Simulation, Control and Stability Analysis of the Delayed Coking Unit in Khartoum Refinery

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

May 2016
Simulation, Control and Stability Analysis of the Delayed Coking Unit in Khartoum Refinery

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بِسْمِ اللَّهِ الرَّحْمَنِ الرَّحِيم

اقْرأ بِاسْمِ رَبِّكَ الَّذِي خَلَقَ

صدق اللَّ العظيم

سورة العلق، الآية
DEDICATION

To the most knowledgeable and lighthouse our prophet Mohammed bless and peace be upon him

To my dear mother who never stops praying for me and waves my happiness with strings from her merciful heart

To my father who strives to bless comfort for me and taught me to promote life stairs wisely and patiently

To my very helpful and encouraging brother and his small family who stand beside me.

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

To my colleagues, my friends and anyone who have helped me to succeed in my dissertation.
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Last but certainly not least, to my colleagues and my friends who helped me to complete this research.
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ABSTRACT

Delayed coking is a thermal cracking process used in petroleum refineries to upgrade and convert petroleum residuum and heavy crude oil into more valuable distillate products leaving behind a solid concentrated carbon materials (petroleum coke). Coking and decoking processes have several difficult steps. Method of switching the feed between two drums is very complex, it requires tight control of pressure, temperature and time. The aim of this research is to direct the raw oil flow to the empty drum by selecting suitable controller, good stability and appropriate tuning parameters. If coking or process is stopped from one drum, the feed should be directed to the other standby drum, so that the transfer from one drum to the other is automatically done. A control strategy was developed. Control loops were identified depending upon controllability and performance. These loops were the control of the furnace temperature, the coker drums pressure and the transfer line temperature. The transfer functions were identified and the characteristic equations were calculated and used in Routh-Hurwitz array with direct substitution to get the ultimate gain (Ku) and the ultimate period (Pu). The open loop transfer function's equations were calculated and used in Root Locus method and bode plot using MATLAB software. It is observed that the three methods of investigating the stability gave optimum and identical parameters Ku and Pu, and they were almost the same. The average of ultimate gains and periods were found and used in Ziegler-Nichols table to get the adjustable parameters (kc, τI and τd). The adjustable parameters were used to develop the overall transfer functions to determine the offset upon a unit step change in the set point using proportional controller (P-only), proportional integral (PI) and proportional integral derivative (PID). The responses were obtained and simulated the system with reasonable overshoot, rise time, settling time and decay ratio. The results of this study were found as the average of Kc for loops 1, 2, 3 and 4 equals 1.99, 46.82, 10.49 and 11.96 respectively, and also as the average of Pu for loops 1, 2, 3 and 4 equals 1.37, 1.59, 5.34 and 5.43 per seconds respectively, however the average was taken to give more precise and correct results. Finally the stability of the system was checked by using Routh array and Nyquist plot methods, and the system was found to be stable. It was found that the PID controller has been selected because it gives minimum offset and faster the speed of the closed-loop response. It is recommended to investigate the stability of the system by using digital control on Z-domain and compare it with the conventional analysis to get more precise results.
محاكاة وتحكم وتحليل الاستقرارية لوحدة التفحيم المتاخر في مصفاة الخرطوم

تستنح محمد إبراهيم أحمد

المستخلص

التحفيز المتاخر هو عملية تكسير حرارية تستخدم في مصافي البترول لتحويل البترول المتبقي والزيت الخام لمنتجات مقطرة عالية القيمة وتركها وراءها مواد كاربونية صلبة (الفحم البترولي). عمليات التفحيم وإزالة الفحم لديها العديد من الخطوات الصعبة. وطريقة تبديل التغذية بين برميلين معقدة جدا وتحتاج لتحكم محكم في الضغط ودرجة الحرارة والزمن. الهدف من هذا البحث هو توجيه سريان الزيت الخام للبرميل الفارغ، وذلك باختيار وحدة تحكم مناسبة واستقرارية جيدة وطريقة ضبط مناسبة. اذا توقفت عمليات التفحيم وازالة الفحم من أحد البرميلين، التغذية ينبغي أن توجه للبرميل الآخر، في ذلك الانتقال من برملي لآخر يحدث تلقائيًا، طورت استراتيجية التحكم. تم التعرف على حلقات التحكم إعتمادًا على الأداء، وتمثل هذه الحلقات التحكم في درجة حرارة الفرن، ضغط البرميل ودرجة حرارة خط النقل. تم تحديد دوال الانتقال وحساب التعواصمات مميزة واستعملت في مصفوفة راوث والاستبدال المباشر لإيجاد المكاسب الحرجة والفرة الحرجة. بعد ذلك حسبت معدلات دوال انتقال الحلقة المفتوحة واستعملت في طرق تحليل مسار الغرور ومخطط بوتي باستخدام تنسيق متالاب. لوحظ أن الطرق الثلاثة المستخدمة لحساب الاستقرارية تعطي قيمة مثالية لـ $K_u$ و $K_p$ و التي هي في الأغلب متساوية. تم إيجاد متوسط المكاسب الحرجة والفترات الحرجة واستخدمت في جدول زيغتر-نيكولاس للحصول على المعاملات القابلة للتجميع $K_c$, $T_i$, $T_d$)

$\text{PID}$ و $\text{PI}$ و $	ext{P}$ للحلقات 1 و 2 و 3 و 4

$t_\text{rise}$ و $t_\text{fall}$ و $t_\text{damp}$ و $t_\text{rate}$.

تم الحصول على الاستجابات وأعدت محاكاة النظام بتجاوز مقبول وزمن الصعود وزمن الهبوط ونسبة التدهور. وجدت النتائج هذه التجربة على أساس متوسط $K_u$ للحلقات 1 و 2 و 3 و 4

1.989 و 4.816 و 46.816

$K_u$ للحلقة 1 و 2 و 3 و 4

$K_p$ في التدفق 1.365 و 1.196 و 10.49 و 11.96 على التوالي، أيضا وجدت على أساس متوسط $t_\text{rise}$ و 5.43 و 5.34 و 1.587 و 11.96 رابطًا على التوالي، أخذ المتوسط للحصول على نتائج أكثر دقة وصحة، وأخيرا تم اختبار استقرارية النظام باستخدام مصفوفة راوث ومخطط نيكولاس وجميع الأنظمة وجدت مستقرة، وهو المتوقع عند استخدام قيمة $K_c$.

$K_p$ عند نظام تحكم PID. وجد أن نظام تحكم $K_c$ قد تم اختياره لأنه يعطي إزاحة قليلة وسرعة استجابة الحلقة المغلقة. يوصى بالتحقق من استقرارية النظام باستخدام تحكم رقمي على مجال Z المتطوع، ومقارنته مع النتائج التقليدية للحصول على نتائج أكثر دقة.
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<td>DCU</td>
<td>Delayed Coking Unit</td>
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<tr>
<td>P</td>
<td>Proportional Controller</td>
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<td>PI</td>
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<tr>
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<td>Proportional Integral Derivative Controller</td>
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<td>VM</td>
<td>Volatile Matter</td>
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<td>RCO</td>
<td>Reduced Crude Oil</td>
</tr>
<tr>
<td>VR</td>
<td>Vacuum Residue</td>
</tr>
<tr>
<td>CTE</td>
<td>Coefficient of Thermal Expansion</td>
</tr>
<tr>
<td>PNA</td>
<td>Poly Nuclear Aromatics</td>
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<tr>
<td>VRC</td>
<td>Vacuum Reduced Crude</td>
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<td>Heavy Coker Gas Oil</td>
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<td>RR</td>
<td>Recycle Ratio</td>
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<td>HGO</td>
<td>heavy Gas Oil</td>
</tr>
<tr>
<td>TPR</td>
<td>Throughput Ratio</td>
</tr>
<tr>
<td>LPG</td>
<td>Liquefied Petroleum Gas</td>
</tr>
<tr>
<td>FCCU</td>
<td>Fluidized Catalytic Cracking Unit</td>
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<tr>
<td>Z-N</td>
<td>Zigler–Nichols</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Time Constant</td>
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<tr>
<td>$K_c$</td>
<td>Controller Gain</td>
</tr>
<tr>
<td>$K_u$</td>
<td>Ultimate Gain</td>
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<tr>
<td>$P_u$</td>
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<tr>
<td>$\omega_{co}$</td>
<td>Crossover frequency</td>
</tr>
<tr>
<td>$\tau_i$</td>
<td>Integration time</td>
</tr>
<tr>
<td>$\tau_d$</td>
<td>Deviation time</td>
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\begin{align*}
C(s) & \quad \text{Laplace transform of controlled output } C(t) \\
R(s) & \quad \text{Laplace transform of controlled input } r(t) \\
G(c) & \quad \text{Controller transfer function} \\
G(p) & \quad \text{Process transfer function} \\
G(v) & \quad \text{Valve transfer function} \\
G(m) & \quad \text{Measurement transfer function} \\
OLTP & \quad \text{Open Loop Transfer Function}
\end{align*}
Chapter One
Introduction
Chapter One

Introduction

1.1 Overview

In recent years the performance requirements for process plants have become increasingly difficult to satisfy. Stronger competition, tougher environmental and safety regulations, and rapidly changing economic conditions have been key factors in tightening product quality specifications. A further complication is that modern plants have become more difficult to operate because of trend towards complex integrated processes.

Process control has become increasingly important in the process industries as a consequence of global competition, rapidly changing economic conditions, and more stringent environmental and safety regulations. Process control is also a critical concern in the development of more flexible and more complex processes for manufacturing high value added products.

One of the complex and difficult in process control is control tuning. Control tuning is the major key issue to operate the plant. Process tuning is a key role in ensuring that the plant performance satisfies the operating objectives. Controller tuning inevitably involves a tradeoff between performance and robustness. The performance goals of excellent set point tracking and disturbance rejection should be balanced against the robustness goal of stable operation over a wide range of conditions. Before starting the tuning, it is general to make various reason and criteria for selecting which controller type will be adequate for which application. In control tuning, feedback control was used. Feedback control is that the controlled variables is measured and the measurement is used to adjust the manipulated variables and the disturbance variable is not measured. This controller is used to make tuning in process control [1].

The selection made on the basis of the general characteristics of the different feedback controllers are the most practical. They are three major type of feedback controller, proportional controller (P), proportional-integral controller, (PI) and proportional-integral-derivative controller, (PID). P controller can only achieve acceptable offset with moderate value and it is only used for gas pressure and liquid-level control. To provide sufficiently
small steady-state errors PI controller is normally used. Consequently, integral control mode make the speed of the closed-loop system remains satisfactory despite the slowdown of flow system response in PI controller.

The combination of the process, the feedback controller and the instrumentation is referred to as a feedback control loop or a closed-loop system [1].

To increase the speed of the closed-loop response and retain robustness, PID controller is used. PID controllers are widely used in industrial practice for more than 60 years. The development went from pneumatic through analogue to digital controllers, but the control algorithm remains the same. The PID controller is a standard and proved solution for the most of industrial control applications. Over the years, there are many formulas derived to tune the PID controller for adjusted parameters and achieved optimum value. There are three parameters must be tuning to achieved optimum value (Proportional gain, integral time, and derivative time) [1].

### 1.2 Control of Delayed Coking Unit:

Delayed coking is one of the most difficult refinery units to operate and control. The unit takes vacuum residue (fresh feed), heats it and injects it into the main fractionator bottom, where it is mixed with an internal reflux recycle of heavy cracked material. The total fresh and recycled feed is then heated in the coker furnace to a high cracking temperature. Coke remains in the drums and is periodically removed. That is the main reason for the coker being a difficult unit to operate. Twice daily filled coke drums are switched off for coke removal and empty drums are connected. The drum that was just filled then goes through a cycle of steaming out, cooling, opening, coke removal, closing, steaming and pressure testing, heating and finally reconnecting to the furnace and fractionators[2].

Al-fula crude is pumped from the two surge tanks unit through several heat train exchangers and into the fractionator. The flow rate of coker feed is controlled upstream of the exchangers by the flow controller leading to the fractionating tower. Coker feed is preheated through three heat exchangers prior to entering the fractionators. Controlling the temperature of the product quality is controlled by throttling the amount of reflux pumped back to the tower at various control point.
1.3 Problem Statement:

During the operation of delayed coking unit in Khartoum refinery, the processes of coking and decoking have several difficult steps, and the method of switching the feed between two drums is very complex, it requires tight control of pressure, temperature and time, also the size of coke should be kept at certain level so that the output remains stable and constant. The aim of this research is to direct the flow of residual oil to the empty drum by keeping these conditions at the desired value, and all that by selecting suitable controller, good stability and appropriate tuning parameters.

1.4 Objectives

1.4.1 General Objectives to:

1. Describe what control systems do and the primary principles of control.
2. Develop control systems to protect people and equipment.
3. Reduce the environment effect of control systems failure.
4. Reduce cost of production and maintenance.
5. Know how to use MATLAB software package.

1.4.2 Specific Objectives to:

1. Investigate tuning and stability analysis for the control system.
2. Control the residual oil flow direction that switching between two drums at the right condition by using controller that gives the best performance.
3. Develop a control strategy of the delayed coking unit operation.
4. Compare between the performance and select the best tuning method.
Chapter Two
Literature Review
Chapter Two

Literature Review

2.1 Background:

Petroleum, along with oil and coal, is classified as a fossil fuel. Fossil fuels are formed when sea plants and animals die, and the remains become buried under several thousand feet of silt, sand or mud. Fossil fuels take millions of years to form and therefore petroleum is also considered to be a non-renewable energy source. **Petroleum** is formed by hydrocarbons (a hydrocarbon is a compound made up of carbon and hydrogen) with the addition of certain other substances, primarily sulphur. Petroleum in its natural form when first collected is usually named **crude oil**, and can be clear, green or black and may be either thin like gasoline or thick like tar. In 1859 Edwin Drake sank the first known oil well, this was in Pennsylvania. Since this time oil and petroleum production figure grew exponentially. Originally the primary use of petroleum was as a lighting fuel, once it had been distilled and turned into kerosene. When Edison opened the world's first electricity generating plant in 1882 the demand for kerosene began to drop[3].

2.1.1 Thermal Cracking:

It is simple and cost effective process. However, rapid uncontrolled thermal cracking produces undesirable products like gas and coke[4].

Various Thermal Cracking Processes:

1- Visbreaking :

   It is a thermal cracking process producing gas, distillates and visbroken residue (FO).

2- Delayed coking :

   Continuous thermal cracking process which generates coke and produces various distillates in fractionators from vacuum residue. Coke drum temperature remains around (415 – 450 °C).

3- Fluid coking :

   Continuous coking process where residuum is sprayed on to fluidized bed of hot coke particles. Here cracking takes place at much higher temperature than delayed coking (temperature up to 565 °C).
4- Flexi coking:

Continuous coking process like Fluid coking which includes a gasification section of coke produced in Fluid coking operation.
Among the above processes Delayed coking is most popular.

2.1.2 Coking:

coking is the primary process used to upgrade petroleum residue. There are two types of coking processes delayed coking and fluid coking. Both are physical processes that occur at pressures slightly higher than atmospheric and at temperatures greater than 900°F that thermally crack the feedstock into products such as naphtha and distillate, leaving behind petroleum coke.

