Studies on the Design of Control System for a Fluid Catalytic Cracking Unit (FCCU) of a Modern Refinery using AspenHysys version 8.4

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Abstract
The FCCU remain the most useful and relevant capacity unit of a modern refinery plant. It is a sensitive unit because it produces about 45% reformate (premium motor spirit, PMS) of the whole refinery production. The operations of the FCCU to converting long chain hydrocarbons into useful and more economic reformate of high octane rating under fluidised catalyst influence at reasonable pressure is a crux of the subject. The quest to continue to achieving a better process operation remains a subject of investigation. To improve the efficiency of the FCCU in terms of product quality, excellent controller systems and safe operation of the equipments and personnel is the focus of this work. This paper presents some ideas on the FCCU schematic flow diagram, design and controller systems, and the analysis of the each unit operations using Aspen Hysys v8.4 licensed version. In this simulation study it was found that the cracked naphtha has a value of 3.047x10^4 Ib/hr or 1691 Ibmol/hr at 105.8 °F (41.0 °C).

***Keywords**: Aspen Hysys v8.4, VDU, unit operations, improvement and proper procedure*

1.0 Introduction

The fluid catalytic cracking (FCC) unit present challenging multivariable controls problems, because it is a very sensitive and complex refinery system. The selection of inputs and outputs variables is an important issue, as the pairing of chosen controlled and manipulated variables for decentralized control. Continuous catalyst regeneration makes it possible to manage the yields which are achieved by catalyst cycling between the reaction and regeneration units. This ensures the reactor is continuously supplied with freshly regenerated catalyst, and product yields are maintained at fresh catalyst levels. Reliable and accurate control is important for total process efficiency USEIA, (2015).

Unlike atmospheric distillation and vacuum distillation, which are physical separation processes, FCC is a chemical conversion process used in petroleum refineries. It is used to convert the high-boiling, high-molecular weight hydrocarbon (HC) fractions of petroleum crude oils to more valuable gasoline, olefinic gases, and other products. Catalytic cracking produces more gasoline with a higher octane rating. It also produces by-product gases that are more olefinic and more valuable, than by thermal cracking Gary and Handwerk (2001), and Speight, (2006). The feedstock to an FCC is usually that portion of the crude oil that has an initial boiling point of 340 °C or higher at atmospheric pressure and an average molecular weight ranging from about 200 to 600 or higher. This portion of crude oil is often referred to as heavy gas oil (HGO) and/or vacuum gas oil (HVGO). The FCC process vapourises and breaks the long-chain molecules of the high-boiling hydrocarbon liquids into much shorter molecules by contacting the feedstock, at high temperature and moderate pressure, with a fluidized powdered catalyst Speight (2006).

1.1 Problem Statement

The oldest Nigerian refineries were built in late 70s, which in technological age can be considered as young plant. But where we have issues of improper maintenance, the refineries will continue to be on epileptic operations and at low capacities. To resolving these problems through indigenous input and local contents development, there is the need for the application of world-class Aspen Hysys v8.4 software to study the pressure issues, temperatures, controllers, flow situation, fluctuation and stabilization of the FCC column.

1.2 Justification of the Study

Refineries overseas that are over 100 years old are still operating effectively at a reasonable and higher capacity till today. Unfortunately, the peculiar nature of the Nigerian refineries has problems of base capacity, technologies, quality manpower, crude oil supply etc. The application of indigenous technology would assist a long way in achieving the quality operation of our refineries. These technologies include using local contents inputs and involvement in conceptual plant designs, operational software, quality maintenance, capable building and qualified manpower.

2.0 Background Literatures

2.1 Historical Background on FCC

In 1922, a French mechanical engineer named Eugene Jules Houdry and a French pharmacist named E.A Prudhomme set up a laboratory near Paris to develop a catalytic process for converting lignite coal to gasoline. Supported by the French government, they built a small demonstration plant in 1929 that processed about 60 tons per day of lignite coal. The results indicated that the process was not economically viable and it was subsequently shut down Raterman, (1985). Houdry had found that Fuller's earth a clay mineral containing aluminosilicates, could convert oil derived from the lignite to gasoline. He then began to study the catalysis of petroleum oils and had some success in converting vaporized petroleum oil to gasoline. In 1930, the Vacuum Oil Company invited him to come to the United States and he moved his laboratory to Paulsboro, New Jersey.

