University of Gezira

Control and Simulation of Fluidized Catalytic Cracking Unit

Ahmed Badrelddin Mohammed Gibril

B.Sc (Honours) in Chemical Engineering Technology, University of Gezira (2014)

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

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Control and Simulation of Fluidized Catalytic Cracking Unit

Ahmed Badrelddin Mohammed Gibril

The Supervision Committee

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<td>Co- supervisor</td>
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اقْرأْ بِإِسْمِ رَبِّكَ الَّذِي خَلَقَ

سورة العلق، الآية 1
DEDICATION

For my family, who offered me unconditional love and support throughout the course of this work.

Also, this thesis is dedicated to my supervisors who have been a great source of motivation and inspiration.
ACKNOWLEDGMENTS

Great thanks and thankful praises to Almighty Allah for all the favors and guidance a bestowed upon me through my life. This research work would have never been successfully undertaken without the unreserved support of my main adviser Prof. Gurashi Abdella Gasmelseed. I would like to express my deepest gratitude to Ust. Maab Salah Mohamed Elamin Ali for her rigorous interest and for sharing me his profound knowledge and experience. His continued discussion and critical comments helped me a lot to improve and refine the final draft of the thesis.

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Master of Science in Chemical Engineering Technology (2016)

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Abstract

Fluid catalytic cracking is now a major secondary conversion process in petroleum refinery. The main objective is the conversion of straight-run atmospheric gas oils, vacuum gas oils, certain atmospheric residues and heavy stocks recovered from other refinery operations into high-octane gasoline, light fuel oils and olefin-rich light gases. Simultaneously with the desired reactions, coke, carbonaceous material having low ratio of hydrogen to carbon (H/C) deposits on the catalyst and renders it less catalytically active. This study has tried to control spent catalyst and the converted products which are separated. The catalyst passes to a separation chamber. The regenerator; where the coke is combusted to rejuvenate the catalyst. The rejuvenated catalyst then passes to the bottom of the reactor riser, where the cycle begins again. FCC has many parameters to control; the most important are temperature of the reactor, the level and flow rate of the catalyst. The temperature of the reactor should be kept at 505 °C and the catalyst temperature 655 °C. The control strategy was developed and the transfer functions were identified. From these transfer functions the characteristic equations were calculated as well as the open- loop transfer functions. Routh direct substitution, Root – Locus and bode methods were used for tuning, stability analysis and simulation response of the system with adjustable parameters. The obtained results for loop one are $K_c = 4.56$, $T_i = 8.2\text{ min}$, $T_d = 1.2\text{ min}$. The systems simulation results were found to be initially oscillatory and finally settled. From the response the following parameters were determined for loop1 these are: peak time =3.5 sec, overshoot 0.373, decay ratio 0.391, settling time =73 sec and rise time 7.21 sec. Peak time 00.18 sec, overshoot 5.9, decay ratio 0.395settling time =6.08 sec and rise time 0.478 for loop2. Whereas, peak time 2.31sec, overshoot 0.489, decay ratio 0.342, setting time =40.1 sec and rise time of 4.78 for loop3. But, peak time of 2 sec, overshoot 0.54, decay ratio 0.319, setting time =29 sec and rise time of 3.76 for loop4. This means that the stability and tuning methods give almost equal results showing that the average leads to more accurate results. For future study, it is recommended that the control system should be analyzed by using ASPENHYSYS process simulator and compare its results with results of MATLAB software application which is used in this study. It is recommended that the control system in this unit should always be renewed by
other controllers as those types of controllers which can adapt themselves according to the change of catalyst activity, temperature and pressure.
تحكم ومحاكاة لوحدة التكسير الصرف المتميع

أحمد بدرالدين محمد جبريل

ماجستير العلوم في تكنولوجيا الهندسة الكيميائية (2016)

قسم الهندسة الكيميائية وطبيعة الجيولوجيا الكيميائية

كلية الهندسة

جامعة الجزيرة

المستخلص

عملية التكسير المحفز التي تتم في طبقة متميزة حاليا هي العملية التحويلية الثانوية في المصفاة وعرضها الأساسي هو تحويل نواتج التقطير تحت الضغط الجوي والتحكم في التفريغ لتوضيح نواحي التكسير الأولي. تتم هذه العملية في طبقة متميزة أو طبقة مصغرة من خلال التقطير تحت الضغط الجوي والتحكم في التفريغ وتوضيح نواحي التكسير الأولي. تتم هذه العملية في طبقة متميزة أو طبقة مصغرة من خلال التقطير تحت الضغط الجوي والتحكم في التفريغ وتوضيح نواحي التكسير الأولي.

في هذه الدراسة حاولنا أن نتحكم في الحفاز المتبقي والمنتجات المحولة التي يتم تحرير الحفاز إلى غرفة الفصل، ومدفوع الحفاز أن يكون حرق الحفاز لتنشيط الحفاز المنشط يمرر إلى أسفل المفاعل لبدء العملية من جديد. تميزة وحدة التكسير الحفزي بعدة عوامل والتي يمكن التحكم فيها وأهم هذه العوامل درجة حرارة المفاعل ومستوى الحفاز ومعملة التحكم. يجب أن تكون حرارة المفاعل عند 505 م، ودرجة حرارة الحفاز 655 م. وعلي هذا الأساس تم إنشاء خطة التحكم وتحديد دوال الإنتقال ومن هذه الدوال تم حساب المعادلات المميزة للحلقات المفتوحة، حيث تم استخدام طريقة روت للتعويض المباشر لتحديد الاستقرارية وحساب معاملات التحكم. كما استخدمت طرق جذور لوكاس وخطط بوكلي لزيادة الدقة وتحليل الاستقرارية مع معاملات التحكم. على سبيل المثال النتائج المتوقعة في الدائرة رقم (1) هي (4.56 Kc، 2.66 min) عند عمل المحاكاة فأن القدرة لزايد مثلاً هي 1.2 ثانية ونسبة التشويه تساوي 0.373 وزمن الصعود يساوي 7.21 ثانية ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 0.484 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية. ونسبة التشويه تساوي 0.395 وزمن الصعود يساوي 6.08 ثانية ونسبة التشويه تساوي 0.342 وزمن الصعود يساوي 4.78 ثانية.

استقرارية التحكم تؤدي إلى نتائج متقاربة جدا وهذا يشير إلى أن استخدام المتوسط يقود إلى نتائج أكثر دقة. استخدم هذه الدراسة لتحل نظام التحكم باستخدام محاكي العمليات هاوسن (ASPHENYSYS) ومقارنة نتائجه مع نتائج تطبيقات المحلول (MATLAB) الذي تم استخدامه في هذه الدراسة. أيضاً أوصت هذه الدراسة بأن نظام التحكم لهذه الوحدة يجب
تجديده باستمرار بمتحكمات أخرى كتلك الأنواع من المتحكمات التي يمكن ان تكيف نفسها وفقا للتغير في فعالية العامل الحفز، درجة الحرارة والضغط.
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<tr>
<td>API</td>
<td>American Petroleum Institute</td>
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<tr>
<td>WTI</td>
<td>West Texas Intermediate</td>
</tr>
<tr>
<td>ORB</td>
<td>OPEC Reference Basket</td>
</tr>
<tr>
<td>OPEC</td>
<td>organization petroleum export country</td>
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<td>RFCCU</td>
<td>Residual fluidized catalytic</td>
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<tr>
<td>$K_c$</td>
<td>Proportional controller gain</td>
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<tr>
<td>$K_u$</td>
<td>Ultimate gain</td>
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<td>$P_u$</td>
<td>Ultimate period</td>
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<tr>
<td>Z-N</td>
<td>Ziegler –Nichols</td>
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<td>$A_v$</td>
<td>Average</td>
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<tr>
<td>LPG</td>
<td>Liquid petroleum gas</td>
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<td>CNPC</td>
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<td>OMV</td>
<td>Open Market Value</td>
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<td>RTD</td>
<td>Riser Termination Device</td>
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<td>CDU</td>
<td>Crude Distillation Unit</td>
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Chapter One
Introduction

1.1 Crude Oil

Crude oil (a non-renewable resource) is usually found in underground areas called reservoirs. It is liquid in nature and yellowish black in colour. They are composed mainly of hydrocarbons and organic compounds. They are usually discovered by oil prospecting scientists. Sometimes petroleum and crude oil are used to mean the same thing, but petroleum itself is a broad range of petroleum product including crude oil itself. Crude oil can exist either deep down in the earth's surface or deep below the ocean beds [1].

1.1.1 Composition of Crude Oil

Petroleum or crude oil is a complex mixture of hydrocarbons and other chemical. The composition varies widely depending where and how the petroleum was formed. In fact, a chemical analysis can be used to fingerprint the source of the petroleum. However, raw petroleum or crude oil has characteristic properties and composition.

1.1.1.1 Hydrocarbons in Crude Oil

There are four main types of hydrocarbons found in crude oil.
1. Paraffin (15-60%).
2. Naphthenic (30-60%).
3. Aromatics (3-30%).
4. Asphaltic (remainder).

The hydrocarbons primarily are alkanes, cycloalkanes and aromatic hydrocarbons.

1.1.1.2 Elemental Composition of Petroleum

Although there is considerable variation between the ratios of organic molecules, the elemental composition of petroleum is well-defined:
- Carbon - 83 to 87%
- Hydrogen - 10 to 14%
- Nitrogen - 0.1 to 2%
- Oxygen - 0.05 to 1.5%
- Sulfur - 0.05 to 6.0%
- Metals - < 0.1%

The most common metals are iron, nickel, copper and vanadium.
1.1.1.3 Petroleum Color and Viscosity

The color and viscosity of petroleum vary markedly from one place to another. Most petroleum is dark brown or blackish in color, but it also occurs in green, red or yellow [2].

1.1.2 Crude Oil Assay

Using a variety of both standard and innovative procedures the Crude Oil Assay testing laboratories provide the molecular and chemical characterizations of crude oil. Information is generated on the boiling-range and on each requested fraction within the range using a variety of physical distillation procedures. Sulfur content, nitrogen content, viscosity measurements, cold properties and metals content are all measured as part of the normal analysis of the general properties of the crude oil. From the basic petroleum assay atmospheric and vacuum distillations we produce distillate fractions and residual bottoms similar to those produced during the actual refining process. Crude oil assay testing generates the detailed hydrocarbon analysis data that may be used to inform and reassure the customers and supply chain [3].

1.1.3 Classifications of Crude Oil

The different Types of crude oil are classified based on the American Petroleum Gravity (API) gravity and viscosity. The properties may vary in terms of proportion of hydrocarbon elements, sulfur content etc as it is extracted from different geographical locations all over the world. If the API gravity of the crude oil is of 20 degrees or less, it is graded as 'heavy', those with an API gravity of 40.1 degrees or greater than that is known as 'light' and if the oil ranges between 20 and 40.1 degrees, it is graded as 'intermediate'. Classifications are made based on the sulfur content as well. Crude oil with low content of sulfur means 'sweet' and the presence of high content sulfur is known as 'sour'. The purity of crude oil increases or decreases based on the sulfur content as sulfur is an acidic material one of the largest and major Classifications of Crude oil is Brent Blend, which is found in the North Sea. With an API gravity of (38.3) degrees and 0.37% of sulfur, this blend of crude oil comes from 15 various oil fields in the North Sea. Brent Blend is refined in the United States and Gulf coasts during the times of export. West Texas Intermediate (WTI) otherwise known as Texas Light Sweet, OPEC Reference Basket (ORB) and Dubai Crude are other major benchmarks or references. The deposits for West Texas Intermediate are found in Texas and Mexico whereas for OPEC Reference Basket oil is sourced from Bonny light (Nigeria), Arab light (Saudi Arabia), Basra light (Iraq), Saharan blend (Algeria) and Minas (Indonesia). Although, Brent blend is graded as a light crude oil, it is not as light as WTI.
Brent crude and Brent Sweet Light Crude are the other Classifications of Brent Blend. Again, Brent sweet Light Crude is not as light as WTI. Due to the presence of low sulfur content in Brent Blend, this can be easily refined and it is best suitable for the production of gasoline and oil products. This light grade of crude oil is also ideal for the conversion of gasoline as it contains an API gravity of 39.6 degrees and 0.24% of sulfur usually lighter than Bent crude. When compared to Brent Blend and West Texas Intermediate, the OPEC Reference Basket benchmark is a heavier blend. The lighter version of the crude oils is priced high in comparison to the crude oils that are classified as heavy [4].

1.2 Processes in the Petroleum Refinery

Refinery processes have developed in response to changing market demands for certain products. With the advent of the internal combustion engine the main task of refineries became the production of petrol. The quantities of petrol available from distillation alone were insufficient to satisfy consumer demand. Refineries began to look for ways to produce more and better quality petrol.

Two types of processes have been developed:
- Breaking down large, heavy hydrocarbon molecules.
- Reshaping or rebuilding hydrocarbon molecules [4].

1.2.1 Distillation (Fractionation)

Because crude oil is mixture of hydrocarbons with different boiling temperatures, it can be separated by distillation into groups of hydrocarbons that boil between two specified boiling points. Two types of distillation are performed: atmospheric and vacuum [4].

1.2.2 Reforming

Reforming is a process which uses heat, pressure and a catalyst (usually containing platinum) to bring about chemical reactions which upgrade naphtha into high octane petrol and petrochemical feedstock. The naphtha is hydrocarbon mixtures containing many paraffins and naphthenes. In Australia, this naphtha feedstock comes from the crudes oil distillation or catalytic cracking processes, but overseas it also comes from thermal cracking and hydrocracking processes. Reforming converts a portion of these compounds to isoparaffins and aromatics, which are used to blend higher octane petrol:
- Paraffins are converted to isoparaffins.
- Paraffins are converted to naphthenes.
- Naphthenes are converted to aromatics [4].

1.2.3 Cracking
Cracking processes break down heavier hydrocarbon molecules (high boiling point oils) into lighter products such as petrol and diesel. These processes include catalytic cracking, thermal cracking and hydrocracking [4].

1.2.3.1 Catalytic cracking

Is used to convert heavy hydrocarbon fractions obtained by vacuum distillation into a mixture of more useful products such as petrol and light fuel oil. In this process, the feedstock undergoes a chemical breakdown under controlled heat (450 - 500°C) and pressure, in the presence of a catalyst a substance which promotes the reaction without itself being chemically changed. Small pellets of silica-alumina or silica – magnesia have proved to be the most effective catalysts. The cracking reaction yields petrol, LPG, unsaturated olefin compounds, cracked gas oils, a liquid residue called cycle oil, light gases and a solid coke residue. Cycle oil is recycled to cause further breakdown and the coke, which forms a layer on the catalyst, is removed by burning. The other products are passed through fractionators to be separated and separately processed [4].

1.2.3.2 Thermal cracking

Uses heat to break down the residue from vacuum distillation. The lighter elements produced from this process can be made into distillate fuels and petrol. Cracked gases are converted to petrol blending components by alkylation or polymerization. Naphtha is upgraded to high quality petrol by reforming. Gas oil can be used as diesel fuel or can be converted to petrol by hydro cracking. The heavy residue is converted into residual oil or coke which is used in the manufacture of electrodes, graphite and carbides [4].

1.2.3.3 Hydrocracking

Can increase the yield of petrol components, as well as being used to produce light distillates. It produces no residues, only light oils. Hydrocracking is catalytic cracking in the presence of hydrogen. The extra hydrogen saturates, or hydrogenates the chemical bonds of the cracked hydrocarbons and creates isomers with the desired characteristics. Hydrocracking is also a treating process, because the hydrogen combines with such as sulphur and nitrogen, allowing them to be removed.

Gas oil feed is mixed with hydrogen, heated, and sent to a reactor vessel with a fixed bed catalyst, where cracking and hydrogenation take place. Products are sent to a fractionator to be separated. The hydrogen is recycled. Residue from this reaction is mixed again with hydrogen, reheated and sent to a second reactor for further cracking under higher temperatures and pressures.
In addition to cracked naphtha for making petrol, hydrocracking yields light gases useful for refinery fuel, or alkylation as well as components for high quality fuel oils, lube oils and petrochemical feedstock.