Therefore, delayed coking is a thermal cracking process used in petroleum refineries to upgrade and convert petroleum residuum (bottoms from atmospheric and vacuum distillation of crude oil) and heavy crude oil into liquid and gas product streams leaving behind a solid concentrated carbon material called petroleum coke. With delayed coking two or more large reactors called coke drums, are used to hold or delay the heated feedstock while the cracking takes place. Coke is deposited in the coke drum as a solid. This solid coke builds up in the coke drum and is removed by hydraulically cutting the coke using water. In order to facilitate the removal of the coke, the hot feed is diverted from one coke drum to another, alternating the drums between coke removal and the cracking part of the process. With fluid coking the feed is charged to a heated reactor, the cracking takes place and the formed coke is transferred to a heater as a fluidized solid where some of it is burned to provide the heat necessary for the cracking process. The remaining coke is collected to be sold. Like other secondary processing units, coking can play an important role in refinery economics depending on the type and cost of the crude oil run at a refinery. As the quality of crude oil inputs to a refinery declines, coupled with greater demands for transportation fuels, coking operations will serve to meet transportation fuel demands and also produce increasing quantities of fuel-grade and anode-grade or needle petroleum coke[4].
2.2 History of the Delayed Coking Process:

Petroleum coke was first made by the pioneer oil refineries in Northwestern Pennsylvania in the 1860's. These primitive refineries boiled oil in small iron stills to recover kerosene, a valuable and much needed luminescent. The stills were heated by wood or coal fires built underneath which over-heated and coked the oil near the bottom. After the distillation was completed, the still was allowed to cool so the workmen could dig out the coke and tar before the next run. The use of single horizontal shell stills for distillation of the crude was used until the 1880's, with the process sometimes stopped before bottoms coked to produce a heavy lubricating oil. Multiple stills were used to process more fractions by running the stills in series with the first still producing the coke. In the 1920's the tube furnace with distillation columns (bubble cap distillation trays patented by Koch ushered in the modern distillation column) were being built with the bottoms from the distillation column going to wrought iron stills in which the total outside of the horizontal still was in direct contact with the flue gases. This produced the maximum amount of heavy gas oil. Some of these units were still in operation after World War II. Operators assigned as decokers used picks, shovels, and wheelbarrows and had rags wrapped around their heads to protect against the heat. The coke that was produced in the horizontal stills had a high density, low volatile matter (VM) content of around 8 wt%, and less than 1 wt% moisture. One problem was that ash content was high, around 1 wt% compared to under 0.2 wt% in most modern delayed cokers. Conners thought that this was due to the lack of desalting and washing of the crude oils processed at that time. The origin of the vertical coke drum was probably from thermal cracking of gas oil for the production of gasoline and diesel fuel. From 1912 to 1935 the Burton process developed by Standard Oil at Whiting, Indiana converted gas oil to gasoline with the production of petroleum coke. Dubbs and other thermal cracking processes also produced petroleum coke. Lack of an adequate supply of crude oil and the lack of a heavy oil market caused land-locked middle American refineries to process the heavy fuel oil (atmospheric distillation bottoms and vacuum distillation bottoms) in a delayed coker to produce more gasoline and diesel fuel. Decoking the drums was very difficult. Manual decoking was a hot and dirty job various mechanical devices were tried. One of the common systems employed was to wind several thousand feet of steel cable on holding devices in the drum. The cable was pulled by a winch, to loosen the coke. Coke was also removed by drilling a small hole, then a large hole, after which beater balls on a rotating stem knocked out the remaining coke [3].
The first delayed coker was built by Standard Oil of Indiana at Whiting, in 1929. The development of hydraulic decoking came in the late 1930's. Shell Oil at Wood River, Illinois presented a paper on hydraulic decoking 4.0 m (13 ft) diameter Dubbs units and stated that they had patents along with Worthington Pump Company on hydraulic decoking bits and nozzles. Standard Oil of Indiana had patents on the original cutting nozzles used by Pacific Pump. A very similar nozzle is currently used in the new compact combination coke cutting unit. A pilot hole is drilled down through the coke in the drum using high pressure water, and then the coke is cut out with a drilling bit with horizontal water nozzles. Roy Diwoky while at Standard Oil Whiting was one of the key people in developing the hydraulic decoking in the 1930's. Diwoky in May 1952, while Executive Vice President of Pan Am Southern Corp. (Owned by Standard Oil of Indiana), worked with Great Lakes Carbon Corporation to produce the first needle coke in a delayed coker. Bernard Gamson, the Director of Research and Development for Great Lakes Carbon at the time, stated in a report that Diwoky was the father of delayed coking.

2.3 Delayed Coking Fundamentals:

The delayed coking process is fundamentally a thermal cracking process to upgrade heavy fractions of a refinery producing into more valuable distillate products and premium grade coke.

In the process the heavy residual feedstock from Crude Distillation Unit is heated to a high temperature (about 500°C) and the resultant mixture is given a certain residence time in large insulated vessels called coke drums. At this high temperature the heavier hydrocarbon molecules undergo cracking and thereby producing light and middle distillates i.e. gas, naphtha, Kerosene, light gas oil, heavy gas oil. At the same time some reactive molecules even larger than those in the original feedstock forming petroleum coke.

2.4 Reaction Mechanism of Coking Process:

The reaction mechanisms of thermal processes are fundamentally the same except the reaction depth is different. Thermal process generally includes two kinds of reactions: the rupture of hydrocarbon molecule chain to form small molecule hydrocarbon and the active molecules resulted from chain rupture to condense into bigger molecules. The former is endothermic reaction, while the later is exothermic reaction. Coking process is a comprehensive process of heavy residual oil deep cracking and condensation reactions. The
composition of heavy residual oil is very complicated. Besides kinds of hydrocarbons, there are also quite a lot of gums, a small amount of asphaltene, alkali metals, heavy metals, nitrides etc. So it has a very complicated thermal conversion reaction mechanism. Thermal conversion mechanism can be explained by free-radical theory. Hydrocarbon molecule thermal cracking refers that under high temperature the chemical bonds with weaker bond energy are ruptured to form free radicals. The smaller radicals such as H·, CH₃·, and C₂H₅· can extract a hydrogen free radical from other hydrocarbon molecules to form hydrogen or methane and a new free radical. The bigger hydrocarbon molecules to form hydrogen or methane and a new free radical. The bigger free radicals are unstable and will soon re-cracked into alkene and smaller free radicals. The series chain reaction will ultimately produce small molecular alkenes and alkanes[4].

Other than methyl free radical, although other free radicals can also extract hydrogen free radical or methyl free radical from hydrocarbon to form alkanes, the speed is very low. Only about ten percent of free radicals can combine with each other to terminate the reaction and form alkanes. The kinds of thermal conversion reaction mechanism happened in residual oil are shown below.

### I. Thermal Conversion of Alkane

1. Two free radicals are formed by the C—C bond rupture of big hydrocarbon molecule.

   \[ C_{16}H_{34} \rightarrow 2C_{8}H_{17}· \]  \hspace{1cm} (2.1)

2. The produced large molecular free radicals rupture further to form smaller free radicals and alkene.

   \[ C_{8}H_{17}· \rightarrow C_{4}H_{8} + C_{4}H_{9}· \] \hspace{1cm} (2.2)

   \[ C_{4}H_{9}· \rightarrow C_{2}H_{4} + C_{2}H_{5}· \] \hspace{1cm} (2.3)

   \[ C_{4}H_{9}· \rightarrow C_{3}H_{6} + CH_{3}· \] \hspace{1cm} (2.4)

   \[ C_{2}H_{5}· \rightarrow C_{2}H_{4} + H· \] \hspace{1cm} (2.5)
(3) Small free radicals (such as methyl free radical, hydrogen free radical) collide with other molecules to form new free radicals and hydrocarbon molecules.

\[
\text{CH}_3^\cdot + \text{C}_{16}\text{H}_{34} \rightarrow \text{CH}_4 + \text{C}_{16}\text{H}_{33}^\cdot \] (2.6)

\[
\text{H}^\cdot + \text{C}_{16}\text{H}_{34} \rightarrow \text{H}_2 + \text{C}_{16}\text{H}_{33}^\cdot \] (2.7)

(4) The unstable big free radicals crack into smaller free radicals and alkene.

\[
\text{C}_{16}\text{H}_{33}^\cdot \rightarrow \text{C}_8\text{H}_{16} + \text{C}_8\text{H}_{17}^\cdot \] (2.8)

(5) Free radicals combine into alkane to terminate chain reaction.

\[
\text{H}^\cdot + \text{H}^\cdot \rightarrow \text{H}_2 \] (2.9)

\[
\text{CH}_3^\cdot + \text{H}^\cdot \rightarrow \text{CH}_4 \] (2.10)

\[
\text{C}_8\text{H}_{17}^\cdot + \text{CH}_3^\cdot \rightarrow \text{C}_9\text{H}_{20} \] (2.11)

\[
\text{C}_8\text{H}_{17}^\cdot + \text{CH}_3^\cdot \rightarrow \text{C}_9\text{H}_{20} \] (2.12)

II. Thermal Conversion of Iso-alkanes:

The thermal conversion reaction mechanisms of iso-alkanes are basically the same as that of normal alkanes.

III. Thermal Conversion of Cyclanes:

The thermal conversions of cyclanes with side chain mainly take place the rupture of C-C bond on the side chain alike that of alkanes. The longer the side chain is, the faster the ruptures speed is. Only at a higher reaction temperature, can the ring of cyclanes rupture into the compounds such as cyclenes, cyclo diolefines and so on.

IV. Thermal Conversion of Aromatic Hydrocarbon:

During the thermal conversion, the alkyl side chain of the aromatic hydrocarbon will take place bond rupture alike that of alkanes. But the aromatic ring won't crack and only form stable aromatic ring free radical which may re-crack or condense to form multi-ring aromatic hydrocarbon and condensed ring aromatic hydrocarbon.
(1) Large molecule side chain cracking of aromatic hydrocarbon:

\[ C_6H_5C_{10}H_{21} \rightarrow C_6H_5C_2H_4 \cdot + C_8H_{17} \cdot \]  
\[ \text{……………………………………………………………(2.13)} \]

(2) Re-cracking of produced free radical:

\[ C_6H_5C_2H_4 \cdot \rightarrow C_2H_4 + C_6H_5 \cdot \]  
\[ \text{…………………………………………………………….}(2.14) \]

(3) Condensation of aromatic ring free radicals:

\[ 2C_6H_5 \cdot \rightarrow (C_6H_5)_2 \]  
\[ \text{……………………………………………………………..}(2.15) \]

The condensates of two or more benzene ring (naphthalene ring, anthracene ring) will gradually converse into condensed ring aromatic hydrocarbon. The deeper the condensation degree is, the fewer the hydrogen number in the ring is.

V. Thermal Conversion of Cyclane Aromatic Hydrocarbon

The thermal conversion reaction of cyclane aromatic hydrocarbon is first the rupture of C-C bond of side chain. The reactions of cyclane ring and aromatic ring will differ with the connection mode of cyclane ring and aromatic ring. The cracking of biphenyl type cyclane aromatic hydrocarbon takes place first the cracking of the bond between cyclane ring and aromatic ring to form aromatic hydrocarbon and cyclene. The cracking of condensed type molecule is mainly the cracking of cyclane ring to produce benzene series derivates or the dehydrogenation of cyclane ring to form naphthalene series derivates or condensed into multi-ring aromatic hydrocarbon.

VI. Thermal Cracking of Asphaltenes:

The reaction trend of asphaltenes at high temperature is the same as that of condensed ring aromatic hydrocarbon, viz, to take place the cracking of side chain of aromatic ring to generate lower molecular hydrocarbons. The free radicals in liquid phase conduct condensation reaction and finally form coke.

VII. Thermal Cracking of Non-hydrocarbon Molecule:

Non-hydrocarbon molecule bonds C-S and C-N are unstable, under the reaction conditions decomposition and polymerization reaction will take place. There will be
VIII. Formation Mechanism of Coke:

The coke generating process can be briefly divided into the following steps:

- The gum-asphaltene in the residual oil is condensed into coke.
- The aromatic hydrocarbon and condensed ring aromatic hydrocarbon in the residual oil are condensed into coke, videlicet, aromatic hydrocarbon.
- The intermediate products of the reaction are condensed into coke, viz. alkane, cyclane with side chain and aromatic hydrocarbon.

2.5 Brief Description of the Delayed Coking Process:

Figure (2.1) shows the schematic flow diagram of the Delayed Coking unit.

The feedstock Reduced Crude Oil (RCO) or vacuum Residue (VR) for delayed coker unit (DCU) is received in a surge tank drum. The feed from the surge drum is preheated in a heat exchangers train to a temperature of 300°C by exchanging heat from the products. The heated feed is fed to the fractionating column in two zones one at the vapor zone and the liquid zone.

The feed material along with the recycled stock is pumped to the furnace coils at a temperature of about 320°C and the material is heated to the coking temperature of the stock (about 500°C), which produces partial vaporization and mild cracking. The vapor liquid mixture then enters the coke chamber which is in coking service, where the vapor experience further cracking as it pass through the coke chamber and the liquid experience successive cracking and polymerization until it converted to vapor and coke. The unit has two coke chambers, one in coking service while the other is being decoked.

The coke chamber overhead vapors enter the fractionators via a quench column at temperature of about 425°C. In the fractionators column, coker off-gas and wild naphtha are obtained as overhead products and Kerosene, Gas oil, Heavy Gas oil are as side draw-off products. The fractionating column temperature profile is maintained through circulating and internal refluxes. The residue from the bottom of the quench column, at a temperature of 400°C is fed to the fractionators and a part of this residue may be recycled to maintain its bottom temperature. The balance quantity of the residue is cooled and sent to storage as intermittent fuel oil. The off-gas from the fractionators overhead reflux drum is compressed and sent to LPG recovery section. The LPG recovery section is comprises of one absorber column, one striper column, one debutanizer column, and caustic wash vessels. The coke from
the filled chamber is cut and cleared by hydraulic jets water is recycled as much as possible. The coke is placed in a intermediate storage area for dewatering dispatch.

The primary variable involved in delayed coking quality and yields is the feed. Coke quality is defined depends on the grade. The primary specification for needle grade coke is the coefficient of thermal expansion (C E). The primary difference between anode and fuel grade coke is contaminant levels, particularly metals and sulfur. The quality of the feed, particularly with regards to contaminant concentrations, can be improved by hydro treating [5].

Figure(2.1) : Schematic flow diagram of the Delayed Coking unit [5]
2.6 Delayed Coking Feedstock:

The coke quality and yields are strongly dependent on the feed to the unit. Some of studies were with poly nuclear aromatics (PNA) done by Lewis et al. Examples of these compounds are p-terphenyl and fluorethene. Coke formation with three widely different coker feeds, a fluidized catalytic cracking unit decant oil, a Pyrolysis tar, and a vacuum residue. In this study, high coke quality was defined by a low coefficient of thermal expansion. Decant oil consists predominantly of condensed poly nuclear aromatics substituted by methyl and other short chain alkyl groups, in addition, decant oil contains a separate fraction of high molecular weight paraffins, also decant oil produces high quality coke. Pyrolysis tar consists of small aromatic nuclei with mainly methyl substituents, these nuclei are joined by biaryl bonds or aliphatic bridges. Pyrolysis tar produces intermediate quality coke. Vacuum residue has a high degree of aliphatic substitution on the polynuclear structures and a large concentration of very high molecular weight. This results in reactive radicals which polymerize rapidly resulting in poor quality coke [3].

In addition to the whole feed, the maltenes are molecules soluble in a paraffinic solvent and therefore, are non-polar. Sphaltenes are not soluble in a paraffinic solvent and are highly polar. The average mesophase domain size, which correlates very well with coke quality, was the measure used for coke quality. The sphaltenes fraction is the dominant effect on mesophase formation and that the effect was dependent on the chemical nature of the sphaltenes rather than sphaltenes concentration. They also concluded that carbonization behavior is governed by the structural features of the individual components rather than an "average" structure. Coal tar pitches are also a possible feed for delayed cokers. However, it is necessary to extract the quinoline insoluble from these pitches before they can be used in the manufacture of high quality needle coke. Removal of the quinoline solubles retards the development of the mesophase [3].

2.6.1 Feed Hydro treating:

The quality of a coker feed can be improved by hydro-treating, which is the addition of H2. Residue hydro-treating reduces sulfur, Conradson Carbon Residue sphaltenes, metals, and the C/H ratio done by DeBiase and Elliott. As a result, this improves the yield of clean liquid products. The hydro-treating a feed resulted in a distillate product that was almost exclusively maltenes. The gases that were produced were almost exclusively H2S and paraffines. A
Hydrotreating residue also makes it possible to produce anode grade coke from heavy, high sulfur, high metals feed. Some results on how mildly hydro-treating a residue obtained from an atmospheric distillation of a Maya crude oil altered the composition presented by Reynolds [2]. Reynolds noted that H2 can be consumed by hydrogenation, hetereo-atom removal, and cracking reactions. For example, hydro-treating residues results in high H2 consumption, primarily because of sulfur removal. Adding a residue hydrotreater can greatly increase a refinery's flexibility done by Teichman. The quality and quantity of the coke can be varied by blending straight run and desulfurized residues. However, high metals residues cannot be economically hydrotreated first because of the high operating cost. In this case, the gas oil produced may need to go through a hydro denitrification process before it is suitable for a fluidized catalytic cracking unit feed [3].

2.6.2 Electrical Desalting Process:

The crude oil exploited from crude oil layer all contains water, in which there are dissolved salts. Generally, there are desalting and dehydration units in oil fields to make the crude oil transporting to refineries reach determined indexes. However, the desalting and dehydration units in oil fields are not perfect enough, so there are also desalting and dehydration facilities in refineries [4].

The salts in crude oil is usually dissolved in the water contained in crude oil, while there is also a portion of them suspending in crude oil in fine particulate state. Different sort of crude oil contains different salt components, mainly is chlorides of sodium, calcium and magnesium, and sodium chloride content is the highest. The existences of these salts have great harm to the processing and mainly represent in:

1. In heat exchanger and heating furnace, with the vaporization of water, salts are deposited on the tube wall to form salt deposit which will decrease heat transfer efficiency and increase flow pressure drop, in severe case, it will block tube to cause shutdown.

2. Lead the corrosion of equipment. CaCl₂, MgCl₂ can be hydrolyzed to generate strong corrosive HCl, especially in the low temperature equipment; the formation of HCl due to the existence of water is more severe.

\[
\text{CaCl}_2 + 2\text{H}_2\text{O} = \text{Ca(OH)}_2 + 2\text{HCl} \tag{2.16}
\]

\[
\text{MgCl}_2 + 2\text{H}_2\text{O} = \text{Mg(OH)}_2 + 2\text{HCl} \tag{2.17}
\]
When processing sulfur containing crude oil, sulfides will be hydrolyzed to give off H$_2$S, which is corrosive to equipment, but the produced FeS will adhere to the metal surface to protect the metal. Whereas, when HCl exists, HCl will react with FeS to spoil the protection layer and give off H$_2$S and react with iron further to exacerbate corrosion.