In 1931, the Vacuum Oil Company merged with Standard Oil of New York (Socony) to form the Socony-Vacuum Oil Company. In 1933, a small Houdry unit processed 200 barrels per day (or 32 m^3/day) of petroleum oil. Because of the economic depression of the early 1930s, Socony-Vacuum was no longer able to support Houdry's work and gave him permission to seek help elsewhere.

In 1933, Houdry and Socony-Vacuum joined with Sun Oil Company in developing the Houdry process. Three years later, that is, in 1936, Socony-Vacuum converted an older thermal cracking unit in their Paulsboro refinery in New Jersey to a small demonstration unit using the Houdry process to catalytically crack 2,000 barrels per day (or 320 m^3/day) of petroleum oil. In 1937, Sun Oil began operation of a new Houdry unit processing 12,000 barrels per day (or 1,900 m^3/day) in their Marcus Hook refinery in Pennsylvania. The Houdry process at that time used reactors with a fixed bed of catalyst and was a semi-batch operation involving multiple reactors with some of the reactors in operation while other reactors were in various stages of regenerating the catalyst. Motor-driven valves were used to switch the reactors between online operation and offline regeneration and a cycle timer managed the switching. Almost 50% of the cracked product was gasoline as compared with about 25% from the thermal cracking processes Speight, (2006) and Sadeghbeigi, (2000).

2.2 FCCU Design and Process Description

There are several different proprietary designs that have been developed for modern FCC units. Each design is available under a license that must be purchased from the design developer by any petroleum refining company desiring to construct and operate an FCC of a given design Sadeghbeigi, (2000). There are two different configurations for an FCC unit: (i) the 'stacked' type where the reactor and the catalyst regenerator are contained in a single vessel with the reactor above the catalyst regenerator and (ii) the 'side-by-side' type where the reactor and catalyst regenerator are in two separate vessels Speight, (2006) and Sadeghbeigi, (2000).

2.2.1 Reactor and Regenerator

The reactor and regenerator are considered to be the *heart* of the FCCU. The schematic flow diagram of a typical modern FCC unit is shown in Figure 1 below is an example of 'side-by-side' configuration. The preheated high-boiling petroleum feedstock (at about 315 to 430 °C) consisting of long-chain hydrocarbon molecules is combined with recycle slurry oil from the bottom of the distillation column and injected into the catalyst riser where it is vaporised and cracked into smaller molecules of vapour by contact and mixing with the very hot powdered catalyst from the regenerator. All of the cracking reactions take place in the catalyst riser within a period of 2–4 seconds. The hydrocarbon vapours 'fluidize' the powdered catalyst and the mixture of hydrocarbon vapours and catalyst flows upward to enter the reactor at a temperature of about 535 °C and a pressure of about 1.72 barg David and Peter (2006).

The reactor is a vessel in which the cracked product vapours are: (a) separated from the so-called spent catalyst by flowing through a set of two-stage cyclone within the reactor and (b) the spent catalyst flows downward through a steam stripping section to remove any hydrocarbon vapours before the spent catalyst returns to the catalyst regenerator. The flow of spent catalyst to the regenerator is regulated by a slide valve in the spent catalyst line USEIA, (2005), David and Peter (2006).

