)(3S + 1)(S + 1) + 1.5 Kc2}
\]
4.5.2 System Response for P-controller

\[ K_c = 0.5 \times 16.98 = 8.49 \] tuning for secondary loop (Proportional controller only) ...............(4-29)

MATLAB format

```matlab
>> % Determination of the overall transfer function:
>> % For P-controller:
>> a = 8.490;
>> num1 = [3];
>> den1 = [0.2 1];
>> b = tf(num1, den1);
>> num2 = [1];
>> den2 = conv([3 1], [1 1]);
>> c = tf(num2, den2);
>> d = 0.5;
>> E = series(a, b);
>> F = series(E, c);
>> k = feedback(F, d, -1)  k =
      25.47

---------------------------------------
0.6 s^3 + 3.8 s^2 + 4.2 s + 13.73
Continuous-time transfer function.
>> step(k) enter
```
The System Response for P-controller

Fig (4.4) step response for \( p \_ \) controller

From the fig (4.4):

Table (4.2) characteristic from step response for a \( p \_ \) controller

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>61.9% at time=1.78sec</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>3 at time 1.78sec and 2.35 at 4.98sec</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.35/3 =0.783</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.62 sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>14.7 sec</td>
</tr>
<tr>
<td>Final value</td>
<td>1.85</td>
</tr>
</tbody>
</table>
4.5.3 System Response for PI-Controller

\( K_{c2} = 7.641 \) tuning for secondary loop (Proportional integral controller)

\[ G(c) = K_c \left(1 + \frac{1}{1.983s}\right) = \frac{15.15s + 7.641}{1.983s} \] .................................(4.30)

MATLAB format

\[
\begin{align*}
\text{>> } & \% \text{Determination of the overall transfer function:} \\
\text{>> } & \% \text{For PI-controller:} \\
\text{>> num0} &= [15.15 \ 7.641] \\
\text{>> den0} &= [1.983] \\
\text{>> a} &= \text{tf(num0,den0)} \\
\text{>> num1} &= [3] \\
\text{>> den1} &= [0.2 \ 1] \\
\text{>> b} &= \text{tf(num1,den1)} \\
\text{>> num2} &= [1] \\
\text{>> den2} &= \text{conv}([3 \ 1],[1 \ 1]) \\
\text{>> c} &= \text{tf(num2,den2)} \\
\text{>> d} &= 0.5 \\
\text{>> E} &= \text{series(a,b)} \\
\text{>> F} &= \text{series(E,c)} \\
\text{>> k} &= \text{feedback(F,d,-1)} \\
\text{k} &= 45.45s + 22.92 \\
\text{---------------------------------} \\
\text{1.19s^3 + 7.535s^2 + 31.05s + 13.44} \\
\text{Continuous-time transfer function.} \\
\text{>> step(k) enter}
\end{align*}
\]
System Response for PI controller

Figure (4.5) step response for a PI controller

From the figure (4.5):

Table (4.3) characteristics from step response for a PI controller

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>5.96% at time=0.819sec</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.81 at time 0.819sec</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.409 sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>1.93 sec</td>
</tr>
<tr>
<td>Final value</td>
<td>1.7</td>
</tr>
</tbody>
</table>
4.5.3 System Response for PID-Controller

\[ K_{c2} = 10.188 \quad \text{tuning for secondary loop (Proportional integral derivative controller)} \]

\[ G(c) = K_c (1 + \frac{1}{t_d s} + t_d s) = 10.188 \left( 1 + \frac{1}{1.19s} + 0.2975 \right) = \frac{(3.61s^2 + 12.124s + 10.188)}{1.19s} \]