FeS+2HCl=FeCl$_2$+H$_2$S .................................................................(2.18)

3. Most of the salts in crude oil resides in residual oil and heavy distillates, and will directly affect the qualities of some products, meanwhile, it will increase the metal content of crude oil for secondary processing to exacerbate the polluting and poisoning of catalyst [4].

7.2 Delayed Coking Hardware:

2.7.1 Feed Preheat:

In some refineries, delayed coker feed which is usually vacuum reduced crude (VRC) arrives at the coker hot, straight from the vacuum distillation unit, but in most cases, delayed coker feed is relatively cold coming from tank age. The feed is preheated by heat exchangers with gas oil products or in some rare cases by a fired coker preheater (tube furnace). In some refineries, the convection section of the main coker furnace is used to preheat the cold feed. The hot coker feed, ranging from 360 to 400 °C (680 to 750F), then enters the bottom of the fractionator / combination tower where the fresh feed is combined with some condensed product vapors (recycle) to make up the feed to the coker heater. The fractionator bottom provides some surge storage capacity for the incoming fresh feed, and in some units, heat is transferred to the fresh feed by flowing a split of the fresh feed above the drum overhead vapor entrance to the fractionator. This practice usually results in increased amounts of heavy coker gas oil recycle in the furnace charge [5].

2.7.2 Coker Charge Pumps:

The coker charge pumps located between the fractionator bottom and the coker heater are normally driven by an electric motor with a steam-driven turbine pump as a backup. The pressure is in excess of 35 bars (500 psig) with a mechanical seal operating up to 382°C (720°F)[5].
2.7.3 Coker Tube Furnace:

The coker tube furnace is the heart of the delayed coking process. The heater furnishes all of the heat in the process. The outlet temperature of a coker furnace is typically around 500°C (930°F) with a pressure of 4bars (60 psig).

**Heater Tube Decoking:** When coke forms in the heater tubes, it insulates the inside of the tube which results in elevated temperatures on the outside of the tube. With good operational practices, coker furnace run lengths of 18 months are possible before decoking of the tubes is needed. When temperatures approach 677°C (1250°F) on the exterior skin thermocouple, the furnace must be steam spalled and/or steam-air decoked or cooled down and cleaned by hydraulic pigging.

**Heater Tube Deposits:** Iron sulfide is probably not totally removed in steam-air decoking. Coke deposits have very high content of iron, silica and sodium. Deposits recovered from return bend clean-out plugs are sometimes long cylindrical shapes and in another case looked like a thick scallop shell. These deposits were mostly sodium and calcium [4].

2.7.4 Transfer Line and Switch Valve:

**Transfer Line:** The line from the furnace to the switch valve and on to the drum is referred to as the transfer line. The transfer line must be very well insulated to prevent coking and plugging. The shorter the line the better. Long transfer lines with many crosses and tee’s used for clean outs will rapidly coke and increase the pressure on the furnace which usually results in increased fouling of the tubes in the furnace. Flanges near the drums are difficult to insulate without causing the joints to leak. Some transfer lines have a pressure relief valve in the line, but most furnaces and transfer lines are designed to withstand the maximum pressure the charge pump can produce in case of an accidental switch into a blinded valve [4].

**Switch Valve:** The switch valve is a four-way valve with ports to the two drums and a port(recirculation line) back to the fractionator which is used in startup and shutdown. Older cokers used a manually operated Wilson-Snyder valve which was a tapered plug valve that required unseating before rotation. The newer units and retrofits are using ball valves which are usually motorized. One problem with the ball valves is that many separate steam purge lines are required to keep coke from forming on the seal bellows. If the steam purges are not
monitored they can decrease the temperature of the oil going to the coke drum resulting in high volatile matter coke being produced[4].

2.7.5 Coke Drums:

The coke drum diameters range from 4 to 9 meters (13 to 30 ft) with the straight side being around 25 meters (82 ft) with a 1.5 meter diameter top blind flange closure and a two meter diameter bottom blind flange in which the 15 to 30 cm diameter inlet nozzle is attached. Both the top blind flange and the bottom must be removed when decoking the drum. Usually the drum is constructed from 25 mm of carbon steel and is clad internally with 2.8 mm of stainless steel for protection against sulfur corrosion. The pressure ranges from 1 to 5.9 bars, typically around 2 to 3 bars. The vapor outlet nozzles, 30 to 60 cm diameter, are located at the top of the drum. Pressure relief valves are also located on the top of the drum on modern cokers. The outside of the drum is insulated with around 10 cm (4 in.) of fiberglass insulation with an aluminum or stainless steel covering. The coke level in the drum is usually determined with three nuclear backscatter devices mounted on the outside of the drum [5].

2.7.6 Overhead Vapor Lines:

The vapor overhead line runs from the top of the coke drum to the fractionator. The temperature in the line is around 443°C (830°F). The temperature is decreased by about 28°C (50°F) by injecting hot heavy coker gas oil into the line as quench oil. This prevents coking in the line. The heavy coker gas oil is a wash oil coating the inside of the pipe. If the liquid layer dries out, coke starts to form. Some refineries leave the insulation off the overhead lines to help drop the temperature and keep the inside wetted. Prevention of coke in the line is important since this will increase the pressure in the coke drum thus increasing reflux of gas oil in the drum. Decreasing coke drum pressure increases liquid yield (decreases coke yield). Also, high pressure drops in overhead lines can cause foaming in the coke drum during the drum switch. Vapor line sizes are very large in order to obtain the minimum amount of pressure drop. One refinery used two 760 mm (30 inch) vapor lines in parallel [5].

2.7.7 Antifoam Injection System:

Injection of silicon antifoam should always be furthest away from the vapor overhead line outlet at the top of the drum to prevent silicon from being carried overhead into the vapor lines to the fractionator. The heaviest possible antifoam that can be handled in the refinery should
be used. Lower viscosity antifoams appear to break down at lower temperatures and are not as effective. Usually a carrier stream is used to carry the antifoam into the drum, heavier carrier material would not be as easily flashed off in the drum. Several refineries are using less antifoam and having less problems with foam since starting continuous injection of antifoam. A Dow Chemical Company representative stated in 1981 that it is easier to prevent a foam than it is to kill a foam. Also, when a foam is broken down, it still leaves a mist which can cause coking in the bottom of the fractionator. A rule of thumb is that antifoam should cost around $0.10 per ton of coke produced. Costs different than this may indicate that too much or too little antifoam is being used [4].

2.7.8 Coker Fractionator:

The fractionator or combination distillation tower separates the coker overheads into gases, gasoline, diesel, heavy coker gas oil (HCGO), and recycle. An oversized fractionator can be used to maximize the amount of diesel product and minimize the heavy coker gas oil to the FCCU. Hot overhead vapors can cause coking in the lower section of the fractionator if trays are not kept washed (wet). The major amount of heat is removed in the heavy coker gas oil section by trapping out the oil and then extracting the heat with heat exchangers or steam boilers. This pump-around HCGO is then pumped back into the tray above the trap-out tray. Some of the HCGO is sprayed below the trap-out tray to wash and cool the hot vapors. Trap-out trays can be used to catch some of this oil and reduce the amount of recycle oil going back to the furnace. Packing can be used in fractionators to reduce the pressure drop, but it is critical to keep the packing wet to prevent coking in the packing [4].

2.7.9 Hydraulic Coke Cutting System:

**Cut Water Pump:** High pressure water is used to cut the coke out of the drum. Cut water pumps are multistage barrel type or split case multistage pumps which were originally developed for feed water pumps for steam boilers. The pumps are usually powered with an electric motor, but some older units use steam-driven turbines.

**Cutting Equipment:** Derricks are built on top of the drum so that the drill stem can be moved with a winch and cable. The high pressure water flows through an API 10,000 psi drilling hose to the top of the drill stem. The drill stem is rotated with an air motor at the top through a rotary joint. The cutting nozzles are the pilot bit with down facing nozzles and the
cutting bit with nozzles acing outward. New units have both nozzles incorporated into a single drilling head [4].

2.8 Operating Parameters:

Three operating parameters govern the yield pattern and product quality of delayed coker, these are:

- Temperature
- Pressure
- Recycle Ratio (RR)

2.8.1 Drum Temperature:

Some research has been done in this area by Ghosal. He found that increasing the temperature of delayed coking increased the gas and naphtha yields while reducing the gas oil and coke yields. This also resulted in an increment of olefins and aromatics in the in distillate products. There was also a slight increase, from 64 to 67, in the naphtha octane number. Higher coking temperature also increased the C/H ratio of the coke.

Of course, increasing the temperature increasing the reaction rate. Mochida mention that the coking of a low sulfur vacuum residue required approximately 135 minutes at 480°C and approximately 175 minutes at 460°C. This may have a negative effect on coke quality because higher reaction rates results in less homogeneous coke. The reaction temperature required depends on the reactivity of the feed. The temperature required for the coking of a hydro treated vacuum residue is significantly lower than that for a coal tar or a fluidized catalytic cracking unit decant oil [3].

The actual temperature control point is at the heater outlet. Since the reactions are endothermic, the coke drum temperature will be lower. Actual operating temperature are within a narrow range. If the temperature is too low, the coke will be too soft and volatile combustible matter specifications will not be met. If the temperature is too high, the coke will be too hard and difficult to remove. this could delay the coking cycle. Changing the temperature can reduce the upset caused by drum switches. Some refiners increase the heater outlet temperature about 5 during the latter stage of drum warm up through the first 0.5 to 1.0 hour after drum switch for this purpose [3].

2.8.2 Drum pressure:

Coke drum pressure also affects product quality and yield. Numbers of researchers have noticed that coke yield increases with operating pressure. Have attributed this effect to vapor liquid equilibrium. At higher pressure, more of the material in the drum remains in the liquid
phase and can therefore be involved in the reactions that lead to coke formation. One method that can be used to lower the effective pressure is the usage of injection steam. Pressure has a great effect on delayed coker design and operation. Typically, the pressure control point is the fractionator overhead accumulator/ compressor suction. If the drum pressure drops below 15 psig, the compressor, inlet will be near atmospheric pressure [3].

2.8.3 Heavy Gas Oil Recycle:

One final operating variable is the amounts of heavy gas oil (HGO)recycle. Recycle is usually quantified by the throughput ratio (TPR). This is calculated by dividing the volumetric flow rate of the drum feed by the volumetric flow rate of the fresh feed [3].

2.9 Coking products:

Under typical operating conditions of the delayed coking unit, the ranges of product yields of the delayed coking process are shown below:

- Coker gasoline: (8 – 15) % (w)
- Coker diesel oil: (26 - 36) % (w)
- Coker gas oil: (20 – 30) % (w)
- Coker gas (including LPG And dry gas): (7 – 10) % (w)

2.9.1 Coker gasoline:

Coker gasoline has high alkenes content, poor stability and low motor-method octane mamba (about 50-60). The sulfa, nitrogen and oxygen contents in the gasoline is quite high depending on the properties of the crude oil. After stabilizing coker gasoline, which can be only used as semi finished product, is refined to remove hydrogen sulfide and thio-alcohol so as to become a blending component of finished gasoline. After hydro-treating, coker heavy gasoline component can be used as the crude oil of catalytic reforming unit to improve its quality further. The coker gasoline produced from the residual oil of heavy crude oil contains more alkene and sulfur and nitrogen impurities than the gasoline processed from virgin or catalytic cracking units. Only after hydrotreating become qualified product [4].

2.9.2 Coker diesel oil:

Coker diesel oil has high cetane number and contains a certain amount of impurities such as sulfur, nitrogen and metals, whose content is related with the type of the coking crude oil. All the Coker diesel oils contains a certain amount of alkenes which is unstable, so they must be refined (hydro-refining or electrochemical refining) to increase their stability so as to
become a blending component of diesel oil. In the course of coking, the hydrogen released by the hydrocarbon converting into coke transfers into coker gas oil, diesel oil, gasoline and gas. Due to the different transferring in the crude oil with catalytic cracking, the quality of coker diesel oil is remarkably advanced than that of catalytic cracking diesel oil [4].

2.9.3 Coker gas oil:

Coker gas oil (CGO) general refers to the coking distilled oil at the range of 350-500°C. The stability of CGO, which is poor, is related with the property of coking raw oil and operating condition of coking. The mixture of CGO and VGO can be used as the raw oil for the catalytic cracking and hydro cracking units. Same crude oil, the main difference between CGO and VGO is that CGO has higher sulfur, nitrogen, aromatic hydrocarbon and gum contents and higher carbon residue than VGO which has lower saturated hydrocarbon content and higher polycyclic aromatic hydrocarbon content. When CGO is used as the crude oil feed of catalytic cracking, whether hydro treating is needed and the required depth of hydro treating will be determined based on the requirement of catalytic cracking unit depending on crude oil properties and the blending conditions of crude oil. If the CGO ratio in the catalytic cracking crude oil is small and the blended raw oil property can meet the requirement, CGO will not have to be hydro-treated, adopting relative low hydro treating causticity will be just all right [4].

2.9.4 Coker gases:

Coker gases contains a certain amount of S, which is related with the sulfur content of vacuum residual oil. The Coker gas also contains a certain amount of olefin. During light component recovery process, Coker gas is separated into coker dry gas and LPG. Coker dry gas is sent of fuel gas pipe network as fuel, while LPG can be regarded as finished product. The yield of Coker gas is about 7% of coking treatment quantity [4].

2.9.5 Coke:

The quality of coke changes with the quality of raw crude oil and operating condition. Sulfur content is an important index of coke, quality. The sulfur content of coke is related with the sphaltenes and carbon residue in crude oil. For two kinds of coking raw crude oil with the same sulfur content, the sulfur content of coke produced from the crude oil with higher sphaltenes and carbon residue contents is also higher. The temperature in the coking tower also effects the sulfur content of coke: When the temperatures is raised, the heavy oil with low sulfur content evaporated from coke is also increased, so the sulfur content of coke is correspondingly increased [6].
Types of Coke:

Coke formed in Delayed Coker Unit can be classified into three different types:

- Sponge Coke
- Needle Coke
- Shot Coke

1. **Sponge Coke:** Sponge Coke is porous, irregular shaped lumps. It was named by its sponge like appearance. Vacuum Residue with low to moderate Vacuum asphaltene produces sponge coke. Most of the sponge coke is used as fuel. Some sponge coke with low sulphur (< 2% wt) and metal content can be used to make anodes used in aluminum industries [7].

2. **Needle Coke:** It is a premium coke from delayed coker named by its needle like appearance. Feedstock with aromatic component (without much asphaltene) helps to produce needle coke. FCCU decant oil after hydro desulphurisation for removal of sulphur used as needle coke feedstock. It has microscopic, elongated, needle like structure. It has very low coefficient of thermal expansion (CTE) and electrical resistance suitable for using as electrodes in steel making [7].

3. **Shot Coke:** It is formed from high asphaltene content feedstock present at high coke drum temperature. Shot coke is undesirable product in delayed coking. With the light ends flashing-off small globules of tar are formed which rapidly converted to coke due to huge heat generation during exothermic asphaltene polymerization reaction. Shot coke is usually blended with sponge coke to use as fuel [7].

2.10 Coking products treatment:

2.10.1 Absorption Tower:

Absorption tower has a relative low temperature of overall tower, small up and down temperature difference, and adopts floating valve trays. Stabilized gasoline and crude gasoline, as absorbent, enters the tower from the top of tower, rich gas enters the tower from the lower section of the tower, and lean gas is discharged out from the top of tower, rich absorbing oil is pumped out from the tower bottom. In the middle section of the tower, there is a layer oil collecting box, the oil in which is pumped out by a pump and after passing through cooler is pumped back to the tower from the next stage. Vapour phase and liquid phase contacts counter-current-wise to complete the absorption process [4].
2.10.2 Re-absorption Tower:

The operating process in re-absorption tower is the same as in absorption tower, except that there is lower treatment capacity, smaller size and no middle section cooling reflux in re-absorption tower. Light diesel oil is pumped in from the top of tower as absorbent, lean gas from the bottom of tower, actual tray number inside the tower is 22. During the completion of absorption, dry gas is discharged out from the top of tower, rich absorbing oil returns back to the fractionation column by self-pressure. Light diesel oil, as absorbent, is adopted to absorb a small amount of gasoline and liquid hydrocarbon entrained in lean gas. For light diesel oil is very easy to dissolve gasoline, so after proper light diesel oil is given, it can satisfy the quality requirement of dry gas without any more adjustment. The operation of re-absorption tower is mainly to control liquid level at the bottom of tower to prevent the level out of control, which will lead dry gas entraining diesel oil to cause black smoke sent out of heating furnace. On the other hand, blank pressure of level should be prevented from gas pressed into fractionation column to cause pressure fluctuation [4].