The former can be achieved by several chemical processes such as alkylation and isomerization [4].

1.2.4 Alkylation

Olefins such as propylene and butylenes are produced by catalytic and thermal cracking. Alkylation refers to the chemical bonding of these light molecules with isobutane to form larger branched-chain molecules (isoparaffins) that make high octane petrol.

Olefins and isobutane are mixed with an acid catalyst and cooled. They react to form alkylate, plus some normal butane, isobutane and propane. The resulting liquid is neutralized and separated in a series of distillation columns. Isobutane is recycled as feed and butane and propane sold as liquid petroleum gas (LPG) [4].

1.2.5 Isomerization

Isomerization refers to chemical rearrangement of straight-chain hydrocarbons (paraffins), so that they contain branches attached to the main chain (isoparaffins). This is done for two reasons:

- They create extra isobutane feed for alkylation.
- They improve the octane of straight run pentanes and hexanes and hence make them into better petrol blending components.

Isomerization is achieved by mixing normal butane with a little hydrogen and chloride and allowed to react in the presence of a catalyst to form isobutane, plus a small amount of normal butane and some lighter gases. Products are separated in a fractionator. The lighter gases are used as refinery fuel and the butane recycled as feed. Pentanes and hexanes are the lighter components of petrol. Isomerization can be used to improve petrol quality by converting these hydrocarbons to higher octane isomers. The process is the same as for butane isomerization [4].

1.2.6 Polymerization

Under pressure and temperature, over an acidic catalyst, light unsaturated hydrocarbon molecules react and combine with each other to form larger hydrocarbon molecules. Such process can be used to react butenes (olefin molecules with four carbon atoms) with iso-butane (branched paraffin molecules, or isoparaffins, with four carbon atoms) to obtain a high octane olefinic petrol blending component called polymer gasoline [4].

1.2.7 Hydrotreating and Sulphur plants

A number of contaminants are found in crude oil. As the fractions travel through the refinery processing units, these impurities can damage the equipment, the catalysts and the
quality of the products. There are also legal limits on the contents of some impurities, like Sulphur, in products. Hydrotreating is one way of removing many of the contaminants from many of the intermediate or final products. In the hydrotreating process, the entering feedstock is mixed with hydrogen and heated to (300 - 380°C). The oil combined with the hydrogen then enters a reactor loaded with a catalyst which promotes several reactions:

- Hydrogen combines with sulphur to form hydrogen sulphide (H₂S).
- Nitrogen compounds are converted to ammonia.
- Any metals contained in the oil are deposited on the catalyst.
- Some of the olefins, aromatics or naphthenes become saturated with hydrogen to become paraffins and some cracking takes place, causing the creation of some methane, ethane, propane and butanes [4].

1.3 Sudanese crude oil

Oil was discovered in Sudan in the mid-1970s, but production did not start until 1999. The pioneer companies Chevron and Shell were forced to bow out in 1984, after the outbreak of civil war. They eventually sold their rights in 1990, booking a $1 billion loss. Mid-1990s, the CNPC and PETRONAS Calgary from Malaysia, both fully state controlled, grasped this unique opportunity to invest in an oil rich area that was out of bounds for the oil majors. They continue to dominate the scene. In 2003, when the violent displacement campaign in their areas of operation became public knowledge, their junior western partners, OMV (Austria) and Talisman Energy (Canada), left Sudan, while Lund in Petroleum from Sweden kept its interest in block 5B. ONGC from India stepped in, completing the prevailing position of Asian national oil companies in Sudan’s oil industry [5].

1.4 Khartoum Refinery

1.4.1 Summary Information

- Ownership: Khartoum Refinery Company, CNPC.
- Location: Located 70 kilometers north of Khartoum.
- Capacity: 5.0 million.
- Tons/annum: 100,000 bbl/day [6].

1.4.2 Refining Units

Atmospheric distillation, heavy oil catalytic cracking, catalytic reforming, diesel hydrofining, aviation kerosene, gasoline-diesel mixed hydrofining and continuous reforming units in addition to the first delayed coker in the world for high-calcium acid crude [6].

1.4.3 History
May 16, 2000 - Khartoum Refinery became operational on with a designed capacity of 2.5 million metric tons per annum and a daily crude run of 50,000 barrels.

August 2003 - The extension project of the refinery started June 30, 2006 -The project was completed, boosting the crude processing capacity to 5 million metric tons per annum and the daily crude run to 100,000 barrels [6].

1.5 Statement of the Research Problems

Fluid Catalytic Cracking process is an important and widely used way to convert heavy feedstock into lighter, more valuable products. Various feedstocks can be used, such as gas oils, vacuum gas oils or residual materials. Typical products are gasoline, light fuel oils and olefin-rich gases. Hot catalyst from the regenerator section flows in a fluidized state through the riser tube into the Reactor. The incoming feed together with recycling slurry meet hot catalyst, start vaporizing and cracking in reactor. While the reactions take place, coke is formed on the catalyst. The spent catalyst is separated from cracked material and being regenerated through burning off the coke. After regeneration, the catalyst is sent back to the reactor with a lot of heat absorbed in regeneration phase. The cracked hydrocarbons enter a fractionating tower, where it is separated into gas, light cycle oil, heavy cycle oil and slurry. The gasoline product has good overall octane characteristics suitable to be used for gasoline blending. Many valves installed in fluid catalytic units. This application bulletin describes the requirements and flow control solutions available for the FCCU. FCC-technology represents one of the most expanded processes producing motor fuels from heavy distillates and residues. On the one side the FCC technology from the engineering point of view is one of the most sophisticated equipment in the chemical industry. On the other side, the key factor in such technology is good active, stable and selective catalyst, converting specific feed of heavy distillates and residues into desired products.

1.6 Objective of this Research

The objectives of this study are to:
1- Evaluate the performance of operational variables on reactor and regenerators in an industrial fluid catalytic cracking unit using MATLAB computer software.
2- Know how Control and simulate systems using some output state of a system and a desired state to make control decisions.
3- Develop control systems to protect operators and equipment.
4- Reduce the environment effect due to control systems failure.
5- Reduce cost of production and maintenance ...etc.
Chapter Two

Literature Review

2.1 Fluid Catalytic Cracking Process

The fluid catalytic cracking (FCC) process is a process for the conversion of straight-run atmospheric gas oils, vacuum gas oils, certain atmospheric residues, and heavy stocks recovered from other refinery operations into high-octane gasoline, light fuel oils, and olefin-rich light gases.

The product gasoline has an excellent front-end octane number and good overall octane characteristics. Further, FCC gasoline is complemented by the alkylate produced from the gaseous olefinic byproducts because alkylate has superior midrange octane and excellent sensitivity.

In a typical FCC unit the cracking reactions are carried out in a vertical reactor riser in which a liquid oil stream contacts hot powdered catalyst. The oil vaporizes and cracks to lighter products as it moves up the riser and carries the catalyst powder along with it. The reactions are rapid, and only a few seconds of contact time are necessary for most applications. Simultaneously with the desired reactions, coke, a carbonaceous material having a low ratio of hydrogen to carbon (H/C), deposits on the catalyst and renders it less catalytically active. The spent catalyst and the converted products are then separated; and the catalyst passes to a separate chamber, the regenerator, where the coke is combusted to rejuvenate the catalyst. The rejuvenated catalyst then passes to the bottom of the reactor riser, where the cycle begins again.

A typical FCC unit configuration has a single regenerator to burn the coke from the catalyst. Although the regenerator can be operated in either complete or partial combustion, complete combustion has tended to predominate in new unit designs because an environmentally acceptable flue gas can be produced without the need for additional hardware, such as a CO boiler. This boiler would be required for the partial combustion mode to keep CO emissions low.

Hot regenerated catalyst flows to the riser bottom. After a short re-acceleration zone to stabilize the catalyst flow, it is contacted with finely atomized feedstock. At the riser top, a riser termination device (RTD) rapidly disengages vapor products from the catalyst to reduce further thermal and catalytic cracking. The spent channel is degassed to remove most of the entrained hydrocarbons in a counter-current dense phase steam stripper with multiple steam injections. The stripped spent catalyst is then introduced on top of the first regenerator fluidized bed, where the hot flue gas provides ultimate stripping. The first regenerator acts as a mild pre-combustion zone to achieve 40 to 70% of the coke combustion [7].
2.2 Fluid Catalytic Cracking Feedstocks

Examples of common feedstocks for conventional distillate feed FCC units are:

- Atmospheric gas oils
- Vacuum gas oils
- Coker gas oils
- Thermally cracked gas oils
- Solvent Deasphalted oils
- Lube extracts
- Hydrocracker bottoms

Residual FCCU (RFCCU) processes Conradson carbon residue and metals-contaminated feedstocks such as atmospheric residues or mixtures of vacuum residue and gas oils. Depending on the level of carbon residue and metallic contaminants (nickel and vanadium), these feedstocks may be hydrotreated or Deasphalted before being fed to an RFCCU.

Feed hydrotreating or deasphalting reduces the carbon residue and metals levels of the feed, reducing both the coke-making tendency of the feed and catalyst deactivation [7].

2.3 Products

Products from the FCC and RFCCU processes are typically as follows:

- Fuel gas (ethane and lighter hydrocarbons)
• C3 and C4 liquefied petroleum gas (LPG)
• Gasoline
• Light cycle oil (LCO)
• Fractionator bottoms (slurry oil)
• Coke (combusted in regenerator)
• Hydrogen Sulfide (from amine regeneration)

Although gasoline is typically the most desired product from an FCCU or RFCCU, design and operating variables can be adjusted to maximize other products. The three principal modes of FCC operation are (1) maximum gasoline production, (2) maximum light cycle oil production, and (3) maximum light olefin production, often referred to as maximum LPG operation. These modes of operation are discussed below:

2.3.1 Maximum Gasoline

The maximum gasoline mode is characterized by use of an intermediate cracking temperature (510 to 540°C), high catalyst activity, and a high catalyst/oil ratio. Recycle is normally not used since the conversion after a single pass through the riser is already high.

Maximization of gasoline yield requires the use of an effective feed injection system, a short-contact-time vertical riser, and efficient riser effluent separation to maximize the cracking selectivity to gasoline in the riser and to prevent secondary reactions from degrading the gasoline after it exits the riser.

2.3.2 Maximum Middle Distillate

The maximum middle distillate mode of operation is a low-cracking-severity operation in which the first pass conversion is held to a low level to restrict recracking of light cycle oil formed during initial cracking. Severity is lowered by reducing the riser outlet temperature (below 510°C) and by reducing the catalyst/oil ratio. The lower catalyst/oil ratio is often achieved by the use of a fired feed heater which significantly increases feed temperature.

Additionally, catalyst activity is sometimes lowered by reducing the fresh catalyst makeup rate or reducing fresh catalyst activity. Since during low-severity operation a substantial portion of the feed remains unconverted in a single pass through the riser, recycle of heavy cycle oil to the riser is used to reduce the yield of lower-value, heavy streams such as slurry product. When middle distillate production is maximized, upstream crude distillation units are operated to minimize middle distillate components in the FCCU feedstock, since these components either degrade in quality or convert to gasoline and lighter products in the FCCU. In addition, while maximizing middle distillate production, the FCCU gasoline endpoint would typically be minimized within middle distillate flash point constraints, shifting gasoline product into LCO. If
it is desirable to increase gasoline octane or increase LPG yield while also maximizing LCO production, ZSM-5 containing catalyst additives can be used. ZSM-5 selectively cracks gasoline boiling-range linear molecules and has the effect of increasing gasoline research and motor octane ratings, decreasing gasoline yield, and increasing C3 and C4 LPG yield. Light cycle oil yield is also reduced slightly.

2.3.3 Maximum Light Olefin Yield

The yields of propylene and butylenes may be increased above that of the maximum gasoline operation by increasing the riser temperature above 540°C and by use of ZSM-5 containing catalyst additives [7].

2.4 Process description

The FCC process may be divided into several major sections, including the converter section, flue gas section, main fractionator section, and vapor recovery units (VRUs). The number of product streams, the degree of product fractionation, flue gas handling steps, and several other aspects of the process will vary from unit to unit, depending on the requirements of the application. The following sections provide more detailed descriptions of the converter, flue gas train, main fractionator, and VRU [7].

2.4.1 Converter

The FCCU shown in Fig (2.2) consists of regenerator, stripper and disengager vessels, with continuous closed-loop catalyst circulation between the regenerator and disengage/stripper. The term derives from the in-line stacked arrangement of the disengager and stripper over the regenerator. This arrangement has the following operational and cost advantages:

- Essential all-vertical flow of catalyst in standpipes and risers.
- Short regenerated and spent catalyst standpipes allowing robust catalyst circulation.
- Uniform distribution of spent catalyst in the stripper and regenerator.
- Low overall converter height.
- Minimum structural steel and plot area requirements.

Preheated fresh feedstock, plus any recycle feed, is charged to the base of the riser reactor.

Upon contact with hot regenerated catalyst, the feedstock is vaporized and converted to lower-boiling fractions (light cycle oil, gasoline, C3 and C4 LPG, and dry gas). Product vapors are separated from spent catalyst in the disengager cyclones and flow via the disengager overhead line to the main fractionator and vapor recovery unit for quenching and fractionation. Coke formed during the cracking reactions is deposited on the catalyst, thereby reducing its activity. The coked catalyst, which is separated from the reactor products in the disengager
cyclones, flows via the stripper and spent catalyst standpipe to the regenerator. The discharge rate from the standpipe is controlled by the spent catalyst plug valve. In the regenerator, coke is removed from the spent catalyst by combustion with air.

Figure (2.2): FCC converter (McGraw 2004)

Air is supplied to the regenerator air distributors from an air blower. Flue gas from the combustion of coke exits the regenerator through two-stage cyclones which remove all but a trace of catalyst from the flue gas. Flue gas is collected in an external plenum chamber and flows to the flue gas train. Regenerated catalyst, with its activity restored, is returned to the riser via the regenerated catalyst plug valve, completing the cycle [7].

2.4.2 Feed Injection System

The FCC design employs a regenerated catalyst standpipe, a catalyst plug valve, and a short inclined lateral to transport regenerated catalyst from the regenerator to the riser.

The catalyst then enters a feed injection cone surrounded by multiple, flat-spray, atomizing feed injection nozzles, as shown in Fig. (2.3) the flat, fan-shaped sprays provide uniform coverage and maximum penetration of feedstock into catalyst, and prevent catalyst from bypassing feed in the injection zone. Proprietary feed injection nozzles, known as nozzles, are used to achieve the desired feed atomization and spray pattern, while minimizing feed pressure.
requirements. The hot regenerated catalyst vaporizes the oil feed, raises it to reaction temperature, and supplies the necessary heat for cracking.

The cracking reaction proceeds as the catalyst and vapor mixture flow up the riser. The riser outlet temperature is controlled by the amount of catalyst admitted to the riser by the catalyst plug valve [7].

![Feed injection cone](image)

**Figure (2.3): Feed injection cone (McGraw 2004)**

### 2.4.3 Riser Quench

The riser quench system consists of a series of nozzles uniformly spaced around the upper section of riser. A portion of the feed or a recycle stream from the main fractionators is injected through the nozzles into the riser to rapidly reduce the temperature of the riser contents. The heat required to vaporize the quench is supplied by increased fresh feed preheat or by increased catalyst circulation. This effectively increases the temperature in the lower section of the riser above that which would be achieved in a non-quenched operation thereby increasing the vaporization of heavy feeds increasing gasoline yield, olefin production and gasoline octane [7].

### 2.4.4 Riser Termination

At the top of the riser all the selective cracking reactions have been completed. It is important to minimize product vapor residence time in the disengager to prevent unwanted thermal or catalytic cracking reactions which produce dry gas and coke from more valuable products. Closed cyclone technology is used to separate product vapors from catalyst with minimum vapor residence time in the disengager. This system (Fig. 4) consists of riser cyclones.
directly coupled to secondary cyclones housed in the disengager vessel. The riser cyclones effect a quick separation of the spent catalyst and product vapors exiting the riser.