**MATLAB format**

```matlab
>> % Determination of the overall transfer function:
>> % For PID-controller:
>> num0 = [3.61 12.124 10.188];
>> den0 = [1.19];
>> a = tf(num0, den0);
>> num1 = [3];
>> den1 = [0.2 1];
>> b = tf(num1, den1);
>> num2 = [1];
>> den2 = conv([3 1], [1 1]);
>> c = tf(num2, den2);
>> d = 0.5;
>> E = series(a, b);
>> F = series(E, c);
>> k = feedback(F, d, -1)

k =

10.83 s^2 + 36.37 s + 30.56

---------------------------------
0.714 s^3 + 9.937 s^2 + 23.18 s + 16.47

Continuous-time transfer function.

>> step(k) enter
```
The System Response Plot Appears for PID- Controller

Fig (4.6) step response for a PID_ controller

From the fig (4.6): Table (4.4) characteristics 'from step response for a PID_ controller

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>0.324% at time=2.5sec</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>≥1.86 at time 2.5sec</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.623 sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>1.33 sec</td>
</tr>
<tr>
<td>Final value</td>
<td>1.86</td>
</tr>
</tbody>
</table>
4.5.4 System response for three types of controller:

MATLAB format:

```matlab
>> %System Response:
>> %For three type of controller:
>> num=[25.47];
>> den=[0.6 3.8 4.2 13.73];
>> sys=tf(num,den);
>> step(sys)
>> hold
Current plot held
>> num=[45.45 22.93];
>> den=[1.19 7.535 31.05 13.44];
>> sys=tf(num,den);
>> step(sys)
>> num=[10.83 36.37 30.56];
>> den=[0.714 9.937 23.18 16.47];
>> sys=tf(num,den) enter
```
Fig (4.7) step response for a P,PI,PID - controllers
Fig (4.7) : Step Response of the Three Type of Controllers
4.5.5 The Comparison Between the Three Type of Controller:

Table (4.5) characteristics from step response for a P, PI and a PID - controllers

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Rise time (sec)</th>
<th>Settling time (sec)</th>
<th>Overshoot %</th>
<th>Decay ratio</th>
<th>Final value (ss)</th>
<th>Peak amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.620</td>
<td>14.70</td>
<td>61.9 at 1.78sec</td>
<td>0.783</td>
<td>1.85</td>
<td>3</td>
</tr>
<tr>
<td>PI</td>
<td>0.0.409</td>
<td>1.93</td>
<td>5.96 at 0.819sec</td>
<td>0.0</td>
<td>1.70</td>
<td>1.81</td>
</tr>
<tr>
<td>PID</td>
<td>0.0.623</td>
<td>1.33</td>
<td>0.324 at 2.5sec</td>
<td>0.0</td>
<td>1.86</td>
<td>≥1.86</td>
</tr>
</tbody>
</table>

The secondary loop

\[ G(s) = \frac{c(s)}{R(s)} = \frac{\pi F}{1+\pi L} = \frac{3 Kc_2}{(0.2S+1)(3S+1)(S+1)+1.5Kc_2} \]  \hspace{1cm} (4-31)

\[ K_{c2} = 0.5*16.98 = 8.49 \] tuning for secondary loop (Proportional controller only) \hspace{1cm} (4-32)

4.5.1 The primary loop

Figure (4.8) Block diagram of the reduced cascade loop

The characteristic equation of the closed-loop of the primary loops:

The Characteristic equation:

\[ 1+OLTF = 0 \] \hspace{1cm} (4-33)
4.7: The Transfer Function of Primary loop

\[ \pi F = \frac{3 \cdot K_{C2} \cdot K_{C1}}{(0.2 \cdot S + 1)(3 \cdot S + 1)(5 + 1)} \cdot \frac{0.8}{(4 \cdot S + 1)} \] ................................. (4-37)

\[ \pi L = \frac{0.5 \cdot 3 \cdot K_{C2} \cdot K_{C1}}{(0.2 \cdot S + 1)(3 \cdot S + 1)(5 + 1)} \cdot \frac{0.8}{(4 \cdot S + 1)} \] ................................. (4-38)

\[ G(s) = \frac{2.4 \cdot K_{C2} \cdot K_{C1}}{2.4 \cdot S^4 + 15.8 \cdot S^3 + 20.6 \cdot S^2 + 59.14 \cdot S + 13.735 + 10.188 \cdot K_{C1}} \] ................................. (4-39)

\[ K_{C2} = \frac{k_u}{2} = \frac{16.98}{2} = 8.49 \text{ for proportional controller only} \] ................................. (4-40)