2.10.3 Desorption Tower:

If the equilibrium partial pressure of a certain component in a solution is bigger than the partial pressure of the component in mixed gas, the component will transfer from liquid phase to vapour phase, this process is called desorption. In desorption tower, C₂ component in rich absorbing oil should be removed completely. During the desorption of C₂ component, a portion of C₃ and C₄ components will be desorbed as well due to the phase equilibrium relationship, so the desorbed gases should be sent back to absorption tower to carry through absorption once more [4].

2.10.4 Stabilization Tower:

Stabilization tower, in fact a rectification tower, is applied to separate the LPG recovered from absorption and desorption systems as much as possible and is a multi component rectification process under pressure. The whole stabilization tower is composed of rectification section, feeding section and stripping section. Forty-eight layer floating trays are installed inside the tower, a condenser is furnished at the top of tower to supply liquid phase reflux, a re-boiler is installed at the bottom of tower to supply vapour phase reflux and three inlets are in the middle section of tower. The function of stabilization tower is to separate C₃ and C₄ components in stabilized gasoline further. Liquid hydrocarbon is discharged out from the top
of tower; stabilized gasoline is discharged from the bottom of tower. Control the product quality to guarantee the qualification of vapour pressure of stabilized gasoline, to ensure the C_3 and C_4 contents in gasoline to be no more than 1 percent and recover LPG as much as possible. At the same time, try to reduce the component content above C_4 in LPG, there had better to contain no C_5 in LPG, thereby, the yield of stabilized gasoline won't be decreased [4].

2.10.5 Desulfurization and Sweeting Process of LPG:

Principle of Hydrogen Sulfide Removing from Dry Gas and LPG:

The basic principle of amine treating plants is two-fold:

1. An absorption stage where the H_2S brought in by the feed is absorbed by a liquid amine solution.

2. A desorption stage where the rich H_2S containing amine is regenerated before being routed back to the absorption stage. This stage is also known as the amine regeneration stage.

The same chemical reaction is used in both stages. This reaction is actually an equilibrated one which will move in one direction or the other depending upon the applied operating conditions [4].

\[
\begin{align*}
R \quad N - H + H_2S & \quad \xrightarrow{1} \quad R \quad NH_2SH + \text{heat} \\
R \quad N - H + H_2S & \quad \xrightarrow{2} \quad R \quad \text{amine complex}
\end{align*}
\]

N-methyl di ethanol amine is a kind of alkalescent material and can neutralize acidic gas such as H_2S and CO_2 to form amine complex.

\[
\begin{align*}
2\text{NH}-(\text{CH}_2\text{CH}_2\text{OH})_2 + \text{H}_2\text{S} & \quad [\text{NH}_2(\text{CH}_2\text{CH}_2\text{OH})_2]\text{2S} \quad \text{..................}(2.19) \\
[\text{NH}_2(\text{CH}_2\text{CH}_2\text{OH})_2]\text{2S} + \text{H}_2\text{S} & \quad 2[\text{NH}_2(\text{CH}_2\text{CH}_2\text{OH})_2\text{HS}]\quad \text{..................}(2.20)
\end{align*}
\]
**Chemical reaction features:**

- **H₂S Absorption:**
  1. Exothermal reaction
  2. H₂S is consumed
  3. The number of gas molecules drops

- **H₂S Desorption:**
  1. Endothermal reaction
  2. H₂S is produced
  3. The number of gas molecules increases

**2.10.7 Hydraulic Decoke:**

![Figure(2.2): The hydraulic decoke system](image-url)
Hydraulic decoke adopts high pressure water effluent at a pressure of 14~28MPa to remove the coke in the coking tower by specialized cutting tool. A specialized cutter with various usages such as drilling and cutting can be promptly installed on a drill pipe. The rotation of drill pipe is driven by a pneumatic motor on the top of the drill pipe; the lift of the drill pipe is driven by a pneumatic winch and a pulley block. The drill pipe and the relevant equipment such as guide gliding block and vertical sliding track are all fixed on the specialized derrick at the top of the coking tower. High pressure water for cutting is guided into the drill pipe via hose and then sent to the cutter. High pressure water pump is furnished to supply high pressure water to decoke system [4].

Figure (2.2) shows the hydraulic decoke system of coking tower, figure (2.3) describes the process of hydraulic decoke.

![Image of hydraulic decoke system]

Figure (2.3): The process of hydraulic decoke

First of all, driller is adopted to drill a guide hole at a diameter of 0.6~0.9m in the coking tower until penetrating through the coke layer. Then final cutter is adopted to cut the coke in the tower completely in several times. A kind of automatic conversion combined drill-cutter has been developed in China successfully, which can converse drilling case to cutting case automatically in the coking tower to eliminate the manual converse operation and shorten the decoke period [4].
Chapter Three
Materials and Methods
Chapter Three
Materials and Methods

This chapter contains information about types of materials used in this research such as: sensors or transmitters, controllers, valves, type of control and brief history about MATLAB software. Also the methods for tuning controllers, stability test and the system response.

3.1 Four Way Valve:

The switch valve is a four-way valve with ports to the two drums and a port (recirculation line) back to the fractionators.

![Four way valve](image)

- A Lantern ring with steam block and extra deep stuffing box minimizes the risk of leakage occurring through the packing chamber. Live-loading is available on request.
- The sturdy one-piece ball and stem provides optimal strength, and is well suited to applications where fouling due to coke fines are a concern. The one-piece design avoids the problems generally associated with the more conventional two-piece ball and stem, which is highly susceptible to solids buildup in the ball-stem joint and a resulting increase in operating torques.
- Strong bellows offer a unique seat loading design that maintains the floating seats in constant contact with the ball and ensures a positive seal.
- Scraper type seats: Velan’s unique seat design scrapes coke buildup from the surface of the ball during each cycle. Seats are hard-faced to ensure a long, trouble-free service life.
- Steam purges to bellows and body area ensure the valve cavities are kept free of coke buildup.
3.2 System Stability and Tuning:

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

3.2.1 Stability:
Systems have several properties such as controllability, stability and invariability, that play a very decisive role in their behavior. From these characteristics, stability plays the most important role. The most basic practical control problem is the design of a closed-loop system such that its output follows its input as closely as possible, unstable systems cannot guarantee such behavior and therefore are not useful in practice. Another serious disadvantage of unstable systems is that the amplitude of at least one of their state and/or output variables tends to infinity as time increases, even though the input of the system is bounded. This usually results in driving the system to saturation and in certain cases the consequences may be even more undesirable: the system may suffer serious damage, such as burn out, breakdown, explosion, etc. For these and other reasons, in designing an automatic control system, our primary goal is to guarantee stability. As soon as stability is guaranteed, then one seeks to satisfy other design requirements, such as speed of response, settling time, bandwidth, and steady-state error. The concept of stability has been studied in depth, and various criteria for testing the stability of a system have been proposed. Among the most celebrated stability criteria are those of Routh, Hurwitz, Nyquist, and Bode [8]. Mathematically, the stability of a linear system can be determined by an analysis of the roots of the characteristic equation from the differential equation describing the process (which corresponds to the roots of the denominator of the transfer function). Here the roots of the characteristic equation for given K are on the imaginary axis, and the system is oscillating [9].

3.2.1.1 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 (3.1). The steps are:

- Express the characteristic equation as an expanded polynomial:
  \[
  (1 + Gp Gf Gc Gm) = a_n s^n + a_{n-1} s^{n-1} + \ldots + a_1 s + a_0 \quad (3.1)
  \]

- 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 (3.1) : Routh Array:

<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:

\[
b_1 = \frac{a_{n-1} a_{n-2} - a_n a_{n-3}}{a_{n-1}} = a_{n-2} - \frac{a_n a_{n-3}}{a_{n-1}} \quad \text{.........}(3.1)
\]

\[
b_2 = \frac{a_{n-1} a_{n-4} - a_n a_{n-5}}{a_{n-1}} = a_{n-4} - \frac{a_n a_{n-5}}{a_{n-1}} \quad \text{.........}(3.2)
\]

\[
c_1 = \frac{b_1 a_{n-3} - a_1 b_2}{b_1} = a_{n-3} - \frac{a_1 b_2}{b_1} \quad \text{.........}(3.3)
\]

\[
c_2 = \frac{b_1 a_{n-5} - a_{n-1} b_3}{b_1} = a_{n-5} - \frac{a_{n-1} b_3}{b_1} \quad \text{.........}(3.4)
\]

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.

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 [10].

**The procedure:**

1- The characteristic equation is put in Routh array.

2- taken row number n and the first value in the first column is equated to zero with is solve to give the ultimate Ku.
3.2.1.2 Direct Substitution Method:

The closed-loop poles may lie on the imaginary axis at the moment a system becomes unstable. We can substitute $s = i\omega$ in the closed-loop characteristic equation to find the proportional gain that corresponds to this stability limit (which may be called marginal unstable). The value of this specific proportional gain is called the critical or ultimate gain. The corresponding frequency is called the crossover or ultimate frequency. The ultimate gain and ultimate period that can be used in Z-N continuous cycling relations, and the result on ultimate gain is consistent with Routh array analysis and limited to relatively simple systems [11].

3.2.1.3 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. [12]

The procedure is as follows:

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

![Figure (3.2): Rout locus plot](image-url)
3.2.1.4 Bode Diagram:

Some of the important properties of the bode stability criterion are: It provides a necessary and sufficient condition for closed-loop stability based on the properties of the open-loop transfer function. Consider an open-loop transfer function $G(OL) = G_c G_v G_m$ 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 [13].

The procedure is as follows:

1- The open-loop transfer function is obtained.

2- Using MATLAB the phase angle, the amplitude ratio are plotted against the frequency $\omega$.

3- A horizontal line from -180 degree is extended the cute phase angle carve and by dupl 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 , and from the horizontal line we read the amplitude ratio db.

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

$$20 \log AR = db \quad \text{then } Ku = \frac{1}{AR}$$

![Bode Diagram](image)
3.2.1.5 Nyquist Plot:

The Nyquist stability criterion states that: if the open-loop of a feedback system encircles the point (-1, 0) as the frequency takes any value from $-$ to $+\infty$, the closed-loop response is stable [14].

![Nyquist Diagram](image)

Figure (3.4): Nyquist plot

3.2.2 Method of Tuning:

Controller tuning must be chosen to ensure that the response of the controller variable remains stable and returns to its steady-state value, or move to a new desired value, quickly. However the action of controller tends to introduced oscillations [15].

3.2.2.1 Continuous Cycling Method (Ziegler - Nichols tuning):

The system is brought to the edge of instability under proportional control only. Suitable values of parameter can then be determined from proportional gain ($K_c$) found at that condition. [14]

**The procedure is as follows:**

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

Determine the controller settings according to the tuning Ziegler – Nichols rules.
Table (3.2) : Ziegler – Nichols tuning parameter:

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>$K_c$</th>
<th>$\tau_i$</th>
<th>$\tau_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.5$K_u$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.45$K_u$</td>
<td>$\frac{Pu}{1.2}$</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>0.6$K_u$</td>
<td>$\frac{Pu}{2}$</td>
<td>$\frac{Pu}{8}$</td>
</tr>
</tbody>
</table>

3.3 Time Response:

Speed of response is an important measure of how quickly a system responds. When you evaluate how well a system is performing you need to measure speed of response with some metric. When you are designing a system you need to be able to predict speed of response. 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, $\tau$, will respond to a step input so that the system is within 5% of the final value in $3\tau$ seconds - i.e. three time constants [12].

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.

![Figure (3.5): Time response](image-url)
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 [16].

- 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 are 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 time we subjected to particular input. Since the models has been derived consist of different equations, some integration must be performed in order to determine the time response of the system.
Fortunately, MATLAB provides many useful resources for calculate the time response for many types of inputs.

MATLAB provides tools for automatically choosing optimal PID gains.

The tuning algorithm directly using "pidtune" or through using "pidtool". [16]

**The procedure is as follows:**

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

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

3- From to the plot the flowing can be obtained:
   - The rise time.
   - Beak time.
   - the over shoot.
   - the decay ratio.
   - the recovery or settling time.

![Figure (3.7): Step response](image-url)
3.4 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[17]. 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 [18].
Chapter Four

Results and Discussion
Chapter Four
Results and Discussion

Based on the conditions of operation of the delayed coking unit shown in table (4.1), the control strategy was developed as shown in figure (4.1). The block diagrams were constructed and the transfer functions of loop1 through loop4 were identified, and the characteristic equations were obtained and used for tuning, stability analysis and simulation responses.

Table (4.1) : Operating condition of coking part (Source, Khartoum Refinery Company)

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Unit</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inlet temperature of coking tower</td>
<td>°C</td>
<td>485~495</td>
</tr>
<tr>
<td>Outlet temperature of coking tower</td>
<td>°C</td>
<td>415~425</td>
</tr>
<tr>
<td>Pressure of coking tower</td>
<td>MPa</td>
<td>0.17~0.23</td>
</tr>
<tr>
<td>Fractionator tower top temperature</td>
<td>°C</td>
<td>115</td>
</tr>
<tr>
<td>Fractionator tower bottom temperature</td>
<td>°C</td>
<td>350~380</td>
</tr>
<tr>
<td>Fractionator tower top pressure</td>
<td>MPa</td>
<td>0.12</td>
</tr>
<tr>
<td>Coking fractionator tower bottom pressure</td>
<td>MPa</td>
<td>0.15~0.19</td>
</tr>
<tr>
<td>Temperature of heating furnace inlet convection section</td>
<td>°C</td>
<td>278</td>
</tr>
<tr>
<td>Temperature of heating furnace outlet convection section</td>
<td>°C</td>
<td>320</td>
</tr>
<tr>
<td>Fractionator tower bottom oil feed temperature into furnace</td>
<td>°C</td>
<td>366</td>
</tr>
<tr>
<td>Temperature of heating furnace radiation section</td>
<td>°C</td>
<td>495~500</td>
</tr>
<tr>
<td>Circulation ratio</td>
<td></td>
<td>0.5</td>
</tr>
</tbody>
</table>
4.1 Control Strategy

Figure (4.1): Physical Diagram of the Base Case Control Strategy of DCU
A. Control of the Furnace Temperature (Loop 1):

4.2 Loop 1:

4.2.1 Transfer Functions Identification:

Proportional controller:

\[ G(c) = K_c \]  \hspace{1cm} (4.1)

Valve transfer function:

\[ G(v) = 1 \]  \hspace{1cm} (4.2)

Process transfer function:

\[ G(p) = \frac{7.2}{(1.2s+1)(0.48s+1)} \]  \hspace{1cm} (4.3)

Sensor transfer function:

\[ G(m) = \frac{1}{(0.2s+1)} \]  \hspace{1cm} (4.4)
4.2.2 Analysis of Stability and Tuning of Loop 1:

4.2.2.1 Routh-Hurwitz Analysis:

- Calculation of the characteristic equation:

\[
\text{OLTF} = \frac{7.2Kc}{(1.2s+1)(0.48s+1)(0.2s+1)} \quad \text{.................................................................}(4.5)
\]

\[1+\text{OLTF} = 0 \quad \text{.................................................................}(4.6)\]

\[1+\frac{7.2Kc}{(1.2s+1)(0.48s+1)(0.2s+1)} = 0 \quad \text{.................................................................}(4.7)\]

The characteristic equation:

\[7.2Kc + (1.2 + 1)(0.48s + 1)(0.2s + 1) = 0 \quad \text{.................................................................}(4.8)\]

\[0.1152s^3+0.912s^2+1.88s+(1+7.2Kc)=0 \quad \text{.................................................................}(4.9)\]

- Application of Routh array:

Number of rows = \(n+1\)

Number of rows = 3+1=4
\[
\begin{bmatrix}
0.1152 & 1.88 \\
0.912 & 1 + 7.2K_c \\
b_1 & 0 \\
c_1 & 0
\end{bmatrix}
\]

\[b_1 = \frac{(0.912 \times 1.88) - (0.1152 \times (1 + 7.2K_c))}{0.912} = \frac{1.59936 - 0.82944K_c}{0.912} \]...

\[c_1 = 1 + 7.2K_c\]...

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

\[\frac{1.59936 - 0.82944K_c}{0.912} = 0\]...

\[K_c = 1.928\]

**The ultimate gain**  \( ku = 1.928 \)

### 4.2.3.2 Direct Substitution:

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

The characteristic equation:

\[0.1152s^3 + 0.912s^2 + 1.88s + (1 + 7.2K_c) = 0\]...

Set \( s = i\omega \)

\[0.1152(i\omega)^3 + 0.912(i\omega)^2 + 1.88(i\omega) + (1 + 7.2K_c) = 0\]...

- \[0.1152 (i \omega^3) - 0.912(\omega^2) + 1.88(i\omega) + (1 + 7.2K_c) = 0\]...

By taking the imaginary part:

- \[0.1152 (i \omega^3) + 1.88(i\omega) = 0\]...