Secondary cyclones and then to the main fractionator for rapid quenching. Closed cyclones almost completely eliminate postriser thermal cracking with its associated dry gas and butadiene production. Closed cyclone technology is particularly important in operation at high riser temperatures (say, 538°C or higher), typical of maximum gasoline or maximum light olefin operations [7].

2.4.5 Spent Catalyst Stripping

Catalyst separated in the cyclones flows through the respective diplex and discharges into the stripper bed. In the stripper, hydrocarbon vapors from within and around the catalyst particles are displaced by steam into the disengager dilute phase, minimizing hydrocarbon carry-under with the spent catalyst to the regenerator. Stripping is a very important function because it minimizes regenerator bed temperature and regenerator air requirements, resulting in increased conversion in regenerator temperature or air-limited operations. See Fig (2.5) the catalyst entering the stripper is contacted by up flowing steam introduced through two steam distributors. The majority of the hydrocarbon vapors entrained with the catalyst is displaced in the upper stripper bed. The catalyst then flows down through a set of hat and doughnut baffles. In the
baffled section, a combination of residence time and steam partial pressure is used to allow the hydrocarbons to diffuse out of the catalyst pores into the steam introduced via the lower distributor. Stripped catalyst, with essentially all strippable hydrocarbons removed, passes into a standpipe, which is aerated with steam to maintain smooth flow. At the base of the standpipe, a plug valve regulates the flow of catalyst to maintain the spent catalyst level in the stripper. The catalyst then flows into the spent catalyst distributor and into the regenerator [7].

![Figure (2.5): Spent catalyst stripper (McGraw 2004)](image)

2.4.6 Regeneration

In the regenerator, coke is burned off the catalyst with air in a fluid bed to supply the heat requirements of the process and restore the catalyst’s activity. The regenerator is operated in either complete CO combustion or partial CO combustion modes. In the regenerator cyclones, the flue gas is separated from the catalyst. Regeneration is a key part of the FCC process and must be executed in an environment that preserves catalyst activity and selectivity so that the reaction system can deliver the desired product yields.

The converter uses a countercurrent regeneration system to accomplish this. This is made possible by the spent catalyst distributor. Air is introduced near the bottom of the bed. The design allows coke burning to begin in a low-oxygen partial pressure environment which controls the initial burning rate. Controlling the burning rate prevents excessive particle temperatures which would damage the catalyst. The hydrogen in the coke combusts more quickly than the carbon and most of the water formed is released near the top of the bed. These features together minimize catalyst deactivation during the regeneration process. With this unique approach, the
countercurrent regenerator achieves the advantages of multiple regeneration stages, yet does so with the simplicity, cost efficiency, and reliability of a single regenerator vessel [7].

2.4.7 Catalyst Cooler

A regenerator heat removal system may be included to keep the regenerator temperature and catalyst circulation rate at the optimum values for economic processing of the feedstock. The requirement for a catalyst cooler usually occurs when processing residual feedstocks which produce more coke, especially at high conversion [7].

2.4.8 Flue Gas Section

Flue gas exits the regenerator through two-stage cyclones and an external plenum chamber into the flue gas train, as shown in Fig. 3.1.10. Energy from the regenerator flue gas is recovered in two forms: Energy is recovered in the form of mechanical energy by means of a flue gas expander and in the form of heat by the generation of steam in the flue gas cooler or CO boiler [7].

2.5 Main Fractionator Section

The process objectives of the main fractionator system are to:

- Condense superheated reaction products from the FCC converter to produce liquid hydrocarbon products.
- Provide some degree of fractionation between liquid side stream products
- Recover heat that is available from condensing superheated FCC converter products [7].

2.5.1 Fractionator Overhead

Fractionator overhead vapor flows to the fractionator overhead air cooler and then to the overhead trim cooler. Fractionator overhead products consisting of wet gas, raw gasoline, a small amount of reflux, and sour water are condensed in the overhead reflux system. Net products and reflux are recovered in the fractionator overhead reflux drum. Wet gas flows to the wet gas compressor low-pressure suction drum in the vapor recovery section. Raw gasoline is pumped to the top of the primary absorber and serves as primary lean oil [7].

2.5.2 Heavy Naphtha Pumparound

Fractionation trays are provided between the LCO and heavy naphtha draw in the main fractionator. Desired fractionation between the LCO and raw gasoline is achieved by induced reflux over these trays. Circulating reflux and lean oil are pumped to the Pumparound system [7].

2.5.3 Light Cycle Oil

Light cycle oil is withdrawn from the main fractionator and flows by gravity to the top tray of the LCO stripper. Steam is used to strip the light ends from the LCO to improve the flash point.
Stripped LCO product is pumped through the fresh feed/LCO exchanger, the LCO air cooler, and the LCO trim cooler and then is delivered to the battery limits [7].

2.5.4 Heavy Cycle Oil Pumparound

Net wet gas, raw gasoline, and LCO products are cooled, and HCO reflux is condensed in this section. Total condensed material is collected in a total trap-out tray, which provides suction to the Pumparound pump. Net tray liquid is pumped back to the cleanup trays below. The circulating reflux is cooled by first exchanging heat with the debutanizer in the vapor recovery section and then preheating fresh FCC feed [7].

2.5.5 Main Fractionator Bottoms Pumparound

FCC converter products—consisting of hydrocarbon gases, steam, inert gases, and a small amount of entrained catalyst fines—flow to the main fractionator tower above the fractionator bottoms steam distributor. The converter products are cooled and washed free of catalyst fines by circulation of a cooled fractionator bottoms material over a baffled tower section above the feed inlet nozzle. Heat removed by the bottoms Pumparound is used to generate steam in parallel kettle type boilers and to preheat fresh FCC feed, as required. Fractionator bottoms product is withdrawn at a point downstream of the feed preheat exchangers. The bottoms product is cooled through a boiler feed water preheater and an air cooler, and then it is delivered to the battery limits [7].

2.5.6 Fresh Feed Preheat

The purpose of this system is to achieve required FCC converter feed preheat temperature, often without use of a fired heater. The fresh feed may be combined from several sources in a feed surge drum. The combined feed is then pumped through various exchangers in the main fractionator section to achieve the desired feed temperature [7].

2.5.7 Vapor Recovery Unit

The vapor recovery unit consists of the wet gas compressor section, primary absorber, stripper, secondary absorber, and debutanizer. The vapor recovery section receives wet gas and raw gasoline from the main fractionator overhead drum. The vapor recovery unit is required to accomplish the following:

- Reject C2 and lighter components to the fuel gas system.
- Recover C3 and C4 products as liquids with the required purity.
- Produce debutanized gasoline product with the required vapor pressure.

Additional product fractionation towers may be included depending on the desired number of products and required fractionation efficiency. These optional towers often include a depropanizer to separate C3 and C4 LPG, a C3 splitter to separate propane from propylene, and a gasoline splitter to produce light and heavy gasoline products [7].
2.5.8 Wet Gas Compression

Wet gas from the fractionator overhead reflux drum flows to a two-stage centrifugal compressor. Hydrocarbon liquid from the low-pressure stage and high-pressure gas from the high-pressure stage are cooled in the air-cooled condenser and combined with liquid from the primary absorber and vapor from the stripper overhead. This combined two-phase stream is further cooled in the high-pressure trim cooler before flowing into the high-pressure separator drum [7].

2.5.9 Stripper

Liquid from the high-pressure separator is pumped to the top tray of the stripper. The stripper is required to strip C2’s and lighter components from the debutanizer feed and thus serves to control the C2 content of the C3/C4 LPG product. Stripped C2’s and lighter products are rejected to the primary absorber. Absorbed C3’s and heavier products are recovered in the stripper bottoms [7].

2.5.10 Primary Absorber

Vapor from the high-pressure separator drum flows to a point below the bottom tray in the absorber. Raw gasoline from the main fractionator and supplemental lean oil from the bottom of the debutanizer combine and flow to the top tray of the absorber. This combined liquid feed serves to absorb C3’s and heavier components from the high-pressure vapor [7].

2.5.11 Secondary Absorber

Vapor from the primary absorber overhead contains recoverable liquid products. Gasoline boiling-range components and a smaller quantity of C4 and C3 boiling-range material are recovered in the secondary absorber by contacting the primary absorber overhead with heavy naphtha lean oil from the main fractionator. Rich oil containing recovered material returns to the main fractionator. Sour fuel gas from the top of the secondary absorber flows to the amine treating section and finally to the fuel gas system [7].

2.5.12 Debutanizer

Liquid from the bottom of the stripper exchanges heat with the debutanizer bottoms and then flows to the debutanizer. The debutanizer is required to produce a gasoline product of specified vapor pressure as well as produce a C3/C4 stream containing minimal amounts of C5 boiling-range materials. The debutanizer reboiler is heated by HCO Pumaparound.

The debutanizer and overhead condensing duty is supplied by an air-cooled condenser followed by a trim condenser utilizing cooling water. The debutanizer overhead liquid product, C3/C4 LPG, is pumped to amine and caustic treating sections, then to product storage. The debutanizer bottoms stream, debutanized gasoline, exchanges heat with the debutanizer feed and cooling water, prior to caustic treating and delivery to product storage [7].
2.6 Process Variables

There are a large number of variables in the operation and design of an FCC unit which may be used to accommodate different feedstocks and operating objectives. Operational variables are those that may be manipulated while on-stream to optimize the FCCU performance. Decisions on design variables must be made before the unit is constructed [7].

2.6.1 Operational Variables

FCCU operating variables can be grouped into categories of dependent and independent variables. Many operating variables, such as regenerator temperature and catalyst circulation rate, are considered dependent variables because operators do not have direct control of them. Independent variables are the ones over which the operators have direct control, such as riser outlet temperature or recycle rate. Two dependent operating variables useful in a discussion of other variables are conversion and catalyst/oil ratio. Conversion is a measure of the degree to which the feedstock is cracked to lighter products and coke during processing in the FCCU. It is defined as 100 percent minus the volume percent yield of LCO and heavier liquid products. In general, as conversion of feedstock increases, the yields of LPG, dry gas, and coke increase, while the yields of LCO and fractionator bottoms decrease; gasoline yield increases, decreases, or remains constant depending on the situation. Catalyst/oil ratio (cat/oil) is the ratio of catalyst circulation rate to charge rate on a weight basis. At a constant charge rate, cat/oil increases as catalyst circulation increases. At constant riser temperature, conversion increases as cat/oil increases due to the increased contact of feed and catalyst.

Following is a discussion of six important independent operating variables:

- Riser temperature.
- Recycle rates.
- Feed preheat temperature.
- Fresh feed rate.
- Catalyst makeup rate.
- Gasoline endpoint [7].

2.6.1.1 Riser Temperature

Increasing the riser temperature set point will signal the regenerated catalyst valve to increase the hot catalyst flow as necessary to achieve the desired riser outlet temperature. The regenerator temperature will also rise because of the increased temperature of the catalyst returned to the regenerator and because of increased coke lay down on the catalyst. When steady state is reached, both the catalyst circulation and the regenerator temperature will be higher than
they were at the lower riser temperature. The increased riser temperature and increased catalyst circulation (cat/oil) result in increased conversion. Compared to the other means of increasing conversion, increased riser temperature produces the largest increase in dry gas and C3 yields but less increase in coke yield. This makes increasing riser temperature an attractive way to increase conversion when the unit is close to a regenerator air limit, but has some spare gas-handling capacity [7].

2.6.1.2 Recycle Rates

HCO and slurry from the main fractionators can be recycled to the riser to increase conversion and/or increase regenerator temperature when spare coke burning capacity is available. Coke and gas yield will be higher from cracking HCO or slurry than from cracking incremental fresh feed, so regenerator temperature and gas yield will increase significantly when recycling HCO or slurry to the riser. As such, recycle of slurry to the riser is an effective way to increase regenerator temperature if this is required. If the FCCU is limited on gas-handling capacity, the use of HCO or slurry recycle will require a reduction in riser temperature which will depress octane, and conversion could also fall. Operation with HCO or slurry recycle together with lower riser temperature is sometimes used when the objective is to maximize LCO yield. This maximizes LCO yield because the low riser temperature minimizes cracking of LCO boiling-range material into gasoline and lighter products while the recycle of the heavy gas oil provides some conversion of these streams to LCO. Sometimes slurry recycle is employed to take entrained catalyst back into the converter. This is most often done when catalyst losses from the reactor are excessive [7].

2.6.1.3 Feed Preheat Temperature

Decreasing the temperature of the feed to the riser increases the catalyst circulation rate required to achieve the specified riser outlet temperature. The increase in catalyst circulation rate (cat/oil) causes increased conversion of the FCC feedstock. Compared to raising the riser outlet temperature increasing conversion via lower preheat temperature produces a larger increase in coke yield but smaller increases in C3 and dry gas yield and octane. Feed preheat temperature has a large effect on coke yield because reducing the heat supplied by the charge to the riser requires an increase in heat from the circulating catalyst to satisfy the riser heat demand. When the FCCU is near a dry gas or C3 production limit, but has spare coke-burning capacity, reducing preheat temperature is often the best way to increase conversion. Conversely, if the FCCU is air-limited, but has excess light ends capacity, high preheat (and higher riser temperature) is often the preferred mode of operation. In most cases, reducing preheat will lead to a lower regenerator temperature because the initial increase in coke yield from the higher catalyst circulation (cat/oil) is not enough to supply the increased reactor heat demand. In other cases,
reducing the feed preheat temperature may result in an increased regenerator temperature. This can occur if the feed preheat temperature is reduced to the point that it hinders feed vaporization in the riser or if catalyst stripping efficiency falls because of higher catalyst circulation rate [7].

2.6.1.4 Fresh Feed Rate

As feed rate to the riser is increased, the other independent operating variables must usually be adjusted to produce a lower conversion so that the unit will stay within controlling unit limitations, such as air blower capacity, catalyst circulation capability, gas compressor capacity and downstream C3 and C4 olefin processing capacity. They yield and product quality effects associated with the drop in conversion are chiefly a function of changes in these other independent variables [7].

2.6.1.5 Catalyst Makeup Rate

Each day, several tons of fresh catalyst is added to the FCCU catalyst inventory. Periodically, equilibrium catalyst is withdrawn from the FCCU to maintain the inventory in the desired range. Increasing the fresh catalyst makeup rate will increase the equilibrium catalyst activity because in time it lowers the average age and contaminant (Ni, V, and Na) concentrations of the catalyst in the inventory.

With other independent FCCU operating variables held constant, increasing catalyst activity will cause greater conversion of feedstock and an increase in the amount of coke deposited on the catalyst during each pass through the riser. To keep the coke burning in balance with the process heat requirements, as the activity increases, the regenerator temperature will increase and the catalyst circulation (cat/oil) will fall, to keep the coke burning consistent with the process heat demand. The conversion will usually increase with increasing activity because the effect of higher catalyst activity outweighs the effect of the lower catalyst circulation rate. If riser or feed preheat temperatures are adjusted to keep conversion constant as activity is increased, the coke and dry gas yields will decrease. This makes increasing catalyst activity attractive in cases where the air blower or gas compressor is limiting, but where some increase in regenerator temperature can be tolerated. (Typically, regenerator temperature will be limited to around 720°C in consideration of catalyst activity maintenance.) If the riser temperature has to be lowered to stay within a regenerator temperature limitation, the conversion increase will be lost [7].

2.6.1.6 Gasoline Endpoint

The gasoline/LCO cut point can be changed to significantly shift product yield between gasoline and LCO while maintaining both products within acceptable specifications. Changing the cut point can significantly alter the gasoline octane and sulfur content. A lower cut point
results in lower sulfur content and generally higher octane, but of course the gasoline yield is reduced [7].