4.8 The Ultimate Gain \( K_u \) and the Ultimate Period \( P_u \)

4.8.1 Direct substitution

The Characteristic equation:

\[ 2.4 \cdot S^4 + 15.8 \cdot S^3 + 20.6 \cdot S^2 + 59.14 \cdot S + 13.735 + 10.188 \cdot K_{C1} = 0 \] ................................. (4-41)

Set \( S = j \omega \)

\[ 2.4(j\omega)^4 - 15.8j(\omega)^3 - 20.6(\omega)^2 + 59.14j(\omega) + (13.735 + 10.188K_{C1}) = 0 \] ................................. (4-42)

By taking the imaginary part

\[ -15.8i(\omega)^3 + 59.14i(\omega) = 0 \] ................................. (4-43)

\[ \omega = \sqrt{\frac{59.14}{15.8}} = 1.935 \text{ rad/sec} \] ................................. (4-44)

Ultimate period \( P_u \)

\[ P_u = \frac{2\pi}{\omega} = \frac{2\pi}{1.935} = 3.25 \text{ sec} \] ................................. (4-45)

By taking the real part

\[ 2.4(\omega)^4 - 20.6(\omega)^2 + (13.735 + 10.188K_{u1}) = 0 \] ................................. (4-46)

\[ \omega = 1.935 \text{ rad/sec} \]

\[ k_{u1} = 2.92 \]
4.8.2 Root-locus Criteria

$$\text{OLTF} = \frac{1.2 \cdot 8.49 + kl}{2.4s^4 + 15.8s^3 + 20.6s^2 + 59.14s + 13.735 + 10.188 kl}$$

MATLAB format:

```matlab
>> num = [10.188];
>> den = [2.4 15.8 20.6 59.14 13.735 10.188];
>> sys = tf(num, den);
>> rlocus(sys) inter
```

![Root Locus Plot](image)

**Fig (4.9)**: Root Locus plot of the cascade system (Primary loop)

From figure (4.9), the system is stable since the root of the characteristic equation is not have positive real parts (i.e., root locus plot does not cross the imaginary access).

Table (4.6) characteristic from Root Locus plot of the cascade system (Primary loop)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate gain</td>
<td>2.36</td>
</tr>
<tr>
<td>Ultimate period</td>
<td>7.43 sec</td>
</tr>
<tr>
<td>Overshoot</td>
<td>99.3%</td>
</tr>
<tr>
<td>Crossover frequency</td>
<td>0.846 rad/sec</td>
</tr>
</tbody>
</table>
4.8.3 Bode Criteria

MATLAB format

MATLAB format:
>> num=[10.188];
>> den=[2.4 15.8 20.6 59.14 13.735 10.188];
>> sys=tf(num,den);
>> bode(sys),grid

![Bode Diagram](image)

**Fig (4.10) Bode diagram of the cascade system (primary loop)**

From **fig(4.10) system stability** the system was stable up to -180 not reach -180 at the cross over frequency and would be unstable under -180 deg.

**Table (4.7) characteristics from Bode diagram of the cascade system (primary loop)**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ultimate gain</td>
<td>1/0.418 =2.39</td>
</tr>
<tr>
<td>Ultimate period</td>
<td>2π/0.854 =7.357</td>
</tr>
<tr>
<td>Amplitude Ratio</td>
<td>0.418abs</td>
</tr>
<tr>
<td>Crossover frequency</td>
<td>0.854 rad/sec</td>
</tr>
</tbody>
</table>

4.8.4 Routh Array Criteria

From Characteristic equation =

\[2.4S^4 + 15.8S^3 + 20.6S^2 + 59.14S + 13.735 + 10.188Kc1 = 0 \quad \text{............... (4.47)}\]
Routh array:
Number of rows=5

\[
\begin{bmatrix}
2.4 & 20.6 & 13.735 + 10.188K_{c1} \\
15.8 & 59.14 & 0 \\
11.6 & 13.735 - 10.188K_{c1} & 0 \\
40.43 - 13.8767K_{c1} & 0 & 0 \\
0 & 0 & 0
\end{bmatrix}
\]