Dividing equation (4.14) by \( (i\omega)\):

\[-0.1152\omega^2 + 1.88 = 0\]...

\[0.1152\omega^2 = 1.88\]...

\[\omega_{co} = 4.0397 \text{ (rad/sec)}\]

\[P_u = \frac{2\pi}{\omega_{co}}\]...

\[P_u = \frac{2\pi}{4.0397}\]

**The ultimate period**  \( P_u = 1.55 \text{ sec} \)
4.2.2.3 Root Locus Method:

The OLTF of loop 1:

\[
\text{OLTF} = \frac{7.2K_c}{(1.2s+1)(0.48s+1)(0.2s+1)} \tag{4.20}
\]

Figure (4.4): Root Locus plot of loop 1

\[K_u = 1.99\]

**The ultimate gain** \(K_u = 1.99\)

\[\omega_{co} = 4.94 \text{ (rad/sec)}\]

\[P_u = \frac{2\pi}{\omega_{co}} \tag{4.21}\]

\[P_u = \frac{2\pi}{4.94}\]

\[P_u = 1.272 \text{ sec}\]

**The ultimate period** \(P_u = 1.272 \text{ sec}\)
4.2.2.4 Bode Plot Method:

The OLTF of loop 1:

\[
\text{OLTF} = \frac{7.2K_c}{(1.2s+1)(0.48s+1)(0.2s+1)}
\] ................................. (4.22)

Figure (4.5): Bode plot of loop 1

- At \(-180^{\circ}\)\(\omega_{co} = 4.98\) (rad/sec)

\[
P_u = \frac{2\pi}{\omega_{co}}
\] ..........................................................(4.23)

\[
P_u = \frac{2\pi}{4.98}
\]

\[
P_u = 1.272\ \text{sec}
\]

- Magnitude = - 6.24

\[
20 \log \text{AR} = -6.24................................................................. (4.24)
\]

\[
\log \text{AR} = -0.312................................................................(4.25)
\]

\[
\text{AR} = 0.488
\]
Ku = $\frac{1}{AR}$ .................................(4.26)

Ku = $\frac{1}{0.488}$

Ku = 2.05

4.2.2.5 The Average of Ultimate Gains and Ultimate Periods:

Ku (average) = $\frac{K_u(R) + K_u(R-L) + K_u(B)}{3}$ .................................(4.27)

Ku (average) = $\frac{1.928 + 1.99 + 2.05}{3} = 1.989$

Pu (average) = $\frac{P_u(R) + P_u(R-L) + P_u(B)}{3}$ .................................(4.28)

Pu (average) = $\frac{1.55 + 1.272 + 1.272}{3} = 1.365$ sec

Table (4.2): (Ziegler-Nichols) Tuning parameters by using Ku (average) and Pu (average):

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>τi</th>
<th>τd</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.9945</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>0.89505</td>
<td>1.1375</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>1.1934</td>
<td>0.6825</td>
<td>0.170625</td>
</tr>
</tbody>
</table>

4.2.2.6 Checking the Stability:

- By using Routh array analysis:

The characteristic equation of loop(1):

$0.1152s^3 + 0.912s^2 + 1.88s + 8.1604 = 0$ .................................(4.29)

$$
\begin{bmatrix}
0.1152 & 1.88 \\
0.912 & 1 + 7.2Kc \\
0.849 & 0 \\
8.1604 & 0
\end{bmatrix}
$$
The first column of the array to check the stability

\[
\begin{bmatrix}
0.1152 \\
0.912 \\
0.849 \\
8.1604
\end{bmatrix}
\]

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

- **By using Nyquist plot:**

The OLT of loop 1:

\[
\text{OLT} = \frac{7.1604K_c}{(1.2s+1)(0.48s+1)(0.2s+1)}
\]  

\[(4.30)\]

Figure (4.6): Nyquist plot of loop 1

The system is stable, the polar plot of the OLT encircle the \((-1,0)\) point.
4.2.4 Offset Investigation:

4.2.3.1 For P-Controller:

The overall transfer function:

\[
G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1+\pi l} \tag{4.31}
\]

\[
\pi f = \frac{7.2Kc}{(1.2s+1)(0.48s+1)} \tag{4.32}
\]

\[
\pi l = \frac{7.2Kc}{(1.2s+1)(0.48s+1)(0.2s+1)} \tag{4.33}
\]

\[
1 + \pi l = \frac{7.2Kc + [(1.2s+1)(0.48s+1)(0.2s+1)]}{(1.2s+1)(0.48s+1)(0.2s+1)} \tag{4.34}
\]

Using (Z-N) table for P-Controller:

Kc=0.9945

\[
G(s) = \frac{C(s)}{R(s)} = \frac{1.43208s + 7.1604}{0.1152s^3 + 0.912s^2 + 1.88s + 8.1604} \tag{4.35}
\]

\[
r(t) = \frac{1.43208s + 7.1604}{0.1152s^3 + 0.912s^2 + 1.88s + 8.1604} \tag{4.36}
\]

\[
C(s) = \left[ \frac{1.43208s + 7.1604}{0.1152s^3 + 0.912s^2 + 1.88s + 8.1604} \right] \cdot \frac{1}{s} \tag{4.37}
\]

Offset = C_\infty - C_{id} \tag{4.38}

C_{id} = \text{magnitude of unit step change} = 1

\[
C_\infty = \lim_{s \to 0} [s \cdot C(s)] \tag{4.39}
\]

\[
C_\infty = \frac{7.1604}{8.1604} = 0.8775 \tag{4.40}
\]

\[
\therefore \text{offset} = 0.8775 - 1 = -0.1225 \tag{4.41}
\]

4.2.3.2 For PI-Controller:

\[
G(s) = Kc(1 + \frac{1}{T_i s}) \tag{4.42}
\]

\[
G(s) = 1 \tag{4.43}
\]

\[
G(s) = \frac{7.2}{(1.2s+1)(0.48s+1)} \tag{4.44}
\]
\[ G(m) = \frac{1}{0.2s+1} \] .................................................................(4.43)

Using (Z-N) table for PI-Controller :

\[ K_c = 0.89505 \quad \tau_i = 1.1375 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l} \] .................................................................(4.44)

\[ \pi f = \frac{6.44436 + \frac{5.666}{s}}{(1.2s+1)(0.48s+1)} \] .................................................................(4.45)

\[ \pi l = \frac{6.44436 + \frac{5.666}{s}}{(1.2s+1)(0.48s+1)(0.2s+1)} \] .................................................................(4.46)

\[ 1 + \pi l = \frac{6.44436 + \frac{5.666}{s} + [(1.2s+1)(0.48s+1)(0.2s+1)]}{(1.2s+1)(0.48s+1)(0.2s+1)} \] .................................................................(4.47)

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{1.28872s^2 + 7.57756s + 5.666}{0.1152s^4 + 0.912s^3 + 1.88s^2 + 7.44436s + 5.666} \] .................................................................(4.48)

\[ r(t) = 1 \] ........................................................................................................(4.49)

\[ R(S) = \frac{1}{s} \] ........................................................................................................(4.49)

\[ C(s) = \left[ \frac{1.28872s^2 + 7.57756s + 5.666}{0.1152s^4 + 0.912s^3 + 1.88s^2 + 7.44436s + 5.666} \right] \frac{1}{s} \] ........................................................................................................(4.50)

Offset = \( C_x - C_{id} \) ........................................................................................................(4.51)

\( C_{id} \) = magnitude of unit step change = 1

\[ C_x = \lim_{s \to 0} [s * C(s)] \] ........................................................................................................(4.52)

\[ C_x = \frac{5.666}{5.666} = 1 \]

\[ \therefore \text{offset} = 1 - 1 = 0 \]

4.2.3.4 For PID – Controller :

\[ G(c) = K_c \left( 1 + \frac{1}{\tau_i s} + K_c \tau d s \right) \] ........................................................................................................(4.53)

\[ G(v) = 1 \] ........................................................................................................(4.54)
\[ G(p) = \frac{7.2}{(1.2s+1)(0.48s+1)} \] ................................................................. (4.55)

\[ G(m) = \frac{1}{(0.2s+1)} \] ................................................................. (4.56)

Using (Z-N) table for PI-Controller:

\[ K_c = 1.1934 \]

\[ \tau_i = 0.6825 \]

\[ \tau_d = 0.170625 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1+\pi l} \] ................................................................. (4.57)

\[ \pi f = \frac{8.59248+\frac{12.5898}{s}+1.464s}{(1.2s+1)(0.48s+1)} \] ................................................................. (4.58)

\[ \pi l = \frac{8.59248+\frac{12.5898}{s}+1.464s}{(1.2s+1)(0.48s+1)(0.2s+1)} \] ................................................................. (4.59)

\[ 1 + \pi l = \frac{8.59248+\frac{12.5898}{s}+1.464s+[(1.2s+1)(0.48s+1)(0.2s+1)]}{(1.2s+1)(0.48s+1)(0.2s+1)} \] ................................................................. (4.60)

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{0.2928s^3 + 3.1825s^2 + 11.104s + 12.5898}{0.1152s^4 + 0.912s^3 + 3.344s^2 + 9.59248s + 12.5898} \]

\[ r(t) = 1 \] ................................................................. (4.61)

\[ R(S) = \frac{1}{S} \] ................................................................. (4.62)

\[ C(s) = \left[ \frac{0.2928s^3 + 3.1825s^2 + 11.104s + 12.5898}{0.1152s^4 + 0.912s^3 + 3.344s^2 + 9.59248s + 12.5898} \right] \cdot \frac{1}{S} \] ................................................................. (4.63)

Offset = \( C_\infty - C_{id} \) ................................................................. (4.64)

\( C_{id} = \) magnitude of unit step change = 1

\[ C_\infty = \lim_{s \to 0} [s \cdot C(s)] \] ................................................................. (4.65)

\[ C_\infty = \frac{12.5898}{12.5898} = 1 \]

\[ \therefore \text{offset} = 1 - 1 = 0 \]
4.2.4 Simulation of the System for (loop 1):

4.2.4.1 System Response for P-Controller:

The closed loop transfer function:

$$G(s) = \frac{1.43208s + 7.1604}{0.1152s^3 + 0.912s^2 + 1.88s + 8.1604}$$  \hspace{1cm} (4.66)

Figure (4.7): System response of loop 1 using P-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.48</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.493</td>
</tr>
<tr>
<td>Settling time</td>
<td>10.5</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.1904</td>
</tr>
<tr>
<td>Dampness coefficient(( \zeta ))</td>
<td>0.19545</td>
</tr>
<tr>
<td>Offset</td>
<td>-0.1225</td>
</tr>
</tbody>
</table>

Table (4.3): Characteristics of closed loop response with P-controller

\[ \zeta < 1 \]

The system is under damped.
4.2.4.2 System Response for PI-Controller:

The closed loop transfer function:

\[
G(s) = \frac{1.28872s^2 + 7.57756s + 5.666}{0.1152s^4 + 0.912s^3 + 1.88s^2 + 7.44436s + 5.666}
\]

Figure (4.8): System response of loop 1 using PI-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.91</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.519</td>
</tr>
<tr>
<td>Settling time</td>
<td>37.7</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>3.6481</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.248</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.4): Characteristics of closed loop response with PI-controller

\(\zeta < 1\)

The system is underdamped overshoots.
4.2.4.1 System Response for PID-Controller:

The closed loop transfer function:

\[
G(s) = \frac{0.2928s^3 + 3.1825s^2 + 11.1104s + 12.5898}{0.1152s^4 + 0.912s^3 + 3.344s^2 + 9.59248s + 12.5898}
\] (4.68)

Figure (4.9): System response of loop 1 using PID-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.72</td>
</tr>
<tr>
<td>Rise time</td>
<td>0.323</td>
</tr>
<tr>
<td>Settling time</td>
<td>8.16</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.9584</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.1592</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.5): Characteristics of closed loop response with PID-controller

\(\zeta < 1\)

The system is underdamped overshoots.
Root Locus plot, Bode plot, Nyquist plot and response curves were generated by MATLAB with codes illustrated in appendix A. Operating records for furnace temperature were illustrated in appendix E.

Figure (4.10) shows The comparison between different type of controllers:

![Step Response Graph](image)

**Table (4.6): Shows the minimum offset of different types of controllers:**

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>- 0.1225</td>
</tr>
<tr>
<td>PI</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0</td>
</tr>
</tbody>
</table>

Due to the minimum offset and the closed-loop high speed response the PID-controller is selected.
B. Control of the Coker Drum Pressure (Loop 2&Loop3)

![Diagram](image)

Figure(4.11) : coker drum section (loop2 & loop3)

4.3 Loop 2 :

4.3.1 Transfer Functions Identification:

\[ G(c) = K_c \] 
\[ G(v) = \frac{0.5}{s+1} \] 
\[ G(p) = \frac{1.5}{(2s+1)} \] 
\[ G(m) = \frac{1}{(0.1s+1)} \]
Figure (4.12): Block diagram of loop (2) with identified transfer functions

4.3.2 Analysis of Stability and Tuning of loop 2:

4.3.2.1 Routh-Hurwitz Analysis:

- Calculation of the characteristic equation:

\[
\text{OLTF} = \frac{0.75Kc}{(s+1)(2s+1)(0.1s+1)}
\]

\[(4.73)\]

\[1 + \text{OLTF} = 0\]

\[(4.74)\]

\[1 + \frac{0.75Kc}{(s+1)(2s+1)(0.1s+1)} = 0\]

\[(4.75)\]

The characteristic equation:

\[0.75Kc+(2s^2 + 2s + s + 1)(0.1+1)=0\]

\[(4.76)\]

\[0.2s^3+2.3s^2+3.1s+(1+0.75 Kc)=0\]

\[(4.77)\]

- Application of Routh array:

Number of rows = n+1

Number of rows = 3+1=4
\[
\begin{bmatrix}
0.2 & 3.1 \\
2.3 & 1 + 0.75Kc \\
b1 & 0 \\
c1 & 0
\end{bmatrix}
\]

\[b1 = \frac{(2.3 + 3.1) - (0.2 + (1 + 7.2Kc))}{2.3} = \frac{6.93 - 0.15Kc}{2.3} \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots \cdots
The ultimate period \( Pu = 1.5959 \text{ sec} \)

4.3.2.3 Root Locus Method:

The OLTF of loop 2:

\[
\text{OLTF} = \frac{0.75Kc}{(s+1)(2s+1)(0.1s+1)}\]

(4.88)

Figure (4.13): Root Locus plot of loop2

\( Ku = 46.4 \)

The ultimate gain \( Ku = 46.4 \)

\( \omega_c = 3.94 \text{ (rad/sec)} \)

\[
Pu = \frac{2\pi}{\omega_c} \]

(4.89)

\[
Pu = \frac{2\pi}{3.94}
\]

\( Pu = 1.5947 \text{ sec} \)

The ultimate period \( Pu = 1.5947 \text{ sec} \)
4.3.2.4 Bode Plot Method:

The OLTF of loop 2:

\[
\text{OLTF} = \frac{0.75Kc}{(s+1)(2s+1)(0.1s+1)}
\]...........................................................................................................(4.90)

Figure (4.14): Bode plot of loop2

- At -180 \( \omega_{co} = 4 \) (rad/sec)

\[
Pu = \frac{2\pi}{\omega_{co}}
\]...........................................................................................................(4.91)

\[
Pu = \frac{2\pi}{4}
\]

\[
Pu = 1.5707 \text{ sec}
\]

- Magnitude = - 33.6

20 log AR = - 33.6 .....................................................................................................(4.92)
Log AR = - 1.68 .......................................................................................... (4.93)

AR = 0.0209

Ku = \( \frac{1}{AR} \) .......................................................................................... (4.94)

Ku = \( \frac{1}{0.0209} \)

Ku = 47.847

4.3.2.5 The Average of Ultimate Gains and Ultimate Periods:

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

\[
\text{Ku (average)} = \frac{46.2 + 46.4 + 47.847}{3} = 46.816
\]

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

\[
\text{Pu (average)} = \frac{1.5959 + 1.5947 + 1.5707}{3} = 1.5871 \text{ sec}
\]

Table (4.7): (Ziegler-Nichols) Tuning parameters by using Ku (average) and Pu (average):

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>ti</th>
<th>td</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>23.408</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>21.0672</td>
<td>1.3226</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>28.0896</td>
<td>0.78355</td>
<td>0.1984</td>
</tr>
</tbody>
</table>

4.3.2.6 Checking the Stability:

- By using Routh array analysis:

The characteristic equation of loop(2):

\[
0.2s^3 + 2.3s^2 + 3.1s + (1 + 0.75 \text{ Kc}) = 0
\]

\[
\left[\begin{array}{cc}
0.2 & 3.1 \\
2.3 & 1 + 0.75 \text{Kc} \\
b1 & 0 \\
c1 & 0
\end{array}\right]
\]
The first column of array to check stability:

\[
\begin{bmatrix}
0.2 \\
2.3 \\
1.486 \\
18.556
\end{bmatrix}
\]

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

- **By using Nyquist plot**:

The OLTF of loop 2:

\[
OLTF = \frac{24.306}{(s+1)(2s+1)(0.1s+1)}
\]

Figure (4.15): Nyquist plot of loop2

The system is stable, the polar plot of the OLTF encircle the (−1,0) point.
4.3.3 Offset Investigation:

4.3.3.1 For P-Controller:
The overall transfer function:

\[
G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l} \tag{4.99}
\]

\[
\pi f = \frac{0.75 K_c}{(s+1)(2s+1)} \tag{4.100}
\]

\[
\pi l = \frac{0.75 K_c}{(s+1)(2s+1)(0.1s+1)} \tag{4.101}
\]

\[
1 + \pi l = \frac{0.75 K_c + [(s+1)(2s+1)(0.1s+1)]}{(s+1)(2s+1)(0.1s+1)} \tag{4.102}
\]

Using (Z-N) table for P-Controller:

\[K_c = 23.408\]

\[
\therefore G(s) = \frac{C(s)}{R(s)} = \frac{1.7556s + 17.556}{0.2s^3 + 2.3s^2 + 3.1s + 18.556} \tag{4.103}
\]

\[r(t) = 1 \tag{4.104}\]

\[
R(S) = \frac{1}{S} \tag{4.105}
\]

\[
C(s) = \left[ \frac{1.7556s + 17.556}{0.2s^3 + 2.3s^2 + 3.1s + 18.556} \right] \cdot \frac{1}{S} \tag{4.106}
\]

Offset = \(C_\infty - C_{id}\) \tag{4.107}

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

\[C_\infty = \lim_{s \to 0} [s \cdot C(s)] \tag{4.108}\]

\[C_\infty = \frac{17.556}{18.556} = 0.946\]

\[
\therefore \text{offset} = 0.946 - 1 = -0.054
\]

4.3.3.2 For PI-Controller:

\[
G(c) = K_c (1 + \frac{1}{\tau_i S}) \tag{4.109}
\]

\[
G(v) = \frac{0.5}{S+1} \tag{4.110}
\]
Using (Z-N) table for PI Controller:

\[ K_c = 21.0672 \quad \tau_i = 1.3226 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l} \]

\[ \pi f = \frac{15.8004 + 11.946}{(s+1)(2s+1)} \]

\[ \pi l = \frac{15.8004 + 11.946}{(s+1)(2s+1)(0.1s+1)} \]

\[ 1 + \pi l = \frac{15.8004 + 11.946 + [(s+1)(2s+1)(0.1s+1)]}{(s+1)(2s+1)(0.1s+1)} \]

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{1.58004s^2 + 16.995s + 11.946}{0.2s^4 + 2.3s^3 + 3.1s^2 + 16.8004s + 11.946} \]

\[ r(t) = 1 \] ...............................................................(4.117)

\[ R(S) = \frac{1}{S} \] ........................................................... (4.118)

\[ C(s) = \left[ \frac{1.58004s^2 + 16.995s + 11.946}{0.2s^4 + 2.3s^3 + 3.1s^2 + 16.8004s + 11.946} \right] \cdot \frac{1}{S} \]

Offset = \( C_\infty - C_{id} \) ..................................................(4.120)

\( C_{id} \) = magnitude of unit step change = 1

\[ C_\infty = \lim_{s \to 0} [s \cdot C(s)] \] .................................................. (4.121)

\[ C_\infty = \frac{11.946}{11.946} = 1 \]

\[ \therefore \text{offset} = 1 - 1 = 0 \]

4.3.3.4 For PID – Controller:

\[ G(c) = K_c \left( 1 + \frac{1}{\eta s} + K_c \tau d s \right) \] .................................................. (4.121)
\[ G(v) = \frac{0.5}{s+1} \] ................................................................. (4.122)

\[ G(p) = \frac{1.5}{(2s+1)} \] ................................................................. (4.123)

\[ G(m) = \frac{1}{(0.1s+1)} \] ................................................................. (4.124)

Using (Z-N) table for PI-Controller:

\[ K_c = 28.0896 \quad \tau_i = 0.78355 \quad \tau_d = 0.1984 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1+\pi l} \] ................................................................. (4.125)

\[ \pi f = \frac{21.0672 + \frac{26.887}{s} + 4.1797s}{(s+1)(2s+1)} \] ......................................................... (4.126)

\[ \pi l = \frac{21.0672 + \frac{26.887}{s} + 4.1797s}{(s+1)(2s+1)(0.1s+1)} \] ......................................................... (4.127)

\[ 1 + \pi l = \frac{21.0672 + \frac{26.887}{s} + 4.1797s + [(s+1)(2s+1)(0.1s+1)]}{(s+1)(2s+1)(0.1s+1)} \] ......................................................... (4.128)

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{0.41797s^3 + 6.28642s^2 + 23.7559s + 26.887}{0.2s^4 + 2.3s^3 + 7.2797s^2 + 22.0672s + 26.887} \]

\[ r(t) = 1 \] ................................................................. (4.129)

\[ R(S) = \frac{1}{s} \] ................................................................. (4.130)

\[ C(s) = \left[ \frac{0.41797s^3 + 6.28642s^2 + 23.7559s + 26.887}{0.2s^4 + 2.3s^3 + 7.2797s^2 + 22.0672s + 26.887} \right] \cdot \frac{1}{s} \] ................................................................. (4.131)

Offset = \( C_\infty - C_id \) ................................................................. (4.131)

\( C_id = \text{magnitude of unit step change} = 1 \)

\( C_x = \lim_{s \to 0} [s \cdot C(s)] \) ................................................................. (4.132)

\( C_x = \frac{26.887}{26.887} = 1 \)

\[ \therefore \text{offset} = 1 - 1 = 0 \]
4.3.4 Simulation of the System for (loop 2):

4.3.4.1 System Response for P-Controller:

The closed loop transfer function:

\[ G(s) = \frac{1.7556s + 17.556}{0.2s^3 + 2.3s^2 + 3.1s + 18.556} \]........................................... (4.133)

Figure (4.16): System response using P-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.62</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>0.571</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>14.8</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.6244</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.0466</td>
</tr>
<tr>
<td>Offset</td>
<td>- 0.054</td>
</tr>
</tbody>
</table>

Table (4.8): Characteristics of closed loop response with P-controller

\[ \zeta < 1 \]

The system is under damped.
4.2.4.2 System Response for PI-Controller:
The closed loop transfer function:

\[
G(s) = \frac{1.58004s^2 + 16.995s + 11.946}{0.2s^4 + 2.3s^3 + 3.1s^2 + 16.8004s + 11.946}
\]

\[(4.134)\]

Figure (4.17): System response using PI-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.89</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>28</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>6.44e+003</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>3.5721</td>
</tr>
<tr>
<td>Dampness coefficient (( \zeta ))</td>
<td>0.0606</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.9): Characteristics of closed loop response with PI-controller

\( \zeta < 1 \)
The system is under damped
4.2.4.3 System Response for PID-Controller:

The closed loop transfer function:

\[ G(s) = \frac{0.41797s^3 + 6.28642s^2 + 23.7559s + 26.887}{0.2s^4 + 2.3s^3 + 7.2797s^2 + 22.0672s + 26.887} \] \hspace{1cm} \text{(4.135)}

Figure (4.18): System response using PID-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.61</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>0.376</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>8.89</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.5921</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.04603</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.10): Characteristics of closed loop response with PID-controller

\[ \zeta < 1 \]

The system is under damped.
Root Locus plot, Bode plot, Nyquist plot and response curves were generated by MATLAB with code illustrated in appendix B.

Operating records for coker drum pressure and temperature were illustrated in appendix F.

Figure (4.19) shows the comparison between different types of controllers:

![Graph showing step response comparison between P, PI, and PID controllers]

Table (4.11): Shows the minimum offset of different types of controllers:

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Rise time</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>- 0.054</td>
</tr>
<tr>
<td>PI</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0</td>
</tr>
</tbody>
</table>

Due to the minimum offset and the closed-loop high speed response the PID-controller is selected.
4.4 Loop 3:

4.4.1 Transfer Functions Identification:

Proportional control:

\[ G(c) = K_c \] ..................................................(4.136)

Valve transfer function :

\[ G(v) = \frac{2}{s+1} \] ..........................................................(4.137)

Process transfer function :

\[ G(P) = \frac{0.3}{(2s+1)(s+1)} \] .................................................(4.138)

Sensor transfer function:

\[ G(m) = \frac{1}{0.2s+1} \] ..........................................................(4.139)

Figure (4.20): Block diagram of loop (3) with identified transfer functions
4.4.2 Analysis of Stability and Tuning of loop 1:

4.4.2.1 Routh-Hurwitz Analysis:

- Calculation of the characteristic equation:

\[ \text{OLTF} = \frac{0.6Kc}{(s+1)(2s+1)(s+1)(0.2s+1)} \] \hspace{1cm} (4.140)

\[ 1 + \text{OLTF} = 0 \] \hspace{1cm} (4.141)

\[ 1 + \frac{0.6Kc}{(s+1)(2s+1)(s+1)(0.2s+1)} = 0 \] \hspace{1cm} (4.142)

The characteristic equation:

\[ (2s + 1)(s + 1)(s + 1)(0.2s + 1) + 0.6Kc = 0 \] \hspace{1cm} (4.143)

\[ 0.4s^4 + 3s^3 + 5.8s^2 + 4.2s + (1 + 0.6Kc) = 0 \] \hspace{1cm} (4.144)

- Application of Routh array:

Number of rows = n+1

Number of rows = 4+1=5

\[
\begin{bmatrix}
0.4 & 5.8 & 1 + Kc \\
3 & 4.2 & 0 \\
a1 & a2 & 0 \\
b1 & 0 & 0 \\
c1 & 0 & 0
\end{bmatrix}
\]

\[ a1 = \frac{(3*5.8)-(0.4*4.2)}{3} = 5.25 \] \hspace{1cm} (4.145)

\[ a2 = \frac{(3*(1+0.6Kc))-(0.4*0)}{3} = (1 + 0.6Kc) \] \hspace{1cm} (4.146)

\[ b1 = \frac{(5.25*4.2)-(3*(1+0.6Kc))}{5.25} = 3.629-0.343Kc \] \hspace{1cm} (4.147)

\[ c1=1 + 0.6Kc \] \hspace{1cm} (4.148)

For the system to be critically stable the row number (n-1) is equal zero:
3.629-0.343Kc = 0 ...........................................................(4.149)

Kc = 10.58

The ultimate gain  $ku = 10.58$

4.4.2.2 Direct Substitution :

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

The characteristic equation:

$$0.4S^4 + 3S^3 + 5.8S^2 + 4.2S + (1 + 0.6Kc) = 0$$ ........................................(4.150)

Set  $s = i\omega$

$$0.4(i\omega)^4 + 3(i\omega)^3 + 5.8(i\omega)^2 + 4.2(i\omega) + (1 + 0.6Kc) = 0$$ ........................................(4.151)

$$0.4\omega^4 - 3i\omega^3 - 5.8\omega^2 + 4.2i\omega + (1 + 0.6Kc) = 0$$ ........................................(4.152)

By taking the imaginary part :

$$4.2i\omega - 3i\omega^3 = 0$$ .....................................................................................(4.153)

Dividing equation (4.14) by ($i\omega$):

$$4.2 - 3\omega^2 = 0$$ ..................................................................................................(4.154)

$$3\omega^2 = 4.2$$ ...........................................................................................................(4.155)

$$\omega^2 = 1.4$$ ............................................................................................................(4.156)

$\omega_{co}$=1.18 rad / sec

$$Pu = \frac{2\pi}{\omega_{co}}$$ ..................................................................................................(4.157)

$$Pu = \frac{2\pi}{1.18}$$

The ultimate period  $Pu = 5.325$ sec
4.4.2.3 Root Locus Method:

The OLTF of loop 3:

\[
\text{OLTF} = \frac{0.6Kc}{(s+1)(2s+1)(s+1)(0.2s+1)} \quad \text{.................................................(4.158)}
\]

Figure (4.21): Root Locus plot of loop3

\[K_u = 10.3\]

The ultimate gain \[K_u = 10.3\]

\[\omega_{co} = 1.17 \quad \text{(rad/sec)}\]

\[Pu = \frac{2\pi}{\omega_{co}} \quad \text{..........................................................(4.159)}\]

\[Pu = \frac{2\pi}{1.17}\]

\[Pu = 5.37 \text{ sec}\]

The ultimate period \[Pu = 5.37 \text{ sec}\]
4.4.2.4 Bode Plot Method:

The OLTF of loop 3:

\[
\text{OLTF} = \frac{0.6K_c}{(s+1)(2s+1)(s+1)(0.2s+1)} \]

...........................................................................................................(4.160)

Figure (4.22): Bode plot of loop 3

- At \(-180^\circ\) \(\omega_c = 1.18 \text{ rad/sec}\)

\[Pu = \frac{2\pi}{\omega_c} \] ...........................................................................................................(4.161)

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

- Magnitude (db) = -20.5

20 log AR = db ....................................................................................................................(4.162)

20 log AR = -20.5 ....................................................................................................................(4.163)

Log AR = \(-\frac{20.5}{20} \) ...........................................................................................................(4.164)
Log AR = -1.025 ...........................................................................................................(4.165)

AR = 0.094

Ku = \( \frac{1}{AR} \)...........................................................................................................(4.166)

Ku = 10.59

4.4.2.5 The Average of Ultimate Gains and Ultimate Periods:

Ku (average) = \( \frac{Ku(R) + Ku(R - L) + Ku(B)}{3} \) ...........................................................................................................(4.167)

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

Pu (average) = \( \frac{Pu(R) + Pu(R - L) + Pu(B)}{3} \) ...........................................................................................................(4.168)

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

Table (4.12): (Ziegler-Nichols) Tuning parameters by using Ku (average) and Pu (average):

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>( \tau_i )</th>
<th>( \tau_d )</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>

4.4.2.6 Checking the Stability:

- **By using Routh array analysis:**

The characteristic equation of loop(3):

\[
0.4s^4 + 3s^3 + 5.8s^2 + 4.2s + (1 + 0.6Kc) = 0 \] .............................................................(4.169)

\[
\begin{bmatrix}
0.4 & 5.8 & 1 + Kc \\
3 & 4.2 & 0 \\
a1 & a2 & 0 \\
b1 & 0 & 0 \\
c1 & 0 & 0 \\
\end{bmatrix}
\]
The first column of array to check stability:

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

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

- **By using Nyquist plot:**

The OLTF of loop 3:

\[
\text{OLTF} = \frac{3.147}{(s+1)(2s+1)(s+1)(0.2s+1)}
\]

Figure (4.23): Nyquist plot of loop 3

The system is stable, the polar plot of the OLTF encircle the \((-1,0)\) point.
4.4.4 Offset Investigation:

4.4.3.1 For P-Controller:

The overall transfer function:

$$G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l} \tag{4.171}$$

$$\pi f = \frac{0.6Kc}{(s+1)(2s+1)(s+1)} \tag{4.172}$$

$$\pi l = \frac{0.6Kc}{(s+1)(2s+1)(s+1)(0.2s+1)} \tag{4.173}$$

$$1 + \pi l = \frac{0.6Kc + (s+1)(2s+1)(0.2s+1)(0.2s+1)}{(s+1)(2s+1)(s+1)(0.2s+1)} \tag{4.174}$$

Using (Z-N) table for P-Controller:

$$Kc=5.245$$

$$G(s)=\frac{C(s)}{R(s)}=\frac{0.63+3.147}{0.45^4+3.5^3+5.85^2+4.2s+4.147}$$

$$r(t) = 1 \tag{4.175}$$

$$R(S) = \frac{1}{s} \tag{4.176}$$

$$C(s) = \left[\frac{0.63+3.147}{0.45^4+3.5^3+5.85^2+4.2s+4.147}\right] \frac{1}{s} \tag{4.177}$$

Offset = $C_\infty - C_{id} \tag{4.178}$

$C_{id} = \text{magnitude of unit step change} = 1$

$C_\infty = \lim_{s \to 0} [s \cdot C(s)] \tag{4.179}$

$C_\infty = \left[\frac{3.147}{4.147}\right] = 0.759$

$$\therefore \text{offset} = 0.759 - 1 = -0.24 \tag{4.178}$$

For PI-Controller:

$$G(c)=Kc(1+\frac{1}{\tau_i s}) \tag{4.180}$$

$$G(v)=\frac{2}{s+1} \tag{4.181}$$

$$G(p)=\frac{0.3}{(2s+1)(s+1)} \tag{4.182}$$
\[
G(m) = \frac{1}{0.2s + 1}
\]

(4.183)

Using (Z-N) table for PI-Controller:

\[K_c = 4.721\quad \tau_i = 4.45\]

The overall transfer function:

\[
G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l}
\]

(4.184)

\[
\pi f = \frac{2.8326 \cdot 0.637}{s + 1(2s + 1)(s + 1)}
\]

(4.185)

\[
\pi l = \frac{2.8326 + 0.637}{(s + 1)(2s + 1)(s + 1)(0.2s + 1)}
\]

(4.186)

\[
1 + \pi l = \frac{2.8326 + 0.637 + [(s + 1)(2s + 1)(s + 1)(0.2s + 1)]}{(s + 1)(2s + 1)(s + 1)}
\]

(4.187)

\[
\therefore G(s) = \frac{C(s)}{R(s)} = \frac{0.56652s^2 + 2.96s + 0.637}{0.4s^5 + 3s^4 + 5.8s^3 + 4.2s^2 + 3.8326s + 0.637}
\]

(4.190)

\[
r(t) = 1
\]