2.6.2 Design Variables

Several FCCU process design variables are available to tailor the unit design to the requirements of a specific application. Several of these are discussed below:

- Feed dispersion steam rate
- Regenerator combustion mode
- Regenerator heat removal
- Disengager and regenerator pressures
- Feed temperature [7].

2.6.2.1 Feed Dispersion Steam Rate

Selection of a design feed dispersion steam rate influences the sizing of the feed injection nozzles, so dispersion steam rate is both a design and an operating variable. Design dispersion steam rates are commonly in the range between 2 and 5 wt % of feed, depending on the feed quality. The lower values are most appropriate for vacuum gas oil feedstocks while dispersion steam rates near the upper end of the range are most appropriate for higher-boiling, more difficult to vaporize residual feedstocks. Once the feed nozzle design has been specified, dispersion steam operating range is recommended for optimizing the unit during operation [7].

2.6.2.2 Regenerator Combustion Mode

Oxygen-lean regeneration (partial CO combustion) is most appropriate for use with heavy residuals where regenerator heat release and air consumption are high due to high coke yield. In addition, oxygen-lean regeneration offers improved catalyst activity maintenance at high catalyst vanadium levels, due to reduced vanadium mobility at lower oxygen levels. In grassroots applications, therefore, oxygen-lean regeneration is preferred for heavy residual operations with high catalyst vanadium loadings. On the other hand, for better-quality residuals and gas oil feedstocks, complete CO Combustion is preferred for its simplicity of operation. Other factors in the selection of regeneration mode are listed below:

- A unit designed to operate in an oxygen-lean mode of regeneration must include a CO boiler to reduce CO emissions to environmentally safe levels. If a CO boiler is included, the FCC unit may also be operated in a full CO combustion mode, with the CO boiler serving to recover sensible heat from the flue gas.
- Unit investment cost is lower for oxygen-lean regeneration due to reduced regenerator, air blower, and flue gas system size.
Steam production can be maximized by operating in an oxygen-lean mode of regeneration, due to combustion in the CO boiler.

Regenerator heat removal systems (such as catalyst coolers) may be avoided in some cases if the unit is operated in an oxygen-lean mode of regeneration.

In some cases, complete CO combustion will allow the unit to operate with a lower coke yield, thereby increasing the yield of liquid products.

Sox emissions can be controlled to lower levels with complete CO combustion, due to a lower coke-burning rate and because SOx-reducing catalyst additives are more effective at the higher regenerator oxygen content [7].

2.6.2.3 Regenerator Heat Removal

Depending on the feedstock, desired conversion, and regenerator combustion mode, a regenerator heat removal system may be required to Control regenerator temperature in a range chosen to provide an optimum catalyst/oil ratio and minimum catalyst deactivation [7].

2.6.2.4 Disengager and Regenerator Pressures

In the converter design, the regenerator pressure is held 7 to10 lb/in2 higher than the disengager pressure to provide the desired differential pressures across the spent and regenerated catalyst control valves. The process designer may still, however, specify the overall operating pressure of the system. Lower operating pressures tend to favor product yield selectivity, spent catalyst stripper performance, and air blower horsepower requirements; but these advantages come with increased vessel sizes and thus higher investment cost. In addition, the economics of flue gas expanders are improved with increased regenerator operating pressure. Economic analysis comparing high-pressure and low-pressure designs and yield performance have concluded that investment in a lower-pressure unit is the most attractive, even if a flue gas expander is included in the analysis [7].

2.6.2.5 Feed Temperature

The design feed temperature affects the feed preheat exchanger train configuration and the possible requirement of a fired feed heater.

In general modern FCCU designs do not include fired feed heaters, except for those units designed to emphasize the production of middle distillates [7].

2.6.3 Development of FCC Catalysts

At the heart of FCC units are the catalysts themselves. The development of active and stable FCC catalysts went parallel with the FCC design development. It was known, that for cracking of C-C bonds, the acid catalysts are needed. The first acid catalyst, tested for cracking of heavy petroleum fraction, was aluminum chloride. But the problems with the manipulation, corrosion and the wastes treatment were greater than its positive action. In the 1940’s, silica-
alumina catalysts were created and greatly improved over the natural clay catalysts. It was Houdry, who for the first time used acid-activated bentonites as active acid catalyst for catalytic cracking. But the most significant advance came in 1962 when zeolite catalysts were incorporated into the silica-alumina structures. Advances in catalysts have produced the greatest overall performance of FCC units over the last fifty years. After natural alumosilicates, also synthetic alumosilicates were prepared with outstanding cracking properties. Both natural and synthetic aluminosilicates (silica-alumina catalysts) were known for their Lewis acid sites. The early synthetic amorphous alumosilicate catalysts contained about 13 % wt. of Al2O3 (low alumina), in about 1955 the content of Al2O3 increased to about 25%. But when the zeolites were put into their structure, strong Bronsted acid sites resulted, with very easily accessible Lewis acid sites also present. After experimentation, it was found that these new catalysts possessed all of the properties required of a successful catalyst: activity, stability, selectivity, correct pore size, resistance to fouling, and low cost. In 1962 a catalyst known as Zeolite-Y was added to the active alumina catalyst. Researchers from Mobil Oil found that by adding small amounts of zeolite into the matrix of the older silica-alumina catalyst structures, a new catalyst was produced which performed notably better than any catalyst before. The zeolite catalyst vastly improved gasoline yield and quality. The first commercial zeolite catalysts were introduced in 1964, and zeolite catalysts are still in use today. Not only quality of acid component of cracking catalysts has a great importance for the use in FCC-process. The very important properties of the catalysts are size and shape of catalyst particles. In Hourly’s fixed-bed catalytic cracking unit the catalyst – activated bentonite was probably in the form of pellets. For Thermofor catalytic cracking unit the catalysts were of spherical shape with the diameter of about 1-2 mm For FC technology, the finely powdered catalyst was originally obtained by grinding the catalyst material [8].

2.6.3.1 Zeolites as acid component of FCC catalysts

Natural zeolites were known from 1765, when the first natural zeolite was discovered by Swedish mineralogist Croensted. Since that time, more naturally-occurring zeolites as mineralogical rarities were discovered in volcanic rocks Because of the very small quantities of zeolite supply, their use was impossible. Only after the discovery of huge resources of some types of natural zeolites in sedimentary rocks, great applications were opened in ionexchange and sorption areas. At the same time, their catalytic properties were studied, and the great effort to prepare synthetic zeolites started. It is impossible to ion-exchange sodium cation into ammonium cation and to calcine them to obtain H-form, because such form is not stabile and after such treatment the crystalline zeolite structure collapses. To obtain acid catalytic activity of
X-zeolite, the only possibility was the ion-exchange with multivalent cations, partially with calcium, but predominantly with rareearths, mainly Lantanum and/or Cerium (REX). But, such prepared HY-zeolite was still not stabile in the conditions of FCC technology - the presence of 100% steam at high temperature: in riser, reactor and stripper about 550 °C, in regenerator more than 700 °C. At such “hydrothermal” conditions, then hydrolysis of framework aluminium occurs and the frameworks strongly dealuminates, causing partial and even total collapse of zeolite Y structure.

The first solution of the Y-zeolite instability was ion-exchange with rare-earths cations similarly as in the case of X-zeolites. REY zeolites were for long-time the most used zeolites in FCC-catalysts.

Later, the method of stabilization of zeolite Y structure without RE-cations was developed: ammonium-exchanged zeolite was treated in special conditions by 100% steam at the temperature up to 800 °C, causing partial dealumination of framework, creation of extraframeworkaluminium (weak Lewis acid centers), but in the framework still rest strong Broensted acid sites necessary for cracking. Such treated Y-zeolites were extremely stable, and were called as “ultrastablezeolites Y” – USY. This kind of Y-zeolites represented the new generation of acid component in FCC-catalysts.

Special types of FCC catalyst is zeolite ZSM-5 containing catalyst, used as additive to standard FCC catalyst to increase RON of produced gasoline and/or to increase the propylene yield. This ZSM-5 zeolites has strong “reactant selectivity” and crack predominantly nalkanes. Because the cracking over acid centers proceeds via cracking of beta C-C bond to created secondary (or tertiary) carbonium ions, the main product of cracking of longer nalkanes propene (or butenes) [8].

2.6.3.2 Catalyst Handling

The RFCC catalyst handling system has three separate and unique functions:

- Spent catalyst storage and withdrawal.
- Fresh catalyst storage and addition.
- Equilibrium catalyst storage and addition.

The spent hopper receives hot catalyst intermittently from the second-stage regenerator to maintain proper catalyst inventory during operation. In addition, the spent catalyst hopper is used to unload, store, and then refill the entire catalyst inventory during R2R shutdowns. The fresh catalyst hopper provides storage of catalyst for daily makeup. A loader, located just beneath the hopper, loads fresh catalyst from the hopper to the first-stage regenerator.
Fresh catalyst makeup is based on maintaining optimal unit catalyst activity and should be on a continuous basis. Like the fresh catalyst hopper, the equilibrium catalyst hopper provides storage of catalyst for daily makeup. Equilibrium catalyst serves to flush metals from the unit equilibrium catalyst in processing of residual feeds with high metal content. However, equilibrium catalyst usually does not contribute much to cracking activity. As a result; the equilibrium catalyst addition rate is based on targeted metal content on unit equilibrium catalyst, while the fresh catalyst makeup rate is based on maintaining unit catalyst activity. An equilibrium catalyst loader is located just beneath the hopper which supplies equilibrium catalyst to the first-stage regenerator. It is critical that the equilibrium catalyst be compatible with residual operations and usually should not be more than one-third of the total catalyst makeup [7].

2.6.3.3 RFCC Catalyst

Catalyst Type:

A successful residual cracking operation depends not only on the mechanical design of the converter but also on the catalyst selection. To maximize the amount of residual content in the RFCC feed, a low-delta-coke catalyst must be employed. Delta coke is defined as

$$\text{Delta coke} = \text{wt \% carbon on spent catalyst} - \text{wt \% CRC}$$

Where CRC = carbon on regenerated catalyst, or as

$$\text{Delta coke} = \text{coke wt \% feed}$$

Catalyst/oil ratio

Delta coke is a very popular index and when increased can cause significant rises in regenerator temperature, ultimately reducing the amount of residual feed that can be processed. Catalytic coke (deposited slowly as a result of the catalytic reaction)

- Feed-derived coke (deposited quickly and dependent on feed CCR).
- Occluded coke (entrained hydrocarbons).
- Contaminant coke (coke produced as a result of metal contaminants).

Because the feed-derived coke becomes a large contributor to the overall delta coke in processing residual feeds it is crucial that the overall delta coke be minimized in a residual FCC operation [7].

2.6.3.4 Catalyst Addition

Virgin residual feeds may contain large amounts of metals, which ultimately are deposited on the catalyst. Because of the mild two-stage regenerators, the catalyst metal content can be allowed to approach 10,000 wt ppm (Ni +V) before product yields are significantly affected. For an RFCC operation, catalyst addition is based on maintaining catalyst activity as well as metals on catalyst as opposed to maintaining only activity for typical FCC gasoil operations. The
most economical way to maintain both activity and metals is to add both fresh catalyst and purchased equilibrium catalyst. Equilibrium catalyst is an effective metal-flushing agent however equilibrium catalyst does not contribute much cracking activity. As a result, equilibrium catalyst is added with fresh catalyst in order to economically control both the unit catalyst activity and metal content. Care must be taken that the equilibrium catalyst chosen is compatible with residual operations and should not be more than one-third of the total catalyst additions [7].

2.7 Two-Stage Regeneration

In the two-stage regeneration process, the catalyst is regenerated in two steps: 50 to 70 percent in the first-stage regenerator and the balance in the second-stage regenerator. The first-stage regeneration is controlled by operating the first stage in an oxygen deficient environment, producing significant amounts of carbon monoxide. Since the heat of combustion of carbon to carbon monoxide is less than one-third of that for combustion to carbon dioxide, much less heat is transferred to the catalyst than in a single-stage full combustion regenerator. The remaining carbon on the catalyst is burned in the second-stage regenerator in full combustion mode. Because of the possible elevated temperature, external cyclones are employed to minimize regenerator internals and allow carbon-steel construction [7].

2.8 Lower Catalyst Particle Temperature

A catalyst cooler removes heat after it is produced inside the regenerator while less heat is produced in the regenerator with a two-stage regenerator design. This results in a lower catalyst particle temperature during combustion reducing overall catalyst deactivation. Since the combustion is occurring in two steps, the combustion severity of each step is low. In the first-stage regenerator, the catalyst enters the bed from the top through the spent catalyst distributor while the combustion air enters the bed at the bottom of the vessel. This countercurrent movement of catalyst and air prevents the contacting of spent catalyst (high carbon) with fresh air containing 21 percent oxygen. All these factors result in lower catalyst thermal deactivation for the two-stage regeneration system [7].

2.9 Lower Hydrothermal Deactivation

While the catalyst is only partially regenerated in the first stage, most of the water formed by the combustion of the hydrogen in the coke is removed in this vessel. Since the temperature of the first-stage regenerator is low, catalyst hydrothermal deactivation is significantly reduced. In the second-stage regenerator, where the bed temperature is high, moisture is minimal and does not pose a significant hydrothermal deactivation risk for the catalyst [7].
2.10 Better Metal Resistance

When refiners run high-metal feeds, it is very advantageous to be able to run with high metal levels on the equilibrium catalyst. Studies have clearly shown that high metal levels (particularly vanadium) lead to excessive catalyst deactivation in the presence of steam and oxygen. Since most of the steam in a regenerator comes from the hydrogen in the coke, the moisture content can be calculated in a straightforward manner. For a single-stage regenerator this will usually be more than 10 percent moisture. When steam and vanadium react in the presence oxygen, vanadic acid is formed; this attacks the alumina in the catalyst zeolite structure. Massive dealumination causes the collapse of the zeolite structure and the resulting catalyst is left with little activity. The equations

\[ 2V + O_2 \rightarrow V_2O_5 \]  \hspace{1cm} (2.1)

And

\[ V_2O_5 + 3H_2O \rightarrow 2VO(OH)_3 \]  \hspace{1cm} (2.2)

Vanadic acid describe the generation of vanadic acid. As a result catalyst in a single-stage regenerator operating in the presence of excess oxygen and steam is prone to vanadic acid attack. Also \( V_2O_5 \) has a very low melting temperature and can be liquid at typical regenerator conditions. Staging the regeneration can be particularly effective in this situation. In the first-stage regenerator, most of the hydrogen (and subsequent water vapor) is removed at low temperature without the presence of oxygen. This is followed by a full-burn second-stage regenerator where there is excess oxygen but very little moisture. Vanadium destruction of the catalyst structure is minimized, since very little \( V_2O_5 \) is present in the first-stage regenerator because of the lack of oxygen and lower temperature, while vanadic acid is minimized in the second-stage regenerator by lack of water. In other word the reaction

\[ 2V + O_2 \rightarrow V_2O_5 \]  \hspace{1cm} (2.3)

Proceeds very slowly in the first-stage regenerator because of a lack of oxygen while the reaction

\[ V_2O_5 + 3H_2O \rightarrow 2VO(OH)_3 \]  \hspace{1cm} (2.4)

Proceeds slowly in the second-stage regenerator because of low steam content. The two-stage regeneration is clearly less severe with regard to catalyst deactivation; and this coupled with the newer generation of catalyst with vanadium traps, will allow refiners to run heavier crudes more efficiently and economically than ever before [7].
2.11 Process Chemistry

Feed stocks for the FCC process are complex mixtures of hydrocarbons of various types and sizes ranging from small molecules, like gasoline, up to large complex molecules of perhaps 60 carbon atoms. These feed stocks have a relatively small content of contaminant materials, such as organic sulfur, nitrogen compounds, and organometallic compounds.