The ultimate gain \(K_{u1}\)

\[40.43 - 13.8767K_{u1} = 0\] ................................................................. (4-48)

\[K_{u1} = 2.913\]

From direct sub:
\[
\omega = 1.935\text{rad/sec}
\]

\[P_u = \frac{2\pi}{\omega} = \frac{2\pi}{1.935} = 3.25\text{sec} \] ................................................................. (4-49)

4.8.5 The Average of Ultimate Gains \(K_u\) and Ultimate Periods \(P_u\)

\[K_{u2}^{(\text{average})} = \frac{K_u(R) + K_u(R-L) + K_u(B) + K_u(D.S)}{4} = \frac{2.913 + 2.36 + 2.39 + 2.92}{4} = 2.65 \] .........................(4-50)

\[P_{u2}^{(\text{average})} = \frac{K_u(R) + K_u(R-L) + K_u(B) + K_u(D.S)}{4} = \frac{3.25 + 7.43 + 7.357 + 3.25}{4} = 5.322\text{ sec} \] .........................(4-51)

From Table (3.1) Ziegler Nichols tuning parameters

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>(K_c)</th>
<th>(T_i(\text{min}))</th>
<th>(T_d(\text{min}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional controller</td>
<td>(\frac{k_u}{2})</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral controller</td>
<td>(\frac{k_u}{2.2})</td>
<td>(\frac{P_u}{1.2})</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral derivative controller</td>
<td>(\frac{k_u}{1.7})</td>
<td>(\frac{P_u}{2})</td>
<td>(\frac{P_u}{8})</td>
</tr>
</tbody>
</table>
Table 4.8 Ziegler Nichols tuning parameters by using Ku (average) and _Pu (average) for the primary loop

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>$K_c$</th>
<th>$\zeta_l$ (min)</th>
<th>$\zeta_d$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proportional controller</td>
<td>1.325</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral controller</td>
<td>1.204</td>
<td>4.433</td>
<td>-</td>
</tr>
<tr>
<td>Proportional integral derivative controller</td>
<td>1.559</td>
<td>2.660</td>
<td>0.665</td>
</tr>
</tbody>
</table>

4.9 Simulation of the system

4.9.1 Overall transfer function

$$G(s) = \frac{2.4 K_{c2} K_{c1}}{2.4s^4 + 15.8s^3 + 20.6s^2 + 59.14s + 13.735 + 10.188K_{c1}}$$ ......................................................... (4-52)

4.9.2 System response for P-controller

$K_c2=0.5*16.98=8.49$ tuning for secondary loop (Proportional controller only ) .................(4-53)

$Gc_1=K_{c_1} = 1.325$ tuning for primary loop (Proportional controller).............................. (4-54)

$$G(s) = \frac{3*K_{c2}}{0.2s+1}(35+1)(5+1)+1.5K_{c2} = \frac{25.47}{0.6s^3+3.8s^2+4.2s+13.735}$$ ......................................................... (4-55)

MATLAB format:

>> % Determination of the overall transfer function:
>> % For P-controller:
>> a=1.325;
>> num1=[25.47];
>> den1=[0.6 3.8 4.2 13.735];
>> b=tf(num1,den1);
>> num2=[0.8];
>> den2=conv [4 1];
>> c= tf (num2, den2);
>> d=0.5;
>> E=series (a,b);
>> F=series (E,c);
>> k=feedback (F,d,-1)
k = 27

2.4 s^4 + 15.8 s^3 + 20.6 s^2 + 59.14 s + 27.23

Continuous-time transfer function.