(4.188)

\[
R(S) = \frac{1}{S}
\]

(4.189)

\[
C(s) = \left[\frac{0.56652s^2 + 2.96s + 0.637}{0.4s^5 + 3s^4 + 5.8s^3 + 4.2s^2 + 3.8326s + 0.637}\right] \cdot \frac{1}{s}
\]

(4.191)

\[
\text{Offset} = C_{\infty} - C_{id}
\]

(4.192)

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

\[
C_{\infty} = \lim_{S \to 0} [S \cdot C(s)]
\]

(4.193)

\[
C_{\infty} = \frac{0.637}{0.637} = 1
\]

\[
\therefore \text{offset} = 1 - 1 = 0
\]

4.4.3.4 For PID - Controller:

\[
G(c) = K_c \left( 1 + \frac{1}{\eta s} + K_c \tau d \right)
\]

(4.193)

\[
G(v) = \frac{2}{s + 1}
\]

(4.194)
\[ G(p) = \frac{0.3}{(2s+1)(s+1)} \] .................................(4.195)

\[ G(m) = \frac{1}{0.2s+1} \] .................................(4.196)

Using (Z-N) table for PI-Controller:

\[ K_c = 6.294 \quad \tau_i = 2.67 \quad \tau_d = 0.668 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1+\pi l} \] .................................(4.197)

\[ \pi f = \frac{3.78+\frac{1.4144}{s}+2.523s}{(s+1)(2s+1)(s+1)} \] .................................(4.198)

\[ \pi l = \frac{3.78+\frac{1.4144}{s}+2.523s}{(s+1)(2s+1)(s+1)(0.2s+1)} \] .................................(4.199)

\[ 1 + \pi l = \frac{3.78+\frac{1.4144}{s}+2.523s+[(s+1)(2s+1)(s+1)(0.2s+1)]}{(s+1)(2s+1)(s+1)(0.2s+1)} \] .................................(4.200)

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{0.5046s^3+3.279s^2+4.063s+1.4144}{0.4s^5+3s^4+5.2s^3+6.725s^2+4.78s+1.4144} \] .................................(4.201)

\[ r(t) = 1 \] .................................(4.202)

\[ R(S) = \frac{1}{s} \] .................................(4.203)

\[ C(s) = \left[ \frac{0.5046s^3+3.279s^2+4.063s+1.4144}{0.4s^5+3s^4+5.2s^3+6.725s^2+4.78s+1.4144} \right] \cdot \frac{1}{s} \] .................................(4.204)

\[ \text{Offset} = C_x - C_id \] .................................(4.205)

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

\[ C_x = \lim_{s \to 0} [s \cdot C(s)] \] .................................(4.206)

\[ C_x = \frac{1.4144}{1.4144} = 1 \]

\[ \therefore \text{offset} = 1 - 1 = 0 \]
4.4.4 Simulation of the System for (loop 3):

4.4.4.1 System Response for P-Controller:

\[ G(s) = \frac{0.63 + 3.147}{0.45s^4 + 3s^3 + 5.85s^2 + 4.2s + 4.147} \] .................................(4.206)

![Step Response Graph](image)

Figure (4.24): System response using P-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.15</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>2.29</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>25.4</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>1.3225</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.014</td>
</tr>
<tr>
<td>Offset</td>
<td>-0.214</td>
</tr>
</tbody>
</table>

Table (4.13): Characteristics of closed loop response with P-controller

\(\zeta < 1\)

The system is under damped.
4.4.4.2 System Response for PI-Controller:

\[ G(s) = \frac{0.5665s^2 + 2.96s + 0.637}{0.4s^5 + 3s^4 + 5.8s^3 + 4.2s^2 + 3.8326s + 0.637} \]  \hspace{2cm} (4.207)

Figure (4.25): System response using PI-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.46</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>2.63</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>38.3</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.132</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.037</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.14): Characteristics of closed loop response with PI-controller

\(\zeta < 1\)

The system is under damped.
4.4.4.1 System Response for PID-Controller:

\[ G(s) = \frac{0.5046s^3 + 3.279s^2 + 4.063s + 1.4144}{0.4s^5 + 3s^4 + 5.2s^3 + 6.725s^2 + 4.78s + 1.4144} \]  

...(4.208)

Figure (4.26): System response using PID-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.31</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>1.47</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>15.1</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>1.72</td>
</tr>
<tr>
<td>Dampness coefficient((\zeta))</td>
<td>0.014</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.15): Characteristics of closed loop response with PID-controller

\[ \zeta < 1 \]

The system is under damped.
Root Locus plot, Bode plot, Nyquist plot and response curves were generated by MATLAB with code illustrates in appendix C.

**Figure (4.27) shows the comparison between different type of controllers:**

![Step Response Graph](image)

**Table (4.16): Shows the minimum offset of different types of controller**

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>-0.241</td>
</tr>
<tr>
<td>PI</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0</td>
</tr>
</tbody>
</table>

Due to the minimum offset and the closed-loop high speed response the PID-controller is selected.
C. Control of the Transfer Line Temperature (Loop 4):

Figure (4.28): Transfer line section

4.5 Loop 4:

4.5.1 Transfer Functions Identification:

$$G(c) = K_c$$ .................................................................(4.209)

$$G(v) = \frac{1}{(6s+1)}$$ .................................................................(4.210)

$$G(p) = \frac{1}{(0.8s+1)(0.5s+1)}$$ .................................................(4.211)

$$G(m) = \frac{1}{(0.4s+1)}$$ .................................................................(4.212)
4.5.2 Analysis of Stability and Tuning of Loop 4:

4.5.2.1 Routh-Hurwitz Analysis:

- Calculation of the characteristic equation:

\[
\text{OLTF} = \frac{Kc}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \quad \text{(4.213)}
\]

\[
1 + \text{OLTF} = 0 \quad \text{(4.214)}
\]

\[
1 + \frac{Kc}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} = 0 \quad \text{(4.215)}
\]

The characteristic equation:

\[
Kc + [(6s + 1)(0.8s + 1)(0.5s + 1)(0.4s + 1)] = 0 \quad \text{(4.216)}
\]

\[
0.96s^4 + 5.68s^3 + 11.12s^2 + 7.7s + (1+Kc) = 0 \quad \text{(4.217)}
\]

- Application of Routh array:

Number of rows = n+1

Number of rows = 4+1=5
\[
\begin{bmatrix}
0.96 & 11.12 & 1 + Kc \\
5.68 & 7.7 & 0 \\
a1 & a2 & 0 \\
b1 & 0 & 0 \\
c1 & 0 & 0
\end{bmatrix}
\]

\[a_1 = \frac{(5.68 \times 11.12) - (0.96 \times 7.7)}{5.68} = 9.82\] (4.218)

\[a_1 = 1 + Kc\] (4.219)

\[b_1 = \frac{(9.82 \times 7.7) - (5.68 \times (1 + Kc))}{9.82} = 7.12 - 0.58Kc\] (4.220)

\[c_1 = 1 + Kc\] (4.221)

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

\[7.12 - 0.58Kc = 0\] (4.222)

\[Kc = 12.276\]

\[\therefore \text{The ultimate gain } \quad ku = 12.276\]

4.5.2.2 Direct Substitution:

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

The characteristic equation:

\[0.96s^4 + 5.68s^3 + 11.12s^2 + 7.7s + (1 + Kc) = 0\] (4.223)

Set \(s = i\omega\)

\[0.96(i\omega)^4 + 5.68(i\omega)^3 + 11.12(i\omega)^2 + 7.7(i\omega) + (1 + Kc) = 0\] (4.224)

\[0.96(\omega)^4 - 5.68(i\omega)^3 - 11.12(\omega)^2 + 7.7(i\omega) + (1 + Kc) = 0\] (4.225)

By taking the imaginary part:

\[7.7i\omega - 5.68i\omega^3 = 0\] (4.226)

Dividing equation (4.14) by \((i\omega)\):

\[7.7 - 5.68\omega^2 = 0\] (4.227)

\[5.68\omega^2 = 7.7\] (4.228)

\[\omega_{co} = 1.16 \quad \text{(rad/sec)}\]
\[ Pu = \frac{2\pi}{\omega_{co}} \]  
\[ Pu = \frac{2\pi}{1.16} \]  
\[ \therefore \text{The ultimate period} \quad Pu = 5.42 \text{ sec} \]

4.5.2.3 Root Locus Method:

The OLTf of loop 4:

\[ \text{OLTF} = \frac{Kc}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \]  
\[ \therefore \text{The ultimate gain} \quad Ku = 12 \]

\[ \omega_{co} = 1.15 \text{ ( rad/sec)} \]

\[ Pu = \frac{2\pi}{\omega_{co}} \]  
\[ Pu = \frac{2\pi}{1.15} \]  
\[ \therefore \text{The ultimate period} \quad Pu = 5.46 \text{ sec} \]
4.5.2.4 Bode Plot Method:

The OLTF of loop 4:

\[
\text{OLTF} = \frac{K_c}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)}
\] ..........................................................(4.232)

Figure (4.31): Bode plot of loop 4

- At -180  \( \omega_{co} = 1.16 \) (rad/sec)

\[
Pu = \frac{2\pi}{\omega_{co}}
\] ..........................................................(4.233)

\[
Pu = \frac{2\pi}{1.16}
\]

\( Pu \) = 5.42 sec

- Magnitude = - 21.8

\[
20 \log AR = -21.8
\] ..........................................................(4.234)

\[
\text{Log AR} = -1.09
\] ..........................................................(4.235)

\( AR = 0.0862 \)
Ku = \frac{1}{AR} \quad \text{..........................................................(4.236)}

Ku = \frac{1}{0.0862}

Ku = 11.6

4.5.2.5 The Average of Ultimate Gains and Ultimate Periods:

\[
\text{Ku (average)} = \frac{\text{Ku}(R) + \text{Ku}(R-L) + \text{Ku}(B)}{3} \quad \text{..........................................................(4.237)}
\]

\[
\text{Ku (average)} = \frac{12.276 + 12 + 11.6}{3} = 11.96
\]

\[
\text{Pu (average)} = \frac{\text{Pu}(R) + \text{Pu}(R-L) + \text{Pu}(B)}{3} \quad \text{..........................................................(4.238)}
\]

\[
\text{Pu (average)} = \frac{5.417 + 5.46 + 5.42}{3} = 5.43 \text{ sec}
\]

Table (4.17): (Ziegler-Nichols) Tuning parameters by using Ku (average) and Pu (average):

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Kc</th>
<th>(\tau_i)</th>
<th>(\tau_d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>5.98</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>PI</td>
<td>5.382</td>
<td>4.525</td>
<td>-</td>
</tr>
<tr>
<td>PID</td>
<td>7.176</td>
<td>2.715</td>
<td>0.679</td>
</tr>
</tbody>
</table>

4.5.2.6 Checking the Stability:

- By using Routh array analysis:

The characteristic equation of loop(4):

\[
0.96s^4 + 5.68s^3 + 11.12s^2 + 7.7s + (1 + Kc) = 0 \quad \text{..........................................................(4.239)}
\]

\[
\begin{bmatrix}
  0.96 & 11.12 & 1 + Kc \\
  5.68 & 7.7 & 0 \\
  a1 & a2 & 0 \\
  b1 & 0 & 0 \\
  c1 & 0 & 0
\end{bmatrix}
\]
The first column of array to check stability:

\[
\begin{bmatrix}
0.96 \\
5.68 \\
9.82 \\
3.652 \\
6.98
\end{bmatrix}
\]

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

- **By using Nyquist plot :**

The OLTF of loop 4:

\[
\text{OLTFT} = \frac{5.98}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)}
\]

\[\text{Figure (4.32): Nyquist plot of loop 4}\]

The system is stable, the polar plot of the OLTFT encircle the \((-1,0)\) point.
4.5.4 Offset Investigation:

4.5.3.1 For P-Controller:

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l} \] ..............................(4.241)

\[ \pi f = \frac{Kc}{(6s+1)(0.8s+1)(0.5s+1)} \] ......................................................(4.242)

\[ \pi l = \frac{Kc}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \] ......................................................(4.243)

\[ 1 + \pi l = \frac{Kc + [(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)]}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \] ......................................................(4.244)

Using (Z-N) table for P-Controller:

\[ Kc = 5.98 \]

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{2.392s+5.98}{0.96s^4+5.68s^3+11.12s^2+7.7s+6.98} \]

\[ r(t) = 1 \] .................................................................(4.245)

\[ R(S) = \frac{1}{S} \] .................................................................(4.246)

\[ C(s) = \left[ \frac{2.392s+5.98}{0.96s^4+5.68s^3+11.12s^2+7.7s+6.98} \right] \cdot \frac{1}{S} \] .................................................................(4.247)

Offset = \( C_\infty - C_{id} \) .................................................................(4.248)

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

\[ C_\infty = \lim_{s \to 0} [s * C(s)] \] .................................................................(4.249)

\[ C_\infty = \frac{5.98}{6.98} = 0.857 \]

\[ \therefore \text{offset} = 0.857 - 1 = - 0.143 \]

4.5.3.3 For PI – Controller:

\[ G(c) = Kc(1 + \frac{1}{\tau_i s}) \] .................................................................(4.250)

\[ G(v) = \frac{1}{(6s+1)} \] .................................................................(4.251)
\[
G(p) = \frac{1}{(0.8s + 1)(0.5s + 1)}
\]

\[
G(m) = \frac{1}{(0.4s + 1)}
\]

Using (Z-N) table for PI-Controller:

\[
K_c = 5.382 \quad \tau_i = 4.525
\]

The overall transfer function:

\[
G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1 + \pi l}
\]

\[
\pi f = \frac{5.382 + \frac{1.19}{s}}{(0.8s + 1)(0.5s + 1)(0.5s + 1)}
\]

\[
\pi l = \frac{5.382 + \frac{1.19}{s}}{(0.8s + 1)(0.5s + 1)(0.5s + 1)(0.4s + 1)}
\]

\[
1 + \pi l = \frac{5.382 + \frac{1.19}{s} + [(0.8s + 1)(0.5s + 1)(0.5s + 1)(0.4s + 1)]}{(0.8s + 1)(0.5s + 1)(0.5s + 1)(0.4s + 1)}
\]

\[
\therefore G(s) = \frac{C(s)}{R(s)} = \frac{2.153s^2 + 5.858s + 1.19}{0.96s^5 + 0.568s^4 + 11.12s^3 + 7.7s^2 + 6.382s + 1.19}
\]

\[
r(t) = 1
\]

\[
R(S) = \frac{1}{s}
\]

\[
C(s) = \left[ \frac{2.153s^2 + 5.858s + 1.19}{0.96s^5 + 0.568s^4 + 11.12s^3 + 7.7s^2 + 6.382s + 1.19} \right] \cdot \frac{1}{s}
\]

Offset = \(C_\infty - C_{id}\)

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

\[
C_\infty = \lim_{s \to 0} [s \cdot C(s)]
\]

\[
C_\infty = \frac{1.19}{1.19} = 1
\]

\[
\therefore \text{offset} = 1 - 1 = 0
\]

4.5.3.3 For PID – Controller:

\[
G(c) = K_c \left(1 + \frac{1}{\eta s} + K_c \tau d s \right)
\]
\[ G(v) = \frac{1}{(6s+1)} \] .................................................................(4.264)

\[ G(p) = \frac{1}{(0.8s+1)(0.5s+1)} \] .................................................................(4.265)

\[ G(m) = \frac{1}{(0.4s+1)} \] .................................................................(4.266)

Using (Z-N) table for PI-Controller:

\[ K_c = 7.176 \quad \tau_i = 2.715 \quad \tau_d = 0.679 \]

The overall transfer function:

\[ G(s) = \frac{C(s)}{R(s)} = \frac{\pi f}{1+\pi l} \] .................................................................(4.267)

\[ \pi f = \frac{7.176 + \frac{2.64}{s} + 4.873s}{(6s+1)(0.8s+1)(0.5s+1)} \] .................................................................(4.268)

\[ \pi l = \frac{7.176 + \frac{2.64}{s} + 4.873s}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \] .................................................................(4.269)

\[ 1 + \pi l = \frac{7.176 + \frac{2.64}{s} + 4.873s + [(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)]}{(6s+1)(0.8s+1)(0.5s+1)(0.4s+1)} \] .................................................................(4.270)

\[ \therefore G(s) = \frac{C(s)}{R(s)} = \frac{1.95s^3 + 7.743s^2 + 8.236s + 2.64}{0.96s^5 + 5.68s^4 + 11.12s^3 + 12.573s^2 + 8.176s + 2.64} \cdot \frac{1}{s} \] .................................................................(4.271)

\[ r(t) = 1 \] .................................................................(4.272)

\[ R(S) = \frac{1}{S} \] .................................................................(4.273)

\[ C(s) = \left[ \frac{1.95s^3 + 7.743s^2 + 8.236s + 2.64}{0.96s^5 + 5.68s^4 + 11.12s^3 + 12.573s^2 + 8.176s + 2.64} \right] \cdot \frac{1}{s} \] .................................................................(4.274)

Offset = \( C_\infty - C_{id} \) .................................................................(4.275)

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

\[ C_\infty = \lim_{s \to 0} [s \cdot C(s)] \] .................................................................(4.276)

\[ C_\infty = \frac{2.64}{2.64} = 1 \]

\[ \therefore \text{offset} = 1 - 1 = 0 \]
4.5.4 Simulation of the system for (loop 4):

4.5.4.1 System Response for P-Controller:

\[ G(s)= \frac{2.392s+5.98}{0.96s^4+5.68s^3+11.12s^2+7.7s+6.98} \] ..........................(4.276)

Figure (4.33): System response using P-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.28</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>2.25</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>22.8</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>1.64</td>
</tr>
<tr>
<td>Dampness coefficient ((\zeta))</td>
<td>0.024</td>
</tr>
<tr>
<td>Offset</td>
<td>-0.143</td>
</tr>
</tbody>
</table>

Table (4.18): Characteristics of closed loop response with P-controller

\(\zeta < 1\)

The system is under damped
4.5.4.2 System Response for PI-Controller:

\[
G(s) = \frac{2.153s^2 + 5.858s + 1.19}{0.96s^5 + 5.68s^4 + 11.12s^3 + 7.75s^2 + 6.382s + 1.19}
\]  \hfill (4.277)

Figure (4.34): System response using PI-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.64</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>2.38</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>38.6</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.69</td>
</tr>
<tr>
<td>Dampness coefficient((\varsigma))</td>
<td>0.028</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.19): Characteristics of closed loop response with PI-controller

\[ \varsigma < 1 \]

The system is under damped
4.5.4.3 System Response for PID-Controller:

\[
G(s) = \frac{1.95s^3 + 7.743s^2 + 8.236s + 2.64}{0.96s^5 + 5.68s^4 + 11.12s^3 + 12.573s^2 + 8.176s + 2.64}
\]

(4.278)

Figure (4.35): System response using PID-Controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Over shoot</td>
<td>1.49</td>
</tr>
<tr>
<td>Rise time (sec)</td>
<td>1.56</td>
</tr>
<tr>
<td>Settling time (sec)</td>
<td>12.4</td>
</tr>
<tr>
<td>Decay ratio</td>
<td>2.22</td>
</tr>
<tr>
<td>Dampness coefficient (ζ)</td>
<td>0.039</td>
</tr>
<tr>
<td>Offset</td>
<td>0</td>
</tr>
</tbody>
</table>

Table (4.20): Characteristics of closed loop response with PID-controller

ζ < 1
The system is under damped
Root Locus plot, Bode plot, Nyquist plot and response curves were generated by MATLAB with code illustrates in appendix D.