The relative proportions of all these materials vary with the geographic origin of the crude and the particular boiling range of the FCC feedstock. However, feedstock can be ranked in terms of their crackability, or the ease with which they can be converted in an FCC unit. Crack ability is a function of the relative proportions of paraffinic, naphthenic, and aromatic species in the feed. Sulfur compounds do not seriously affect crack ability; the cracked sulfur compounds are distributed into the liquid products, thus creating a need for product cleanup before final use. In addition, sulfur exits from the FCC unit in the form of H2S and sulfur oxides, the latter posing a potential air pollution problem.

The organometallic compounds deposit on the circulating catalyst, and after regeneration, almost all the metals in the feedstock remain deposited on the catalyst. These deposited metals haven two rather serious deleterious effects: They affect product distribution by causing more light gases, especially hydrogen, to be formed, and they have a serious deactivating effect on the catalyst. To counteract these effects more fresh catalyst must be added to maintain activity. Heavy poly nuclear aromatic-ring compounds are extremely refractory and these molecules are generally accepted as coke precursors [7].

2.12 A carbonium ion mechanism

All cracking catalysts, either the older amorphous silica alumina or modern zeolites, are acidic materials; and reactions of hydrocarbons over these materials are similar to well-known carbonium ion reactions occurring in homogeneous solutions of strong acids. These reactions are fundamentally different from thermal cracking. In thermal cracking bond rupture is random; but in catalytic cracking, it is ordered and selective.

Various theories have been proposed to explain how the cracking process is initiated, that is how the first carbonium ions are formed. One theory proposes that the carbonium ion is formed from an olefin, which in turn could be formed by thermal effects on initial catalyst-oil contact or may be present in the feed. The temperatures involved in catalytic cracking are in the range where thermal cracking can also occur. Alternatively, the carbonium ion could be formed by the interaction of the hydrocarbon molecule with a Brønsted or Lewis acid site on the catalyst. The harmonium ions can react in several ways:

- Crack to smaller molecules
- React with other molecules
- Isomerizes to a different form
- React with the catalyst to stop the chain

As coke is produced through these mechanisms, it eventually blocks the active acid sites and catalyst pores. The only recourse is to regenerate the catalyst to retain its activity by burning the coke to CO and CO\(_2\) in the FCC regenerator [7].

2.13 Control of FCCU

There are many control formulations that concern the description of the control system of a fluidized catalytic cracking unit (FCCU) and how to choose the controlled variables, manipulated variables and disturbance variables. The following are some scientific searches in this field.

Snodgrass [9] developed the three principal Feedback loops that provide the automatic control and these are: (1) control of reactor catalyst level by manipulation of spent catalyst rate, (2) control of a reactor temperature by manipulation of the regenerated catalyst rate; and (3) control of flue-gas oxygen composition by manipulation of regenerator air rate. Grosdidieret al[10]. provided simulation results for a representative FCCU regenerator control problem. The problem involves controlling flue gas composition, flue gas temperature, and regenerator bed temperature by manipulating feed oil flow, recycle oil flow and air to the regenerator. McFarlane et al[11]. developed their model as following: controlled variables (cracking temperature and Flue gas oxygen concentration), manipulated variables (lift air compressor speed and flue gas valve opening). Churing et al [12]. Made the formulation of a FCCU control as following: Controlled variables (riser outlet temperature, reactor bed and regenerator differential and reactor bed level), manipulated variables (regenerator catalyst flow rate, flue gas flow rate and spent catalyst flow rate). Moro & Odloak [13] proposed six variables to be controlled: riser temperature, severity, temperature of the dense phase of the regenerator first stage, temperature of the regenerator dense phase of the second stage, the differential valve pressure of the regenerated catalytic and the rotation velocity of the gas compressor. They also proposed the following manipulated variables: feed flow rates to 10 the unit, air flow rate to the regenerator, valve opening of the regenerated catalytic and the feed temperature. The chosen controlled variable here was the temperature of the dense phase of the regenerator first stage, manipulating the air flow rate to the regenerator. Finally, the fluid catalytic cracking (FCC) unit, owing to the tight interaction between the regenerator and the reactor, is dynamically sensitive. It is difficult to accomplish satisfactory control of the FCC operation under frequent disturbances. Since the FCC unit is one of the principal refinery processes for gasoline production, an understanding of its
dynamic characteristics is extremely important. It is, therefore, not surprising that a number of investigators have studied the dynamics and control of the FCC [14].

### 2.14 Severity Control Module

This module manipulates the riser outlet temperature, feed flow rates and feed temperature to operate the unit within its constraints while satisfying a specified operating objective. Typical constraints considered by the system include catalyst valve differential, regenerator temperature, coke-burning rate, wet gas make, and fractionator overhead liquid flow rate. The operating objective is selected by the operator through a menu. Based on client requirements and specific refinery objectives, the menu may include options such as those listed:

- Maximize reactor temperature while maintaining a feed rate target.
- Maximize feed rate while maintaining a reactor temperature target.
- Minimize feed temperature while maintaining a reactor temperature target [6].

### 2.15 Combustion Control Module

This module maintains the oxygen composition in the regenerator flue gas at a specified control target by manipulating the airflow rate. This module compensates for changes in the feed rate, recycle flow rate, riser outlet temperature, and feed temperature in a feed forward manner, which assists the system in maintaining the flue gas oxygen concentration close to the target at all times [6].

### 2.16 Pressure Balancing and Control Module

This module controls the overall converter pressure by manipulating the wet gas compressor suction pressure. The suction pressure is controlled to maximize the utilization of available air blower and wet gas compressor capacity. It also distributes the available pressure differential across the catalyst valves by manipulating the reactor/regenerator pressure differential which maximizes converter catalyst circulation capacity [6].

### 2.17 Control and Simulation of FCC Unit

The analysis and control of FCC process have been known as a challenging problems due to the following process characteristics: (1) very complicated and little known hydrodynamics, (2) complex kinetics of both cracking and coke burning reactions, (3) strong interaction between reactor and regenerator and many operating constrain [15].

### 2.18 Continuous control systems

#### 2.18.1 P – action equation

\[ m_\text{(t)} \alpha e_\text{(t)} \quad \text{ ............... (2.5)} \]

\[ m_\text{(t)} = K_\text{(c)} \ e_\text{(t)} \quad \text{ ........... (2. 6)} \]

Taking L. T of equation (2.5):
\[ m(s) = K_c \cdot E(s) \]

\[ (\text{M/E})_s = K_c \]

The P-controller transfer function is:

\[ G_c = K_c \]

\[ K_c \text{ is referred to as the controller gain.} \]

### 2.18.2 Integral Action, I–Action:

\[ e(t) \quad G_c \quad m(t) \]

the integral action is defined as: \[ m(t) = \alpha \int_0^t e(t) \cdot dt \quad \ldots \ldots \quad (2.7) \]

The proportionality constant = \[ \frac{K_c}{\tau_i} \]

Where:

\[ K_c \text{ = proportional gain} \]

\[ \tau_i \text{ = integral time} \]

Equation (2.3) becomes:

\[ m(t) = \frac{K_c}{\tau_i} \int_0^t e(t) \cdot dt \quad \ldots \ldots \quad (2.8) \]

taking L.T of equation (2.8)

\[ M(s) = \frac{K_c}{\tau_i s} \cdot E(s) \]

\[ G_c = \left( \frac{M}{E} \right)_{(s)} = \frac{K_c}{\tau_is} \]

\[ E(s) \quad \frac{K_c}{\tau_is} \quad M(t) \]

### 2.18.3 Derivative Action (D–Action):

\[ + \quad e(t) \quad - \quad R(s) \quad \text{Controller} \quad G(s) \]

\[ m(t) = \alpha \frac{de(t)}{dt} \quad \ldots \ldots \quad (2.9) \]

\[ m(t) = K_c \cdot TD \frac{de(t)}{dt} \quad \ldots \ldots \quad (2.10) \]

Taking L.T of equation (2.10)
\[ M(s) = K_c \tau_D E(s) \]

\[
\left( \frac{M}{E} \right)_{(s)} = Kc \tau ds \]

(2.11)

Derivative Action Response:

Take step change in the input:

\[ E_{(t)} = A \]

\[
\frac{de(t)}{dt} = 0 \]

(2.12)

Putting eq (2.12) into eq (2.10):

\[ M_{(t)} = 0 \]

(2.13)

This means the D- action gives the same output \( m(t) \), whether \( e(t) = 0 \) or a constant.

\[ \therefore \] D- Action alone is incapable for performing control and a combined PD, or PID must be used, [16].

Chapter three
Materials and Methods

3.1 Materials
This comprise to:

3.1.1 Samples
In the following experiments all samples were taken from the Nile Blend.
The Nile Blend crude was fractionated into product cuts such as lighted hydrocarbons, naphtha, kerosene, diesel and atmospheric residue.

3.1.2 Unit Components and Production Capacity Used in this Analysis
The unit was designed by SINOPEC adopting two stages complete catalyst regeneration technology to process annually 1.8 million tons (225ton/hr) of atmospheric residue counting for 65% to 68% of the total crude oil (Nile Blend) processed by the CDU while the main products of the unit are LPG, High octane gasoline, LCO, HCO along with the dry gas and slurry which are consumed as a fuel in the refinery and electricity as a byproduct and mainly composed of the reaction-regeneration post, fractionation post, absorption post, desulphurization post, heavy machines and west-heat boiler section [17].

3.1.3 Reaction-Regeneration post
This section includes:
1. Riser reactor four primary cyclone separators (coarse cyclones) are installed at the outlet at the outlet of the riser and four single-stage cyclone separators (fine cyclones) are installed inside of settler.
2. 8 sets of two stage cyclone separators are installed inside the first regenerator emptiness is inside of the second regenerator, and 4 sets of two-stage cyclone separators are installed outside of the second regenerator.
3. The high activity ultra-stable molecular sieve catalyst is used in the riser reactor to remove the wasted heat; the external heat recovery device is installed at the outside of the first regenerator (external-type heat exchanger).
4. Flue gas recovery section: in order to sufficiently recover the waste heat, decreasing the energy consumption, high-temperature flue gas cooler, flue gas expander turbine and waste-heat boiler are installed on the mixed flue line of the first regenerator and second regenerator.
5. Catalyst cooler is being to ease the heat balance problem.
6. The cold wall design concept is adopted throughout the unit in riser, settler, regenerators, transfer lines, slide valves and external cyclones [18].
3.1.4 The procedure is as follows:

The procedure includes:
1. The overall transfer function has to be determined.
2. For the overall transfer function the characteristic equation is obtained.
3. Laplace operator (S) is set to be equal (io) and substituted in the characteristic equation.
4. The imaginary part is taken and equated to zero from which \( \omega_{co} \) is calculated; and so is the ultimate period this is equal \( \frac{2\pi}{\omega_{co}} \).

3.2 System Stability Method

This system includes:

3.2.1 Routh Array

We do not necessarily need to know the poles to determine stability, just the knowledge of which side of the complex plane the poles lay may be enough.

We can set up a Routh array to determine this (5). The steps are:

Express the characteristic equation as an expanded polynomial:

\[
(1 + GpGfGcGm) = a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0. \tag{3.1}
\]

- If any of the coefficients are negative, then there is at least one root with appositive real part and the system is unstable.

- Set up a table that looks like the following:

<table>
<thead>
<tr>
<th>Row</th>
<th>Coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( a_n )</td>
</tr>
<tr>
<td>2</td>
<td>( a_{n-1} )</td>
</tr>
<tr>
<td>3</td>
<td>( b_1 )</td>
</tr>
<tr>
<td>4</td>
<td>( c_1 )</td>
</tr>
<tr>
<td>5</td>
<td>( d_1 )</td>
</tr>
<tr>
<td>6</td>
<td>( e_1 )</td>
</tr>
</tbody>
</table>

Where the elements are found from equation as follows:

\[
b_1 = \frac{a_{n-1}a_{n-2} - a_n a_{n-3}}{a_{n-1}} = a_{n-2} - \frac{a_n a_{n-3}}{a_{n-1}} \tag{3.2}
\]

\[
b_2 = \frac{a_{n-1}a_{n-4} - a_n a_{n-5}}{a_{n-1}} = a_{n-4} - \frac{a_n a_{n-5}}{a_{n-1}} \tag{3.3}
\]

\[
c_1 = \frac{b_1 a_{n-3} - a_1 b_2}{b_1} = a_{n-3} - \frac{a_1 b_2}{b_1} \tag{3.4}
\]
The rule is to look at the square matrix above the element to be calculated. Use the values from column I and the column just to the right of the element of interest. Multiply the off diagonal terms, subtract the product of the diagonal terms, and divide by the element just above (5), if all of the elements in the 1st column are positive, then the system is stable.

If some of the elements in the 1st column are negative, the number of roots with a positive real part will be equal to the number of sign changes in the 1st column. The procedure is the flows

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 \(K_u\) [19].

### 3.2.2. 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 \(G_o = G_c G_v G_m\) 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.

**The procedure is the flows**

1- The open-loop transfer function is obtained.

2- using MATLAB the phase angle the amplitude ratio are plotted the gain the frequency \(\omega\).

3- A horizontal line from -180 degree is extended the cute the phase angle carve and by duple clicking and the period the inter section \(\omega_{co}\) is obtained.

4- From this point in part three the vertical line extended to meet AR amplitude ratio curve the horizontal line we read the amplitude ratio \(db\).

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

\[
20 \log AR = db \quad \text{then} \quad K_u = \frac{1}{AR}
\]
3.2.3 Root locus analysis

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, [19].

The procedure is the flows
1- Using MATLAB the root of the open loop is plotted a gain the frequency $\omega$.
2- By duple clacking on the cruces of the curve with imaginary axis $Ku$ and $P_u$ are obtained.
3.2.4 Controller 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 introduce oscillations, [20].

Method of tuning

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, [20].

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 $P_0$ (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 (3.2) Ziegler-Nicolas tuning parameter:

<table>
<thead>
<tr>
<th></th>
<th>Kc</th>
<th>$\tau_1$ (min)</th>
<th>$\tau_D$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5Ku</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PI</td>
<td>0.45Ku</td>
<td>$\frac{Pu}{1.2}$</td>
<td></td>
</tr>
<tr>
<td>PID</td>
<td>0.6Ku</td>
<td>$\frac{Pu}{2}$</td>
<td>$\frac{Pu}{8}$</td>
</tr>
</tbody>
</table>

### 3.2.5 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. Your goals for this lesson relate to that. Speed of response can be a little tricky because we have so many intuitive ideas of what we mean by speed of response. Let's review some of the ideas that often form a foundation for this concept.

- First order systems have time constants. Clearly, in those systems we can take the time constant as a measure of speed of response.
- For two first order systems, the system with the smaller time constant will respond more quickly to a step input or any other input.
- Knowing the time constant allows us to estimate aspects of a response. For example, a first order system with a time constant, $t$, will respond to a step input so that the system is within 5% of the final value in $3t$ seconds - i.e. three time constants.

The concept of a time constant works - and works well - for first order systems because it gives an unambiguous measure of speed of response. However, even having two time constants complicates the issue. Let's consider an example with more than one time constant. Here's a time response.

This response is the response of a linear system to a unit step.
There are other measures, and one of them is the settling time. We're going to take settling time as the time it takes to get within 10% of the final value, or to 90% of the final value - and, most importantly - stay within that 10%. That's going to make it interesting if you measure the settling time of a system that has oscillations.

Now, here's a response that forces us to think harder about what we mean by response time.

- Clearly this system has a short rise time. It looks to be just a few seconds.
- The settling time is also just a few seconds, since the response gets to within 90% in that time.
- The problem is that the response doesn't stay within 10% of the final value. It just passes through that range on its way to oscillation after oscillation.
- Settling time can be defined as the time it takes to get and stay within 10% of the final value.
- There's no substitute for knowing where the poles are zeroes are in a system. Knowing a system has five poles at \( s = -1 \) is more information than knowing rise time because you can plot the response and compute rise time and more. (Root locus analysis will help you determine where the poles are located in a closed loop system.)
Ten-to-Ninety rise time is the time it takes to go from 10% to 90% of the final value. It can be misleading if the system oscillates or if there is a delay getting started. Settling time can be a good way to measure response time as long as care is taken to ensure that the response stays within 10% (or 5%?) of the final, steady-state value.