>> step (k) enter

The response plot appears for P-controller:

![Step Response](image)

Fig (4.1) step response for a P-controller

From the fig (4.11): Table (4.9) characteristics from step response for a P-controller

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>6.04% at time=9.05sec</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.05 at time 9.05sec and=1.03 at 12.2sec</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>1.03/1.05 =0.98</td>
</tr>
<tr>
<td>Rise time</td>
<td>1.75 sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>17.3 sec</td>
</tr>
<tr>
<td>Final value</td>
<td>0.991</td>
</tr>
</tbody>
</table>
4.9.3; System response for PI-controller:

\[ K_c^2 = 8.49 \text{ tuning for secondary loop (Proportional controller only) } \] ........................................ (4-56)

\[ K_c^1 = 1.20 \text{ tuning for primary loop (Proportional integral controller) } \] ........................................ (4-57)

\[ G(s) = \frac{3 + K_c^2}{(0.2s + 1)(3s + 1)(5s + 1) + 1.5K_c^2} = \frac{25.47}{0.6s^3 + 3.8s^2 + 4.2s + 13.735} \] ........................................ (4-58)

\[ G(c) = K_c(1 + \frac{1}{\frac{1}{\tau_{IS}}} ) = 1.204(1 + \frac{1}{\frac{4.433}{S}}) = \frac{(5.337S + 1.204)}{4.433S} \] ........................................ (4-59)

MATLAB format:

>> % Determination of the overall transfer function:
>> % For PI-controller:
>> num0=[5.337 1.204];
>> den0=[4.433];
>> num1=[25.47];
>> den1=[0.6 3.8 4.2 13.735];
>> b=tf(num1,den1);
>> num2=[0.8];
>> den2=conv [4 1];
>> c=tf(num2,den2);
>> d=0.5;
>> E=series(a,b);
>> F=series(E,c);
>> k=feedback(F,d,-1)

\[ k = \frac{108.7s + 24.53}{10.64s^4 + 70.04s^3 + 91.32s^2 + 316.5s + 73.15} \]
Continuous-time transfer function.

>> step(k) enter
The response plot appears for PI-controller:

![Step Response Plot](image)

**Fig (4.12) step response for a PI-controller**

From the fig (4.12): **Table (4.10) characteristics from step response for a PI-controller**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>83% at time=1.61sec</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>0.614 at time=1.61</td>
</tr>
<tr>
<td></td>
<td>0.0492 at time =4.45</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>0.801</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.524 sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>19.4 sec</td>
</tr>
<tr>
<td>Final value</td>
<td>0.335</td>
</tr>
</tbody>
</table>

### 4.9.4 System response for PID-controller

\[ K_{c2}=8.49 \text{ tuning for secondary loop (Proportional controller only) } \] ................................................ (4-60)

\[ K_{c1}=1.559 \text{ tuning for secondary loop (Proportional Integral Derivate controller only) } \] ....... (4-61)

\[ G(s) = \frac{3+K_{c2}}{(0.2s+1)(3s+1)(s+1)+1.5K_{c2}} = \frac{25.47}{0.6s^3+3.85s^2+4.2s+13.735} \] ........................................................ (4-62)
\[ G(c) = K_c \left( 1 + \frac{1}{t_i s} + t_d s \right) = 1.559 \left( 1 + \frac{1}{2.66 s} + 1.0367 s \right) = \frac{(5.41 s^2 + 4.1494 s + 1.559)}{2.66 s} \] 

MATLAB format:

```matlab
>> % Determination of the overall transfer function:
>> % For PID-controller:
>> num0=[5.41 4.1494 1.559];
>> den0=[2.66];
>> num1=[25.47];
>> den1=[0.6 3.8 4.2 13.735];
>> b=tf(num1,den1);
>> num2=[0.8];
>> den2=conv [4 1];
>> c=tf(num2,den2);
>> d=0.5;
>> E=series (a,b);
>> F=series (E,c);
>> k=feedback (F,d,-1)
```

\[ k = \frac{110.4 s^2 + 84.5 s + 31.77}{6.384 s^4 + 42.03 s^3 + 110 s^2 + 199.6 s + 52.42} \]