**Figure (4.36) shows the comparison between different type of controllers:**

![Step Response Diagram](image)

**Table (4.21): Shows the offset of different types of controllers:**

<table>
<thead>
<tr>
<th>Type of controller</th>
<th>Offset</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>- 0.143</td>
</tr>
<tr>
<td>PI</td>
<td>0</td>
</tr>
<tr>
<td>PID</td>
<td>0</td>
</tr>
</tbody>
</table>

Due to the minimum offset and the closed-loop high speed response the PID-controller is selected.
4.6 Discussion of the results:

The control strategy of the delayed coking unit was developed, and the transfer functions of the loops were given from the literature. The characteristic equations were calculated and used by Routh – Hurwitz and direct substitution methods. Also the open loop transfer functions were determined and used by Root locus and Bode plot methods.

As it is seen from the results, the methods of Routh, direct substitution, root locus and bode plots give approximately equal ultimate gains ($K_u$) and ultimate periods ($P_u$) as seen in appendix G.

Therefore the average value of ultimate gains and ultimate periods were taken to normalize the result. They were used in Ziegler – Nichols tuning table to get the adjustable parameters, and then used to investigate the offset and to plot the system responses.

The stability of the system was checked by using Routh array and Nyquist plot methods, and all the system was found to be stable. The PID controller has been selected because it is give minimum offset and faster the speed of the closed-loop response.

Loop 6, 8 and 10 have the same calculation methods for tuning and stability analysis as loop 2.

Also loop 5, 7 and 9 have the same calculation methods for tuning and stability analysis as loop 3.
Chapter Five
CONCLUSIONS AND RECOMMENDATION
Chapter Five

CONCLUSIONS AND RECOMMENDATION

5.1 CONCLUSIONS :

Delay Coking Unit is one of the most valuable units in refineries, because it increases the economic benefits by converting low price residue to valuable products with higher price. Control has a great effect on the response of the chemical plants. It increases the stability and eliminate the offset. There are many methods that are used to get the adjustable parameters such as Routh-Hurwitz and Direct substitution, also there are another three graphical methods, Bode, Nyquist, and root locus. Ziegler-Nicholas criterion is used to tune the adjustable parameters. PID controller has been selected because it eliminates the offset and faster the speed of the closed loop responses.

5.2 RECOMMENDATIONS :

- It is recommended that the result of tuning by Routh array, direct substitution, Root Locus, Bode plot and Nyquist plot is to be compared with actual on-line experiments.
- Also it is recommended to investigate the stability of the system by using digital control on Z-domain and compare it with the conventional analysis to get more precise results.
REFERENCES

4. Dong, Yuming,[2003], "Basic Information of Khartoum Refinery Company (Coking Unit Manual)".


Appendixes
Appendix (A)

Loop 1:

- **Root locus method:**

  ```matlab
  % Loop 1
  % Calculation of the ultimate gain and the ultimate period by using Root
  % Locus Analysis
  % CLTF=7.2Kc/[(1.2s+1)(0.48s+1)(0.2s+1)]
  num=7.2;
  a=conv([1.2 1],[0.28 1]);
  den=conv(a,[0.2 1]);
  rlocus(num,den)
  ```

  **Fig. A1**: MATLAB format of root locus method for loop 1

- **Bode plot method:**

  ```matlab
  % Loop 1
  % Calculation of the ultimate gain and the ultimate period by using Bode plot
  % CLTF=7.2Kc/[(1.2s+1)(0.48s+1)(0.2s+1)]
  num=7.2;
  a=conv([1.2 1],[0.28 1]);
  den=conv(a,[0.2 1]);
  bode(num,den),grid
  ```

  **Fig. A2**: MATLAB format of bode plot method for loop 1
- Nyquist plot:

```
1
2
3
4 - num=7.1604;
5 - a=conv([1.2 1],[0.48 1]);
6 - den=conv(a,[0.2 1]);
7 - nyquist(num,den)
```

Fig. A3 : MATLAB format of Nyquist plot method of loop 1

- System response:

  - For P-controller:

```
1
2
3
4 - num=[1.43208 7.1604];
5 - den=[0.1192 0.912 1.00 0.1604];
6 - sys=tf(num,den);
7 - step(num,den)
```

Fig. A4 : MATLAB format of system response for P-controller for loop 1
- For PI- controller:

```matlab
% loop1
% System response
% For PI-controller:
num=[1.28872 7.57756 5.666];
den=[0.1151 0.912 1.88 7.44436 5.666];
sys=tf(num,den);
step(num,den)
```

Fig. A5: MATLAB format of system response for PI-controller for loop 1

- For PID- controller:

```matlab
% loop1
% System response
% For PID-controller:
num=[0.3228 3.1925 11.1104 12.5898];
den=[0.1151 0.912 3.344 9.59248 12.5898];
sys=tf(num,den);
step(num,den)
```

Fig. A6: MATLAB format of system response for PID-controller for loop 1
Comparison between different types of controllers:

MATLAB input:

```matlab
1    % loop1
2    % System Response:
3    % For different type of controllers:
4    -   num=[1.43208 7.1604];
5    -   den=[0.1152 0.912 1.88 8.1604];
6    -   sys=tf(num,den);
7    -   step(num,den)
8    -   hold
9    -   num=[1.28872 7.57756 5.666];
10   -   den=[0.1152 0.912 1.88 7.44436 5.666];
11   -   sys=tf(num,den);
12   -   step(num,den)
13   -   num=[0.2926 3.1825 11.1104 12.5898];
14   -   den=[0.1152 0.912 3.344 9.59248 12.5898];
15   -   sys=tf(num,den);
16   -   step(num,den)
17
```

Fig. A7: MATLAB format of the comparison between different type of controller for loop 1
Appendix (B)

Loop 2:

- **Root locus method:**

  ![Root locus method code](image1)

  Fig. B1: MATLAB format of root locus method for loop 2

- **Bode plot method:**

  ![Bode plot method code](image2)

  Fig. B2: MATLAB format of bode plot method for loop 2
Nyquist plot:

Fig. B3: MATLAB format of Nyquist plot for loop 2

System response:

- For P-controller:

Fig. B4: MATLAB format of system response for P-controller for loop 2
- For PI-controller:

```matlab
% Loop 2
% System response
% For PI-controller:
num=[1.58004 16.995 11.946];
den=[0.2 2.3 3.1 16.8004 11.946];
sys=tf(num,den);
step(num,den)
```

Fig. B5: MATLAB format of system response for PI-controller for loop 2

- For PID-controller:

```matlab
% Loop 2
% System response
% For PI-controller:
num=[1.58004 16.995 11.946];
den=[0.2 2.3 3.1 16.8004 11.946];
sys=tf(num,den);
step(num,den)
```

Fig. B6: MATLAB format of system response for PID-controller for loop 2
Comparison between different type of controller:

![MATLAB code for system response]

Fig. B7: MATLAB format of Comparison between different type of controller for loop 2
Appendix (C)

Loop 3:

- **Root locus method:**

```matlab
% Loop 3
% Calculation of the ultimate gain and the ultimate period by using Root.
% Locus Analysis
OLTF=0.8Kc/((s+1) (2s+1) (s+1) (0.2s+1))
num=0.6;
a=conv([1 1],[2 1]);
b=conv([1 1],[0.2 1]);
den=conv(a,b);
rlocus(num,den),grid
```

Fig. C1: MATLAB format of root locus method for loop 3

- **Bode plot method:**

```matlab
% Loop 3
% Calculation of the ultimate gain and the ultimate period by using Root.
% Locus Analysis
OLTF=0.8Kc/((s+1) (2s+1) (s+1) (0.2s+1))
num=0.6;
a=conv([1 1],[2 1]);
b=conv([1 1],[0.2 1]);
den=conv(a,b);
bode(num,den),grid
```

Fig. C2: MATLAB format of bode plot method for loop 3
Nyquist plot:

Fig. C3: MATLAB format of Nyquist plot method for loop 3

System response:

For P-controller:

Fig. C4: MATLAB format of system response for P-controller for loop3
- For PI-controller:

![MATLAB code for PI-controller](image1)

Fig. C5: MATLAB format of system response for PI-controller for loop 3

- For PID-controller:

![MATLAB code for PID-controller](image2)

MATLAB input:

Fig. C6: MATLAB format of system response for PID-controller for loop 3
Comparison between different types of controllers:

MATLAB input:

```matlab
1    % Loop 3
2    % System Response:
3    % For P-controller:
4        num=[0.63 3.147];
5        den=[0.4 3 5.8 4.2 4.147];
6        sys=tf(num,den);
7        step(num,den)
8        hold
9    % For PI-controller:
10       num=[0.56652 2.9 0.637];
11       den=[0.4 3 5.8 4.2 3.8326 0.637];
12       sys=tf(num,den);
13       step(num,den)
14    % For PID-controller:
15       num=[0.5046 3.279 4.063 1.4194];
16       den=[0.4 3 5.8 6.725 4.78 1.4144];
17       sys=tf(num,den);
18       step(num,den)
```

Fig. C7: MATLAB format of the comparison between different types of controllers for loop 3
Appendix (D)

Loop 4:

- **Root locus method:**

```
1  % Loop 4
2  % Calculation of the ultimate gain and the ultimate period by using Root.
3  % Locus Analysis
4  % CLTF=Kc/((6s+1)(0.8s+1)(0.5s+1)(0.4s+1))
5  num=1;
6  a=conv([6 1],[0.8 1]);
7  b=conv([0.5 1],[0.4 1]);
8  den=conv(a,b);
9  rlocus(num,den),grid
```

Fig. D1: MATLAB format of root locus method for loop 4

- **Bode plot method:**

```
1  % Loop 4
2  % Calculation of the ultimate gain and the ultimate period by using Bode plot
3  % CLTF=Kc/((6s+1)(0.8s+1)(0.5s+1)(0.4s+1))
4  num=1;
5  a=conv([6 1],[0.8 1]);
6  b=conv([0.5 1],[0.4 1]);
7  den=conv(a,b);
8  bode(num,den),grid
```

Fig. D2: MATLAB format of bode plot method for loop 4
- **Nyquist plot:**

Fig. D3: MATLAB format of Nyquist plot method for loop 4

- **System response:**

  - **For P-controller:**

Fig. D4: MATLAB format of system response for P-controller for loop 4
- For PI-controller:

```matlab
1 % loop4
2 % System Response:
3 % For PI controller:
4 num=[2.159 5.859 1.19];
5 den=[0.96 5.68 11.12 7.7 6.382 1.19];
6 sys=tf(num,den);
7 step(num,den)
```

Fig. D5: MATLAB format of system response for PI-controller for loop 4

- For PID-controller:

```matlab
1 % loop4
2 % System Response:
3 % For PID controller:
4 num=[1.95 7.743 8.235 2.69];
5 den=[0.96 5.68 11.12 12.573 8.176 2.69];
6 sys=tf(num,den);
7 step(num,den)
```

Fig. D6: MATLAB format of system response for PID-controller for loop 4
Comparison between different type of controller:

Fig. D7: MATLAB format of Comparison between different type of controller the for loop 3

```matlab
1 %Loop3
2 %System Response:
3 %For P-controller:
4   num=[2.352 5.98];
5   den=[0.96 5.60 11.12 7.7 6.98];
6   sys=tf(num,den);
7   step(num,den);
8   hold
9 %For PI-controller:
10   num=[2.153 5.858 1.19];
11   den=[0.96 5.60 11.12 7.7 6.382 1.19];
12   sys=tf(num,den);
13   step(num,den)
14 %For PID-controller:
15   num=[1.95 7.743 8.236 2.64];
16   den=[0.96 5.60 11.12 12.573 8.176 2.64];
17   sys=tf(num,den);
18   step(num,den)
```
Appendix (E)

Operating records for furnace temperature:

<table>
<thead>
<tr>
<th>Date</th>
<th>Outlet temperature, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>8-6-2015</td>
<td>487</td>
</tr>
<tr>
<td>9-6-2015</td>
<td>487</td>
</tr>
<tr>
<td>10-6-2015</td>
<td>488</td>
</tr>
<tr>
<td>11-6-2015</td>
<td>487</td>
</tr>
<tr>
<td>12-6-2015</td>
<td>487</td>
</tr>
<tr>
<td>13-6-2015</td>
<td>488</td>
</tr>
</tbody>
</table>

Appendix (F)

Operating records for coker drum temperature and pressure:

<table>
<thead>
<tr>
<th>Time</th>
<th>10:00</th>
<th>6:00</th>
<th>2:00</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crude oil T/H</td>
<td>139</td>
<td>139</td>
<td>140</td>
</tr>
<tr>
<td>Temperature, °C</td>
<td>413</td>
<td>414</td>
<td>413</td>
</tr>
<tr>
<td>Pressure, MPa</td>
<td>0.237</td>
<td>0.230</td>
<td>0.20</td>
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</tbody>
</table>
## Appendix (G)

Summary of ultimate gains (Ku) and ultimate periods (Pu) that were obtained for loop 1, 2, 3, and 4

<table>
<thead>
<tr>
<th>Method</th>
<th>Ku</th>
<th>Pu(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loop(1)</strong></td>
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<td></td>
</tr>
<tr>
<td>Direct substitution and</td>
<td>1.928</td>
<td>1.55</td>
</tr>
<tr>
<td>Routh array method</td>
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<td></td>
</tr>
<tr>
<td>Root-Locus method</td>
<td>1.99</td>
<td>1.272</td>
</tr>
<tr>
<td>Bode diagram tuning</td>
<td>2.05</td>
<td>1.272</td>
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<tr>
<td><strong>Loop(2)</strong></td>
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<td></td>
</tr>
<tr>
<td>Direct substitution and</td>
<td>46.2</td>
<td>1.5959</td>
</tr>
<tr>
<td>Routh array method</td>
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<td>Root-Locus method</td>
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<td>1.5947</td>
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<td>47.847</td>
<td>1.5707</td>
</tr>
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<tr>
<td><strong>Loop(3)</strong></td>
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<td>Direct substitution and</td>
<td>10.58</td>
<td>5.325</td>
</tr>
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<td>Routh array method</td>
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<tr>
<td>Root-Locus method</td>
<td>10.3</td>
<td>5.37</td>
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<td>Bode diagram tuning</td>
<td>10.59</td>
<td>5.325</td>
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<tr>
<td><strong>Loop(4)</strong></td>
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<td>5.42</td>
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<td></td>
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<tr>
<td>Root-Locus method</td>
<td>12</td>
<td>5.46</td>
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<tr>
<td>Bode diagram tuning</td>
<td>11.6</td>
<td>5.42</td>
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<tr>
<td>method</td>
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</tbody>
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