The time response represents how the state of dynamic system changes when subjected to particular input. Since the models have 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 calculating the time response for many types of inputs.

MATLAB provides tools for automatically choosing optimal PID gains.

The tuning algorithm directly using "pidtune" or through using "pidtool" [21].

**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 plot the following can be obtained:

   * The rise time.
   * Break time.
   * The overshoot.
   * The decay ratio.
   * The recovery or settling time.
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, [22].

3.4 Control Loop Identification

One control strategy was developed as shown in Figure (3.6).

1. Temperature control, Riser temperature versus regenerated catalyst from the second regenerator.
2. Catalyst level control versus regenerated catalyst from the first regenerator.
3. Pressure control for second and first regenerators, manipulating exit flue gas.
4. Steam rate versus set point.
5. Level in the reactor versus spent catalyst from the reactor to regenerator 1.
6. Temperature in the second regenerator versus hot air flow rate to the second regenerator.
7. Temperature in the first regenerator versus hot air flow rate to the first regenerator.
8. Local feedback control of the hot air to the first and second regenerator versus desired value or set point.

The system which studied consists of four loops with identified transfer functions. The system stability and adjustable parameters for Routh, locus and bode are studied and calculated by Zeigler-Nicolas Criterion. Results of the evaluation are shown as follow:
Mathematical models were developed for loop 1 through loop 4 and parameters of the transfer functions were cited from the literature [22, 23].

3.5 Transfer function identification

3.5.1 Loop 1

The characteristic equation:

$$4.8s^4 + 33.56s^3 + 50.52s^2 + 13.8s + (1 + 2Kc) = 0 \ldots \ldots \ldots (3.6)$$
Loop (2):

\[ G(s) (+) \]

\[ k \]

\[ \frac{1}{0.2s + 1} \]

\[ \frac{5}{5s + 1} \]

S.P (−)

Fig (3.8) Loop (2) block diagram

The Characteristic equation:

\[ 0.1s^3 + 1.52s^2 + 5.3s + (1 + 5Kc) = 0 \]  \hspace{1cm} (3.7)

Loop (3):

\[ G(s) (+) \]

\[ KC \]

\[ \frac{2}{(7s + 1)(2s + 1)} \]

\[ \frac{1}{0.5s + 1} \]

S.P (−)

Fig (3.9) Loop (3) block diagram

The Characteristic equation:

\[ 1.4s^4 + 10.7s^3 + 20.4s^2 + 9.7s + (1 + 2Kc) = 0 \]  \hspace{1cm} (3.8)
Loop (4):

\[ G(s) + R(s) \]

\[ S.P \]

\[ k_c \]

\[ \frac{0.3}{(2s + 1)(s + 1)} \]

\[ \frac{2}{s + 1} \]

\[ \frac{1}{0.2s + 1} \]

Figure (3.10): loop3 block diagram

\[ 0.4S^4 + 3S^3 + 5.8S^2 + 4.2S + (1 + 0.6Kc) = 0 \] \hspace{0.5cm} (3.9)

Taking loop1 as an example:

Calculation of the overall transfer function and characteristic equation:

\[ G(s) = \frac{n_F}{1 + \pi_L} \] \hspace{0.5cm} (3.10)

\[ \pi_F = \frac{2Kc}{(8s + 1)(5s + 1)(0.6s + 1)} \] \hspace{0.5cm} (3.11)

\[ \pi_L = \frac{2Kc}{(8s + 1)(5s + 1)(0.6s + 1)(0.2s + 1)} \] \hspace{0.5cm} (3.12)

\[ 1 + \pi_L = \frac{(08s+1)(5s+1)(0.6s+1)(0.2s+1)+2Kc}{(08s+1)(5s+1)(0.6s+1)(0.2s+1)} \] \hspace{0.5cm} (3.13)

The characteristic equation:

\[ (8s + 1)(5s + 1)(0.6s + 1)(0.2s + 1) + 2Kc=0 \] \hspace{0.5cm} (3.14)

\[ 4.8S^4 + 33.56S^3 + 50.52S^2 + 13.8S + (1 + 2Kc) = 0 \] \hspace{0.5cm} (3.15)

Application of Routh array:

Number of rows=n+1 =4+1= 5
\[
\begin{pmatrix}
4.8 & 50.52 & (1 + 2Kc) \\
33.56 & 13.8 & 0 \\
a_1 & a_2 & 0 \\
b_1 & 0 & 0 \\
l_c & 0 & 0
\end{pmatrix}
\]

\[
a_1 = \frac{(33.56 \times 50.52) - (4.8 \times 13.8)}{33.56} = 48.546 \ldots \ldots (3.16)
\]

\[
a_2 = \frac{((33.56 \times ) (1 + 2Kc)) - (0 \times 4.8)}{33.56} = (1 + 2Kc) \ldots (3.17)
\]

\[
b_1 = \frac{(47.546 \times 13.8) - (33.56 \times (1 + 2Kc))}{48.546} = (3.18)
\]

\]

\[Cl = 1 + 2Kc\]

For the system to be critically stable the row number (n-1) is equal zero:-

\[b_1 = 0\]

587.829-67.12 \ Kc=0

So \ Kc=8.758

The ultimate gain \ Ku =8.758

Determination of the ultimate period by direct substitution method (\(\omega_{co}\)):-

Set \(s=i\omega\)

\[4.8(i\omega)^4 + 33.56(i\omega)^3 + 50.52(i\omega)^2 + 18.8i\omega + (1 + 2Kc) = 0 \ldots (3.20).\]

\[4.8\omega^4 - 33.56\omega^3 - \omega 50.52^2 + 13.8i\omega + (1 + 2Kc)0 \ldots (4.10). \ \text{Im}=13.8\omega - 33.56\omega^3 \]

18.8 - 33.56\omega^2 = 0

33.56\omega^2 = 13.8

\(\omega^2 = 0.411\)

\(\omega_{co}=0.64 \ \text{rad/ sec}\)

\[Pu = \frac{2\pi}{\omega_{co}} \ldots \ldots \ldots \ldots \ldots (3.21)\]

\[Pu = \frac{2\pi}{0.64} = 9.8 \text{ sec}\]
Root – locus method:

\[ \text{OLTTF} = \frac{2Kc}{(8s + 1)(5s + 1)(0.6s + 1)(0.2s + 1)} \] .... (3.22)

Application of MATLAB:

\begin{verbatim}
≫ num = [2];
≫ den = conv(conv([8 1], [5 1]), conv([0.6 1], [0.2 1]));
≫ sys = tf(num, den);
≫ rlocus(sys), grid
≫ den = conv(conv([8 1], [5 1]), conv([0.6 1], [0.2 1]));
≫ sys = tf(num, den);
≫ rlocus(sys), grid
\end{verbatim}

![Root Locus Diagram]

Fig (3.11) Root-Locus of Loop (1)

\( \omega_{co} = 0.628 \text{ (rad/sec) } \)
\[ Pu = \frac{2\pi}{0.628} = 10.005 \text{ sec} \quad \ldots \quad (3.23) \]

\[ K_u = 9.07 \]

**Bode diagram tuning method**

**Application of MATLAB**

```plaintext
≫ num = [2];
≫ den = conv(conv([8 1], [5 1]), conv([0.6 1], [0.2 1]));
≫ sys = tf(num, den);
≫ bode(sys), grid
```

![Bode Diagram](image)

Fig (3.12) Bode plot of loop (1)

From the overall transfer function of loop (1) is calculated: 

at \(-180\) \[ \omega_{co} = 0.646 \text{ rad/sec} \]

\[ Pu = \frac{2\pi}{0.646} = 9.72 \text{ min} \quad \ldots \quad \ldots \quad (3.24) \]
Magnitude (db) = -19.7

\[20 \log AR = \text{db}\]

20 log AR = -19.7

Log AR = \frac{-19.7}{20}

Log AR = -0.985

AR = 0.1035

\[K_u = \frac{1}{AR}\]

Ku = 9.7

\[K_u(\text{average}) = \frac{K_u(R) + K_u(R - L) + K_u(B)}{3}\]

Ku (average) = \frac{8.70 + 9.07 + 9.7}{3} = 9.157

\[Pu(\text{average}) = \frac{Pu(R) + Pu(R - L) + Pu(B)}{3}\]

Pu (average) = \frac{9.8 + 10.005 + 9.72}{3} = 9.847 \text{ sec}

Table (3.3): Z-N Tuning parameters using average ultimate gains and period (K_u, P_u):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>K_c</th>
<th>T_1 (min)</th>
<th>T_D (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>4.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>4.121</td>
<td>8.2</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>5.494</td>
<td>4.9</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Checking stability using Routh and average design parameters:

The characteristic equation of loop (1) is:

\[4.8S^4 + 33.56S^3 + 50.52S^2 + 13.8S + 10.2 = 0\]
Routh array analysis:

\[
\begin{array}{ccc}
4.8 & 50.52 & 10.2 \\
33.56 & 13.8 & 0 \\
47.8 & 10.2 & 0 \\
10.2 & 0 & 0 \\
10.7 & 0 & 0
\end{array}
\]

The first column of array to check stability:

\[
\begin{array}{c}
4.8 \\
33.56 \\
47.8 \\
10.2 \\
10.7 \\
10.2
\end{array}
\]

The system is stable. All elements of the first column are positive and there is no change of sign and all the roots lie on the LHP.

Off Set Investigation

\[
G(s) = \frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{\pi f}{1 + \pi l}
\]

\[
G(s) = \frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{2Kc (0.2s + 1)}{4.8s^4 + 33.56s^3 + 50.52s^2 + 18.8s + (1 + 2Kc)}
\]

\[
Kc=5.25 \quad \text{from tuning}
\]

\[
\frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{9.2 (0.2s + 1)}{4.8s^4 + 33.56s^3 + 50.52s^2 + 18.8s + 10.2}
\]

Off Set = \( C_u - Cid \)

\[
C_u = \lim_{s \to 0} [s \dot{y}(s)]
\]

Cid = magnitude of unit step change = 1

\[
\dot{y}sp(s) = \frac{1}{s}
\]

\[
C_u = \lim_{s \to 0} \left[ \frac{9.2(0.2s + 1)}{4.8s^4 + 33.56s^3 + 50.52s^2 + 13.8s + 10.2} \right] \frac{1}{s}
\]
\[ C_c = \begin{bmatrix} 9.2 \\ 10.2 \end{bmatrix} = 0.902 \]
\[ \epsilon = 1 - 0.913 = 0.098 \]

**Simulation of the system response**

\[ G(s) = \frac{\pi f}{1 + \pi l} = \frac{2Kc (0.2s + 1)}{4.8s^4 + 33.56s^3 + 50.52s^2 + 13.8s + (1 + 2Kc)} \]

\[ G(s) = \frac{1.84s + 9.2}{4.8s^4 + 33.56s^3 + 50.52s^2 + 13.8s + 10.2} \]

**The response of the system**

**MATLAB application**

\[ \text{≫ } \text{num} = [1.84 \hspace{0.5cm} 10.2]; \]
\[ \text{≫ } \text{den} = [4.8 \hspace{0.5cm} 33.56 \hspace{0.5cm} 50.52 \hspace{0.5cm} 13.8 \hspace{0.5cm} 10.2 ]; \]
\[ \text{≫ } \text{impulse (num,den) } \]

![Impulse Response](image)

Fig (3.13) step response of loop (1)

Beak time = 3.25 sec  
Over shoot = 0.31  
Settling time = 38 sec
Chapter Four
Results and Discussion

4.1 Results

4.1.1 Control Loops

From the characteristic equation of loop1, the ultimate gain and ultimate period are determined by Routh, Root – locus and Bode methods. Results are shown in table (4.1):

Table (4.1): Ultimate gain and ultimate period for loop1

<table>
<thead>
<tr>
<th>Method</th>
<th>Ku</th>
<th>Pu (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh</td>
<td>8.758</td>
<td>9.8</td>
</tr>
<tr>
<td>Root – locus</td>
<td>9.07</td>
<td>10.005</td>
</tr>
<tr>
<td>Bode</td>
<td>9.7</td>
<td>9.72</td>
</tr>
</tbody>
</table>

Ku (average) = 9.157
Pu (average) = 9.847 sec

From the characteristic equation of the loop2, the ultimate gain and ultimate period are determined by Routh, Root – locus and Bode methods. Results are shown in table (4.2):

Table (4.2): Ultimate gain and ultimate period for loop2

<table>
<thead>
<tr>
<th>Method</th>
<th>Ku</th>
<th>Pu (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh</td>
<td>15.9</td>
<td>0.86</td>
</tr>
<tr>
<td>Root – locus</td>
<td>15.7</td>
<td>0.868</td>
</tr>
<tr>
<td>Bode</td>
<td>16.03</td>
<td>0.865</td>
</tr>
</tbody>
</table>

Ku (average) = 15.88
Pu (average) = 0.864 sec
Fig (4.1) Root-Locus of Loop (2)

Fig (4.2) Bode plot of loop (2)
Table (4.3): Z-N Tuning parameters using average ultimate gains and period (Ku, Pu):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>Ke</th>
<th>Tw (sec)</th>
<th>T1 (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>7.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>7.146</td>
<td>0.72</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>9.528</td>
<td>0.432</td>
<td>0.108</td>
</tr>
</tbody>
</table>

Simulation of the system response:

Fig (4.3) step response of loop (2)

Beak time = 0.184 sec

Over shoot = 5.91

Settling time = 6.1 sec
From the characteristic equation of the loop3, the ultimate gain and ultimate period are determined by Routh, Root – locus and Bode methods. Results are shown in table (4.4):

Table (4.4): Ultimate gain and ultimate period for loop3

<table>
<thead>
<tr>
<th>Method</th>
<th>Ku</th>
<th>Pu (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh</td>
<td>8.169</td>
<td>6.6</td>
</tr>
<tr>
<td>Root – locus</td>
<td>7.68</td>
<td>6.8</td>
</tr>
<tr>
<td>Bode</td>
<td>8.3</td>
<td>6.6</td>
</tr>
</tbody>
</table>

Ku (average) = 8.1  
Pu (average) = 6.7 sec

Fig (4.4) Root-Locus of Loop (3)
Fig (4.5) Bode plot of loop (3)

Table (4.5): Z-N Tuning parameters using average ultimate gains and period (K_u, P_u):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>K_c</th>
<th>τ_1 (sec)</th>
<th>τ_1 (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>4.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>3.645</td>
<td>5.6</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>4.86</td>
<td>3.35</td>
<td>0.8375</td>
</tr>
</tbody>
</table>
Simulation of the system response:

Fig (4.6) step response of loop (3)

Beak time = 2.33 sec
Over shoot = 0.459
Settling time = 39.4
Rise time = 4.79
Offset = 0.00128

From the characteristic equation of the loop4 the ultimate gain and ultimate period are determined by Routh, Root – locus and Bode methods. Results are shown in table (4.6):

Table (4.6): Ultimate gain and ultimate period for loop4

<table>
<thead>
<tr>
<th>Method</th>
<th>Ku</th>
<th>Pu (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Routh</td>
<td>10.58</td>
<td>5.325</td>
</tr>
<tr>
<td>Root – locus</td>
<td>10.3</td>
<td>5.37</td>
</tr>
<tr>
<td>Bode</td>
<td>10.59</td>
<td>5.325</td>
</tr>
</tbody>
</table>

Ku (average) = 10.49
Pu (average) = 5.34 sec
Fig (4.7) Root-Locus of Loop (4)

Fig (4.8) Bode plot of loop (4)
Table (4.7): Z-N Tuning parameters using average ultimate gains and period (K_u, P_u):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>K_c</th>
<th>T_1 (sec)</th>
<th>T_2 (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>5.245</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>4.721</td>
<td>4.45</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>6.294</td>
<td>2.67</td>
<td>0.668</td>
</tr>
</tbody>
</table>