Continuous-time transfer function.

```matlab
>> step (k) enter
```
The response plot appears for PID-controller

From the fig (4.13):

**Table (4.11) characteristics from step response for a PID-controller**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>68.2%</td>
</tr>
<tr>
<td>Peak amplitude</td>
<td>1.02 at time 0.826sec</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>0.0</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.268sec</td>
</tr>
<tr>
<td>Settling time</td>
<td>11sec</td>
</tr>
<tr>
<td>Final value</td>
<td>0.606</td>
</tr>
</tbody>
</table>
4.9.5 System response for three types of controller

MATLAB format:

```matlab
>>% System Response
>>% for the three type of controller:
>>num = [27];
>>den = [2.4 15.8 20.6 59.14 27.23];
>>sys = tf(num,den);
>>step(sys)
>>hold

Current plot held
>>num = [108.7 24.53];
>>den = [10.64 70.04 91.32 316.5 73.15];
>>sys = tf(num,den);
>>step(sys)
>>num = [110.4 84.5 31.77];
>>den = [6.384 42.03 110 199.6 52.42];
>>sys = tf(num,den);
>>step(sys)
```
Fig (4.14) : step response of the three type of controllers

step response of the three type of controllers
4.9.6 The comparison between the three types of controller

Table (4.12) characteristics from step response for three type of controller

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Rise time (sec)</th>
<th>Settling time (sec)</th>
<th>Overshoot %</th>
<th>Decay ratio</th>
<th>Final value(ss)</th>
<th>Peak amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>1.75</td>
<td>17.3</td>
<td>6.04 at 9.05sec</td>
<td>0.98</td>
<td>0.991</td>
<td>1.05</td>
</tr>
<tr>
<td>PI</td>
<td>0.524</td>
<td>19.4</td>
<td>83 at 1.61sec</td>
<td>0.801</td>
<td>0.335</td>
<td>0614</td>
</tr>
<tr>
<td>PID</td>
<td>0.268</td>
<td>11</td>
<td>68.2 at 0.826sec</td>
<td>0.0</td>
<td>0.606</td>
<td>1.02</td>
</tr>
</tbody>
</table>

4.10 Selection of the controller

The proper controller mode selected according to the method was based on selecting one that gives the best performance with respect to minimum overshoot; its due to the fact that high overshoot may be dangerous, such as high temperature in a CSTR which may damage the reaction, thus it protects the reactor from temperature disturbances. The controller that gave minimum overshoot was selected it’s a PID-controller for the secondary loop (Slave loop) and a P-controller for the primary loop (Master loop).

4.11 Discussion and Result

Some parameters in exothermic or endothermic reactions are very important and need to be controlled at the optimum levels which are set at the set point. In cascade control the slave controller takes the set point from the master controller, thus it protects the reactor from temperature disturbances. In this study a cascade control system was applied, tuned and simulated. From the simulation the design parameters including the overshoot were registered and the controller that gave minimum overshoot was selected for the secondary loop and it was found to be a PID-Controller, but a P-Controller for the primary loop.
Chapter Five

Conclusions and Recommendations

5.1 Conclusions
It was concluded that cascade control was more effective than conventional feedback control. This was suggested to be due to any deviation in the reaction temperature, the master controller, would change the set point of the slave controller which will manipulate the flow rate of the coolant so as to keep the reaction temperature at the desired temperature. The characteristic equations analysis was made using (P, PI and PID) controller through Ruoth, Root Locus, Bode, criteria and direct substitution. The results of the ultimate gains and ultimate periods were found to be always identical. The controllers were found to be proportional (P) for the primary loop and PID for the secondary loop, these were installed into the system and the system behaves at the optimum conditions.

5.2 Recommendations
It is recommended that the same procedure of the analysis has to be applied using cascade digital control system, this requires the introduction of the analog-digital interface such as a sampler, analog to digital converters and hold elements to make changes from digital to continuous signals as the signal coming digital from the computer (PLC) to the control valve which is working in continuous manner (e.i analog).
References


https://www.researchgate.net/publication/270217670