Simulation of the system response:

Fig (4.9) step response of loop (3)

Beak time = 2 sec

Over shoot = 0.521

Settling time = 29.3 sec

Rise time = 3.76 sec
Applying the Off Set Investigation method for loops 1, 2, 3 and 4 and taking unit step change in the input, the offset are determined and tabulated in the following table:

Table (4.8) Offset investigation values of loops 1, 2, 3 and 4

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>$\varepsilon$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.098</td>
</tr>
<tr>
<td>2</td>
<td>0.025</td>
</tr>
<tr>
<td>3</td>
<td>0.12</td>
</tr>
<tr>
<td>4</td>
<td>0.241</td>
</tr>
</tbody>
</table>
Table (4.9): Summary of ultimate gain (Ku) and ultimate period (Pu) for loop 1, 2, 3 and 4

<table>
<thead>
<tr>
<th></th>
<th>Ku</th>
<th>Pu (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loop (1)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct substitution and Routh array method</td>
<td>8.7</td>
<td>9.8</td>
</tr>
<tr>
<td>Root-Locus method</td>
<td>9.07</td>
<td>10.005</td>
</tr>
<tr>
<td>Bode diagram tuning method</td>
<td>9.7</td>
<td>9.72</td>
</tr>
<tr>
<td><strong>Loop (2)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct substitution and Routh array method</td>
<td>15.9</td>
<td>0.86</td>
</tr>
<tr>
<td>Root-Locus method</td>
<td>15.7</td>
<td>0.868</td>
</tr>
<tr>
<td>Bode diagram tuning method</td>
<td>16.03</td>
<td>0.865</td>
</tr>
<tr>
<td><strong>Loop (3)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct substitution and Routh array method</td>
<td>8.169</td>
<td>6.6</td>
</tr>
<tr>
<td>Root-Locus method</td>
<td>7.68</td>
<td>6.8</td>
</tr>
<tr>
<td>Bode diagram tuning method</td>
<td>8.3</td>
<td>6.6</td>
</tr>
<tr>
<td><strong>Loop (4)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct substitution and Routh array method</td>
<td>10.58</td>
<td>5.325</td>
</tr>
<tr>
<td>Root-Locus method</td>
<td>10.3</td>
<td>5.37</td>
</tr>
<tr>
<td>Bode diagram tuning method</td>
<td>10.59</td>
<td>5.35</td>
</tr>
</tbody>
</table>
4.2 Discussions

It is cleared that in the existing control system depicted in figure (3.7), the level inside the regenerator and the temperature in the riser are controlled by manipulating the regenerated catalyst flow rate by two slide valves, at the same time the hot air rate is not controlled. The system depicted in Fig (3.7) was developed in this study, the transfer functions were identified and the overall transfer functions were calculated the characteristic equations as well as the closed loop and open loop transfer functions were determined as seen in tables (4.1) through (4.9). Routh Hurwitz, Root-Locus and Bode methods are used for stability analysis and tuning.

For all control loops the same calculation method has been used. The characteristic equations were determined as it is seen from eq (3.1) through (3.4). Routh, root-locus and bode method were used to determined ultimate gain and ultimate period as it seen in tables (4.1), (4.3), (4.5) and (4.7). The average ultimate gain and period are inserted into Zigler-Nicolas table to obtain adjustable parameters which shown in tables (4.2), (4.4), (4.6) and (4.8). All the systems in all control loops are shown to be stable. The method that gives the highest sensitivity is selected for simulation of the results, upon a step change in the input; the results are shown in figures ((4.6), (4.9), (4.12)). The values of control gain were taken and substituted in characteristic equations to check up the system stability by Routh method, and the system was actually stable. The Offset investigation has been done and tabulated in table (4.9).

Figures (4.1), (4.4), (4.7) and (4.10) showed Root locus. Root locus shows the ultimate gain and the frequency then the ultimate period could be determined by dividing $2\pi$ over frequency.

Figures (4.2), (4.5), (4.8) and (4.11) were Bode diagrams. Bode diagram shows frequency and magnitude then ultimate period could be calculated as it is done.

Figures (4.3), (4.6), (4.9) and (4.12) are impulse response. Impulse response shows steps response such as peak time, overshoot, rising time and settling time.
Chapter five

Conclusion and recommendations

5.1. Conclusion

Based on the control and simulation study and results of the control system of the FCCU, the following conclusions can be withdrawn:

Different methods were used in the computer simulation to optimize the numerical value of controller parameters; the MATLAB gave a good comparison between all methods. Routh Hurwitz, Root-Locus and Bode methods are used for stability analysis and tuning. All the systems in all control loops are shown to be stable. The tuning methods of Routh and bode give asymptotically equal parameters but with regard to the gain Root Locus does not in agreement with the two other methods as shown in the chapter four. The method that gives the highest sensitivity is selected for simulation of the results, upon a step change in the input; the results are shown in figures (4.3, 4.6, 4.9, and 4.12). Summary of the adjustable parameters are tabulated in tables (4.10).

5.2. Recommendations

It is recommended that the control system should be analyzed by using ASPENHYSYS process simulator and compares its results with results of MATLAB software application which used in this study. It is recommended that the control system in this unit should always be renewed by other controllers as those types of controllers which can adapt themselves according to the change of catalyst activity, temperature and pressure.
References


3. REFINERY ADVICE FROM SGS CRUDE OIL ASSAY TESTING SERVICES. © SGS SA 2011. ALL RIGHTS RESERVED.


5. Ghosh, S. “Recent advances in fluid catalytic cracking”, Petrotech society’s summer school program on advances in Petroleum Refining industry, 3-8 July 2006 held at IIPM, Gurgaon.


7. (Sudan’s Oil Industry Facts and Analysis, April 2008).

8. (A Barrel Full of information for Oil Industry Professionals.khartoum).


18. Operation manual for Residue Fluid Catalytic Cracking of KRC.


Appendix A1

Loop (2)

Proportional control:

\[ G_c = K_c \quad \cdots \cdots \quad (A1.1) \]

Process transfer function:

\[ G_p = \frac{1}{0.2s+1} \quad \cdots \cdots \quad (A1.2) \]

Valve transfer function:

\[ G_v = \frac{5}{5s+1} \quad \cdots \cdots \quad (A1.3) \]

Sensor transfer function:

\[ G_m = \frac{1}{0.01s+1} \quad \cdots \cdots \quad (A1.4) \]

Calculation of the overall transfer function and characteristic equation:

\[ G(s) = \frac{nF}{1+\pi L} \quad \cdots \cdots \quad \cdots \cdots \quad (A1.5) \]

\[ \pi F = \frac{5Kc}{(0.2s+1)(5s+1)} \quad \cdots \cdots \quad (A1.6) \]

\[ \pi L = \frac{5Kc}{(0.2s+1)(5s+1)(0.1s+1)} \quad \cdots \cdots \quad (A1.7) \]

\[ 1 + \pi_L = \frac{(0.2s+1)(5s+1)(0.1s+1)+5Kc}{(0.2s+1)(5s+1)(0.1s+1)} \quad \cdots \cdots \quad (A1.8) \]

The Characteristic equation:

\[ (0.2s + 1)(5s + 1)(0.1s + 1) + 5Kc=0 \quad \cdots \cdots \quad (A1.9) \]

\[ 0.1s^3 + 1.52s^2 + 5.3s + (1 + 5Kc) = 0 \quad \cdots \cdots \quad (A1.10) \]

Application of Routh array:

Number of rows=n+1 =3+1=4
\[
\begin{pmatrix}
0.1 & 5.3 \\
1.52 & 1 + 5Kc \\
a_1 & 0 \\
b_1 & 0
\end{pmatrix}
\]

\[a_1 = \frac{(1.52 \times 5.3) - (0.1 \times (1 + 5Kc))}{1.52} = \ldots \ldots \ldots (A1.11)\]

\[b_1 = \frac{(a_1 \times (1 + 5Kc)) - (0 \times 0.1)}{a_1} = (1 + 5Kc) \ldots (A1.12)\]

\[b_1 = 1 + 5Kc\]

For the system to be critically stable the row number (n-1) is equal zero:-

\[a_1 = 0\]

\[5.3658 - 0.3289Kc = 0\]

So \[Kc = 15.9\]

The ultimate gain \(K_u = 15.9\)

Determination of the ultimate period by direct substitution method \(\omega_{co}\):-

Set \(s = \imath \omega\)

\[0.1(\imath \omega)^3 + 1.52(\imath \omega)^2 + 5.3(\imath \omega) + (1 + 5Kc) = 0 \ldots (4.13).\]

\[-0.1 \imath \omega^3 - 1.52 \omega^2 + 5.3 \imath \omega + (1 + 2Kc) = 0 \ldots (4.14).\]

Im = 5.3 \(\omega = 0.1 \omega^3\)

5.3 \(\omega^3 = 0\)

0.1 \(\omega^2 = 5.3\)

\(\omega^2 = 53\)

\(\omega_{co} = 7.28 \text{ rad/sec}\)
\[ Pu = \frac{2\pi}{\omega_c} \]  

\[ Pu = \frac{2\pi}{7.28} = 0.86 \text{ sec} \]

Root – locus method:-

\[ \text{OLTF} = \frac{5Kc}{(0.2s+1)(5s+1)(0.1s+1)} \]  

Application of MATLAB:-

```matlab
≫ num = [5];
≫ a = conv([0.2 1], [5 1]);
≫ b = [0.1 1];
≫ den = conv(a,b);
≫ sys = tf(num,den);
≫ rlocus(sys), grid
```

Fig (A1.1) Root-Locus of Loop (2)
\[ \omega_{co} = 7.24 \text{ (rad/sec)} \]

\[ Pu = \frac{2\pi}{7.24} = 0.868 \text{ sec} \ldots \ldots \ldots \ldots \text{(A1.17)} \]

\[ K_u = 15.7 \]

**Bode diagram tuning method:-**

**Application of MATLAB:-**

\[
\begin{align*}
\text{≫ } & \text{num} = [5]; \\
\text{≫ } & a = \text{conv([0.2 1],[5 1])}; \\
\text{≫ } & b = [0.1 1]; \\
\text{≫ } & \text{den} = \text{conv}(a,b); \\
\text{≫ } & \text{sys} = \text{tf(num,den)}; \\
\text{≫ } & \text{bode(sys,grid)}
\end{align*}
\]

From the overall transfer function of loop (2) is calculated:-

at -180 \[ \omega_{co} = 7.26 \text{ rad/sec} \]

\[ Pu = \frac{2\pi}{7.26} = 0.865 \text{ sec} \ldots \ldots \ldots \ldots \text{(A1.18)} \]

Magnitude (db) = -24.1
\[20 \log AR = \text{db}\]

\[20 \log AR = -24.1\]

\[
\log AR = \frac{-24.1}{20}
\]

\[
\log AR = -1.205
\]

\[AR = 0.06\]

\[
K_u = \frac{1}{AR}
\]

\[K_u = 16.03\]

\[
Ku \text{ (average)} = \frac{Ku(R) + Ku(R - L) + Ku(B)}{3}
\]

\[
Ku \text{ (average)} = \frac{15.9 + 15.7 + 16.03}{3} = 15.88
\]

\[
Pu \text{ (average)} = \frac{Pu(R) + Pu(R - L) + Pu(B)}{3}
\]

\[
Pu \text{ (average)} = \frac{0.86 + 0.868 + 0.865}{3} = 0.864 \text{ sec}
\]

Table (A1): Z-N Tuning parameters using average ultimate gains and period (Ku, Pu):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>(K_c)</th>
<th>(\bar{T}_1) (sec)</th>
<th>(\bar{T}_1) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>7.94</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>7.146</td>
<td>0.72</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>9.528</td>
<td>0.432</td>
<td>0.108</td>
</tr>
</tbody>
</table>

Checking stability using Routh and average design parameters:

The characteristic equation of loop (1) is:

\[0.1S^3 + 1.52S^2 + 5.3S + 40.7 = 0\]
Routh array analysis:

\[
\begin{pmatrix}
0.1 & 5.3 \\
1.52 & 40.7 \\
2.6 & 0 \\
40.7 & 0 \\
\end{pmatrix}
\]

The first column of array to check stability:

\[
\begin{pmatrix}
0.1 \\
1.52 \\
2.6 \\
41.025 \\
\end{pmatrix}
\]

The system is stable. All elements of the first column are positive and there is no change of sign and all the roots lie on the LHP.

**Off Set Investigation:**

\[
G(s) = \frac{\dot{y}(s)}{\dot{ysp}(s)} = \frac{\pi f}{1 + \pi l}
\]

\[
G(s) = \frac{\dot{y}(s)}{\dot{ysp}(s)} = \frac{5Kc (0.1s + 1)}{0.1S^3 + 1.52S^2 + 5.3S + (1 + 2Kc)}
\]

Kc = 5.25 from tuning

\[
\frac{\dot{y}(s)}{\dot{ys}. p(s)} = \frac{39.7 (0.1s + 1)}{0.1S^3 + 1.52S^2 + 5.3S + 40.7}
\]

Off Set = C_\omega - Cid

C_\omega = \lim s \to 0[\dot{s}[\dot{y}(s)]]

Cid = magnitude of unit step change = 1

\[
\dot{ys}. p(s) = \frac{1}{s}
\]
\[ C = \lim_{s \to 0} \left[ s \frac{39.7(0.1s + 1)}{0.1S^3 + 1.52S^2 + 5.3S + 40.7} \right] \cdot \frac{1}{s} \]

\[ C = \left[ \frac{39.7}{40.7} \right] = 0.975 \]

\[ r = 1 - 0.975 = 0.025 \]

Simulation of the system response:

\[ G(s) = \frac{\pi f}{1 + \pi l} = \frac{5Kc (0.1s + 1)}{0.1S^3 + 1.52S^2 + 5.3S + (1 + 5Kc)} \]

\[ G(s) = \frac{7.94s + 39.7}{0.1S^3 + 1.52S^2 + 5.3S + 40.7} \]

The response of the system:

MATLAB application:

\[
\begin{align*}
\text{≫ num} &= [7.94 \quad 39.7]; \\
\text{≫ den} &= [0.1 \quad 1.52 \quad 5.3 \quad 40.7]; \\
\text{≫ impulse (num,den )}
\end{align*}
\]

![MATLAB simulation](image)

Fig (A1.3) step response of loop (2)

Beak time= 0.184 sec  Over shoot= 5.91  Settling time = 6.1 sec
Appendix A2:-

Loop (3):-

Proportional control:-

\[ Gc = Kc \]  

(A2.1)

Process transfer function :

\[ Gp = \frac{2}{(7s+1)(2s+1)} \]  

(A2.2)

Valve transfer function:

\[ Gv = \frac{1}{0.5s+1} \]  

(A2.3)

Sensor transfer function:

\[ Gm = \frac{1}{0.2s+1} \]  

(A2.4)

Calculation of the overall transfer function and characteristic equation:

\[ G(s) = \frac{\pi F}{1+\pi L} \]  

(A2.5)

\[ \pi F = \frac{2Kc}{(7s+1)(2s+1)(0.5s+1)} \]  

(A2.6)

\[ \pi L = \frac{2Kc}{(7s+1)(2s+1)(0.5s+1)(0.2s+1)} \]  

(A2.7)

\[ 1 + \pi L = \frac{(7s+1)(2s+1)(0.5s+1)(0.2s+1)+2Kc}{(7s+1)(2s+1)(0.5s+1)(0.2s+1)} \]  

(A2.8)

The Characteristic equation:-

\[ (7s + 1)(2s + 1)(0.5s + 1)(0.2s + 1) + 2Kc = 0 \]  

(A2.9)

\[ 1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + (1 + 2Kc) = 0 \]  

(A2.10)

Application of Routh array:-

Number of rows=n+1 =4+1= 5
\[
\begin{pmatrix}
1.4 & 20.4 & (1 + 2Kc) \\
10.7 & 9.7 & 0 \\
a_1 & a_2 & 0 \\
b_1 & 0 & 0 \\
c_1 & 0 & 0
\end{pmatrix}
\]

\[a_1 = \frac{(10.7 \times 20.4) - (1.4 \times 9.7)}{10.7} = 19.13 \ldots \ldots \text{(A2.11)}\]

\[a_2 = \frac{(10.7 \times (1 + 2Kc)) - (1.4 \times 0)}{10.7} = (1 + 2Kc) \ldots \text{(A2.12)}\]

\[b_1 = \frac{(19.13 \times 9.7) - (10.7 \times (1 + 2Kc))}{19.13} = \ldots \ldots \]

\[C_1 = 1 + 2Kc\]

For the system to be critically stable the row number (n-1) is equal zero:-

\[b_1 = 0\]

9.141-1.119Kc=0

So \[Kc = 8.169\]

The ultimate gain \[Ku = 8.169\]

Determination of the ultimate period by direct substitution method (\(\omega_{co}\)):-

Set \[s = (i\omega)\]

\[1.4(i\omega)^4 + 10.7(i\omega)^3 + 20.4(i\omega)^2 + 9.7(i\omega) + (1 + 2Kc) = 0 \ldots \text{(A2.13)}\]

\[1.4\omega^4 - 10.7i\omega^3 - 20.4\omega^2 + 9.7i\omega + (1 + 2Kc) = 0 \ldots \ldots \ldots \text{(A2.14)}\]

\[\text{Im} = 9.7\omega - 10.7\omega^3\]

\[9.7 - 10.7\omega^2 = 0\]

\[10.7\omega^2 = 9.7\]

\[\omega^2 = 0.907\]

\[\omega_{co} = 0.95 \text{ rad/sec}\]
\[ P_u = \frac{2\pi}{\omega_{co}} \] ……………….(A2.15)

\[ P_u = \frac{2\pi}{0.95} = 6.6 \text{ sec} \]

Root – locus method:

\[ \text{OLTF} = \frac{2Kc}{(7s+1)(25s+1)(0.5s+1)(0.2s+1)} \] ……….. (A2.16)

Application of MATLAB:

\[
\begin{align*}
\text{>> } &\text{num }= [2]; \\
\text{>> } &\text{den }= \text{conv}(\text{conv([7 1],[2 1]), conv([0.5 1],[0.2 1])}); \\
\text{>> } &\text{sys }= \text{tf(num,den)}; \\
\text{>> } &\text{rlocus(sys),grid};
\end{align*}
\]

Fig (A2.1) Root-Locus of Loop (3)

\[ \omega_{co} = 0.924 \text{ (rad / sec)} \]

\[ P_u = \frac{2\pi}{0.924} = 6.8 \text{ sec} \] ……….. (A2.17)

\[ K_u = 7.68 \]
Bode diagram tuning method:

Application of MATLAB:

```matlab
>> num = [2];
>> den = conv(conv([7 1], [2 1]), conv([0.5 1], [0.2 1]));
>> sys = tf(num, den);
>> bode(sys), grid;
```

Fig (A2.2) Bode plot of loop (3)

From the overall transfer function of loop (3) is calculated:

At $\omega = 0.959$ rad/sec

$P_u = \frac{2\pi}{0.959} = 6.6 \ sec \ \ldots \ \ldots \ \ldots \ \ldots$ (A2.18)

Magnitude (db) = -18.4

$20 \log AR = \text{db}$

$20 \log AR = -18.4$

$\log AR = -18.4/20$
Log AR = -0.92

AR = 0.120

\( K_u = \frac{1}{AR} \)

Ku = 8.3

\[ Ku\text{ (average)} = \frac{Ku(R) + Ku(R - L) + Ku (B)}{3} \]

\[ Ku\text{ (average)} = \frac{8.169 + 7.68 + 8.3}{3} = 8.1 \]

\[ Pu\text{ (average)} = \frac{Pu(R) + Pu(R - L) + Pu (B)}{3} \]

\[ Pu\text{ (average)} = \frac{6.6 + 6.8 + 6.6}{3} = 6.7 \text{ sec} \]

Table (A2): Z-N Tuning parameters using average ultimate gains and period (Ku, Pu):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>( K_c )</th>
<th>( \bar{T}_1 ) (sec)</th>
<th>( \bar{T}_1 ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>4.05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>3.645</td>
<td>5.6</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>4.86</td>
<td>3.35</td>
<td>0.8375</td>
</tr>
</tbody>
</table>

Checking stability using Routh and average design parameters:

The characteristic equation of loop (1) is:

\[ 1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + 9.1 = 0 \]

Routh array analysis:

\[
\begin{array}{ccc}
1.4 & 20.4 & 9.1
\end{array}
\begin{array}{ccc}
10.7 & 9.7 & 0
\end{array}
\begin{array}{ccc}
19.13 & 9.1 & 0
\end{array}
\begin{array}{ccc}
4.61 & 0 & 0
\end{array}
\begin{array}{ccc}
9.1 & 0 & 0
\end{array}
\]
The first column of array to check stability:
\[
\begin{bmatrix}
  1.4 \\
  10.7 \\
  19.13 \\
  4.61 \\
  9.1
\end{bmatrix}
\]

The system is stable. All elements of the first column are positive and there is no change of sign and all the roots lie on the LHP.

**Off Set Investigation:**

\[
G(s) = \frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{\pi f}{1 + \pi l}
\]

\[
G(s) = \frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{2Kc \ (0.2s + 1)}{1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + (1 + 2Kc)}
\]

\[Kc=4.05 \text{ from tuning}\]

\[
\frac{\dot{y}(s)}{\dot{y}sp(s)} = \frac{8.1 \ (0.2s + 1)}{1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + 9.1}
\]

\[\text{Off Set} = \zeta - Cid\]

\[\zeta = \lim_{s \to 0} [s \dot{y}(s)]\]

\[\text{Cid} = \text{magnitude of unit step change} = 1\]

\[\dot{y}sp(s) = \frac{1}{s}\]

\[\zeta = \lim_{s \to 0} \left[ s \frac{8.1 \ (0.2s + 1)}{1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + 9.1} \right] \cdot \frac{1}{s} = 0.88\]

\[\epsilon = 1 - 0.88 = 0.12\]

**Simulation of the system response:**

\[
G(s) = \frac{\pi f}{1 + \pi l} = \frac{2Kc \ (0.2s + 1)}{1.4S^4 + 10.7S^3 + 20.4S^2 + 9.7S + (1 + 2Kc)}
\]
\[ G(s) = \frac{1.62s + 8.1}{1.4s^4 + 10.7s^3 + 20.4s^2 + 9.7s + 9.1} \]

The response of the system:

MATLAB application :

\[
\begin{align*}
\text{≫ } \text{num} &= [1.62 \quad 8.1]; \\
\text{≫ } \text{den} &= [1.4 \quad 10.7 \quad 20.4 \quad 9.7 \quad 9.1]; \\
\text{≫ } \text{impulse (num,den),grid}
\end{align*}
\]

Fig (A2.3) step response of loop (3)

Beak time= 2.33sec
Over shoot= 0.459
Settling time = 39.4
Rise time =4.79
Offset = 0.00128
Appendix A3:-

Loop (4):-

Proportional control:-

\[ G_c = K_c \] \hspace{1cm} (A3.1)

Process transfer function :

\[ G_p = \frac{0.3}{(2s+1)(s+1)} \] \hspace{1cm} (A3.2)

Valve transfer function :-

\[ G_v = \frac{2}{s+1} \] \hspace{1cm} (A3.3)

Sensor transfer function:-

\[ G_m = \frac{1}{0.2s+1} \] \hspace{1cm} (A3.4)

Calculation of the overall transfer function and characteristic equation:

\[ G(s) = \frac{\pi F}{1+\pi L} \] \hspace{1cm} (A3.5)

\[ \pi f = \frac{0.6Kc}{(2s+1)(s+1)(s+1)} \] \hspace{1cm} (A3.6)

\[ \pi L = \frac{0.6Kc}{(2s+1)(s+1)(s+1)(0.2s+1)} \] \hspace{1cm} (A3.7)

\[ 1 + \pi L = \frac{(2s+1)(s+1)(s+1)(0.2s+1)+0.6Kc}{(2s+1)(s+1)(s+1)(0.2s+1)} \] \hspace{1cm} (A3.8)

The characteristic equation:

\[ (2s + 1)(s + 1)(s + 1)(0.2s + 1) + 0.6Kc = 0 \] \hspace{1cm} (A3 .9)

\[ 0.4s^4 + 3s^3 + 5.8s^2 + 4.2s + (1 + 0.6Kc) = 0 \] \hspace{1cm} (A3. 10)

Application of Routh array:-

Number of rows=\( n+1 = 4+1 = 5 \)
\[
\begin{pmatrix}
0.4 & 5.8 & (1 + 0.6Kc) \\
3 & 4.2 & 0 \\
a_1 & a_2 & 0 \\
b_1 & 0 & 0 \\
c_1 & 0 & 0
\end{pmatrix}
\]

\[a_1 = \frac{(3*5.8) - (0.4*4.2)}{3} = 5.25 \ldots \ldots \ldots \text{(A3.11)}\]

\[a_2 = \frac{(3 * (1 + 0.6Kc)) - (0.4 * 0)}{3} = (1 + 0.6Kc) \ldots \ldots \text{(A3.12)}\]

\[b_1 = \frac{(5.25 * 4.2) - (3 * (1 + 0.6Kc))}{5.25} = \ldots \ldots \ldots \text{(A3.13)}\]

\[C_l = 1 + 0.6Kc\]

For the system to be critically stable the row number \((n-1)\) is equal zero:-

\[b_1 = 0\]

\[3.629 - 0.343Kc = 0\]

So \(Kc = 10.58\)

The ultimate gain \(K_u = 10.58\)

Determination of the ultimate period by direct substitution method \((\omega_{co})\):

Set \(s = (i\omega)\)

\[0.4(i\omega)^4 + 3(i\omega)^3 + 5.8(i\omega)^2 + 4.2(i\omega) + (1 + 0.6Kc) = 0 \ldots \ldots \text{(A3.13).}\]

\[0.4\omega^4 - 3i\omega^3 - 5.8\omega^2 + 4.2i\omega + (1 + 0.6Kc) = 0 \ldots (4.14).\]

\[\text{Im} = 4.2\omega - 3\omega^3\]

\[4.2 - 3\omega^2 = 0\]

\[3\omega^2 = 4.2\]

\[\omega^2 = 1.4\]

\[\omega_{co} = 1.18 \text{ rad/sec}\]
\[ Pu = \frac{2\pi}{\omega_{co}} \ldots \ldots \ldots \ldots \ldots (A3.15) \]

\[ Pu = \frac{2\pi}{1.18} = 5.325 \text{ sec} \]

Root–locus method:

\[ \text{OLTF} = \frac{0.6Kc}{(2s+1)(s+1)(s+1)(0.2s+1)} \ldots \ldots (A3.16) \]

Application of MATLAB:

\[
\begin{align*}
&>> \text{num} = [0.6]; \\
&>> \text{den} = \text{conv(conv([2 1],[1 1]), conv([1 1],[0.2 21]))}; \\
&>> \text{sys} = \text{tf(num,den)}; \\
&>> \text{rlocus(sys), grid};
\end{align*}
\]

Fig (A3.1) Root-Locus of Loop (4)

\[ \omega_{co} = 1.17 \text{ (rad/sec)} \]
\[ Pu = \frac{2\pi}{1.17} = 5.37 \text{ sec} \ldots (4.17) \]

\[ K_u = 10.3 \]

Bode diagram tuning method:-

Application of MATLAB:-

```matlab
>> num = [0.6];

>> den = conv(conv([2 1], [1 1]), conv([1 1], [0.2 1]));

>> sys = tf(num, den);

>> bode(sys), grid;
```

Fig (A3.2) Bode plot of loop (4)

From the overall transfer function of loop (1) is calculated:-

At \(-180\) deg

\[ \omega_{c0} = 1.18 \text{ rad/sec} \]

\[ Pu = \frac{2\pi}{1.18} = 5.325 \text{ sec} \ldots \ldots \ldots \ldots \ldots \ldots \ldots (A3.18) \]

Magnitude (db) = -20.5
20 log AR = db

20 log AR = -20.5

Log AR = -20.5/20

Log AR = -1.025

AR = 0.094

\[ Ku = \frac{1}{AR} \]

Ku = 10.59

Ku (average) = \[ \frac{Ku(R) + Ku(R - L) + Ku(B)}{3} \]

Ku (average) = \[ \frac{10.58 + 10.3 + 10.59}{3} \] = 10.49

Pu (average) = \[ \frac{Pu(R) + Pu(R - L) + Pu(B)}{3} \]

Pu (average) = \[ \frac{5.325 + 5.37 + 5.325}{3} \] = 5.34 sec

Table (A3): Z-N Tuning parameters using average ultimate gains and period (Ku, Pu):

<table>
<thead>
<tr>
<th>Type of Controller</th>
<th>( K_c )</th>
<th>( T_1 ) (sec)</th>
<th>( T_1 ) (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>5.245</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>4.721</td>
<td>4.45</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>6.294</td>
<td>2.67</td>
<td>0.668</td>
</tr>
</tbody>
</table>

Checking stability using Routh and average design parameters:

The characteristic equation of loop (4) is:

\[ 0.4S^4 + 3S^3 + 5.8S^2 + 4.2S + 4.147 = 0 \]
Routh array analysis:

\[
\begin{array}{ccc}
0.4 & 5.8 & 4.147 \\
3 & 4.2 & 0 \\
4.24 & 4.14 & 0 \\
1.266 & 0 & 0 \\
4.147 & 0 & 0 \\
\end{array}
\]

The first column of array to check stability:

\[
\begin{array}{c}
0.4 \\
3 \\
4.24 \\
1.266 \\
4.147 \\
\end{array}
\]

The system is stable. All elements of the first column are positive and there is no change of sign and all the roots lie on the LHP.

**Off Set Investigation:**

\[
G(s) = \frac{\dot{y}(s)}{\dot{ysp}(s)} = \frac{\pi f}{1 + \pi l}
\]

\[
G(s) = \frac{\dot{y}(s)}{\dot{ysp}(s)} = \frac{0.6Kc (0.2s + 1)}{0.4s^4 + 3s^3 + 5.8s^2 + 4.2s + (1 + 0.6Kc)}
\]

Kc=5.25 from tuning

\[
\frac{\dot{y}(s)}{\dot{ys. p}(s)} = \frac{3.147 (0.2s + 1)}{0.4s^4 + 3s^3 + 5.8s^2 + 4.2s + 4.147}
\]

Off Set = \( \zeta - Cid \)

\[\zeta = \lim_{s \to 0}[s\dot{y}(s)]\]
Cid = magnitude of unit step change = 1

\[ \text{ys. } p(s) = \frac{1}{s} \]

\[ \zeta = \lim_{s \to 0} s \left[ \frac{3.147 (0.2s + 1)}{0.4S^4 + 3S^3 + 5.8S^2 + 4.2S + 4.147} \right] \cdot \frac{1}{s} \]

\[ \zeta = \frac{3.147}{4.147} = 0.759 \]

\[ r = 1 - 0.759 = 0.241 \]

**Simulation of the system response:**

**MATLAB application:**

\[ \text{num} = [0.629 \ 3.147] ; \]

\[ \text{den} = [0.4 \ 3 \ 5.8 \ 4.2 \ 4.147] ; \]

\[ \text{impulse (num, den, grid} \]

\[ G(s) = \frac{0.629s + 3.147}{0.4S^4 + 3S^3 + 5.8S^2 + 4.2S + 4.147} \]

The response of the system:

MATLAB application:
Fig (A3.3) step response of loop (4)

Beak time= 2 sec  
Settling time = 29.3 sec 
Rise time = 3.76 sec  
Over shoot= 0.521
Figure (B.1): Root locus loop1

Figure (B.2): Bode diagram loop1
Figure (B.3): Impulse response loop1