Since the cracking reactions produce some carbonaceous material (referred to as catalyst coke) that deposits on the catalyst and very quickly reduces the catalyst reactivity, the catalyst is regenerated by burning off the deposited coke with air blown into the regenerator. The regenerator operates at a temperature of about 715 °C and a pressure of about 2.41 barg, hence the regenerator operated at about 0.7 barg higher pressure than the reactor. The combustion of the coke is exothermic and it produces a large amount of heat that is partially absorbed by the regenerated catalyst and provides the heat required for the vaporization of the feedstock and the endothermic cracking reactions that take place in the catalyst riser. For that reason, FCC units are often referred to as being 'heat balanced'. The hot catalyst (at about 715 °C) leaving the regenerator flows into a catalyst withdrawal well where any entrained combustion flue gas are allowed to escape and flow back into the upper part to the regenerator. The flow of regenerated catalyst to the feedstock injection point below the catalyst riser is regulated by a slide valve in the regenerated catalyst line. The hot flue gas exits the regenerator after passing through multiple sets of two-stage cyclones that remove entrained catalyst from the flue gas. The amount of catalyst circulating between the regenerator and the reactor amounts to about 5 kg per kg of feedstock, which is equivalent to about 4.66 kg per litre of feedstock. Thus, an FCC unit processing 75,000 barrels per day (or

11,900 m^3/day) will circulate about 55,900 tons per day of catalyst USEIA, (2005), Speight (2006) and Sadeghbeigi (2000).

2.2.2 Distillation Column

The reaction product vapours (at 535 °C and a pressure of 1.72 barg) flow from the top of the reactor to the bottom section of the distillation column (commonly referred to as the main fractionator) where they are distilled into the FCC end products of cracked naphtha, fuel oil, and off gas. After further processing for removal of sulphur compounds, the cracked naphtha becomes a high-octane component of the refinery's blended gasoline HP, (2002). The main fractionator off gas is sent to what is called a gas recovery unit where it is separated into butanes and butylenes, propane and propylene, and lower molecular weight gases (hydrogen, methane, ethylene and ethane). Some FCC gas recovery units may also separate out some of the ethane and ethylene.

Although the schematic flow diagram above depicts the main fractionators as having only one side-cut stripper and one fuel oil product, many FCC main fractionators have two side cut strippers and produce a light fuel oil and a heavy fuel oil. Likewise, many FCC main fractionators produce light cracked naphtha and a heavy cracked naphtha. The terminology light and heavy in this context refers to the product boiling ranges, with light products having a lower boiling range than heavy products. The bottom product oil from the main fractionator contains residual catalyst particles which were not completely removed by the cyclones in the top of the reactor. For that reason, the bottom product oil is referred to as slurry oil. Part of that slurry oil is recycled back into the main fractionator above the entry point of the hot reaction product vapours so as to cool and partially condense the reaction product vapours as they enter the main fractionator. The remainder of the slurry oil is pumped through a slurry settler. The bottom oil from the slurry settler contains most of the slurry oil catalyst particles and is recycled back into the catalyst riser by combining it with the FCC feedstock oil. The so-called clarified slurry oil or decant oil is withdrawn from the top of slurry settler for use elsewhere in the refinery, as a heavy fuel oil blending component, or as carbon black feedstock Speight (2006) and Sadeghbeigi (2000).

2.2.3 Regenerator Flue Gas

Depending on the choice of FCC design, the combustion in the regenerator of the coke on the spent catalyst may or may not be complete combustion to carbon dioxide CO2. The combustion air flow is controlled so as to provide the desired ratio of carbon monoxide (CO) to carbon dioxide for each specific FCC design USEIA, (2015), David and Peter (2006). In the design shown in Figure 1, the coke has only been partially combusted to CO_2. The combustion flue gas (containing CO and CO_2) at 715 °C and at a pressure of 2.41 barg is routed through a secondary catalyst separator containing swirl tubes designed to remove 70 to 90 percent of the particulates in the flue gas leaving the regenerator. This is required to prevent erosion damage to the blades in the turbo-expander that the flue gas is next routed through Alex and Lewis (2002).

2.2.4 Zeolite Catalyst

Modern FCC catalysts are fine powders with a bulk density of 0.80 to 0.96 g/cm^3 and having a particle size distribution ranging from 10 to 150 μm and an average particle size of 60 to 100 μm. The desirable properties of an FCC catalyst are: (i) Good stability to high temperature and to steam, (ii) High activity, (iii) Large pore sizes, (iv) Good resistance to attrition and (v) Low coke production. A modern FCC catalyst has four major components: (a) crystalline zeolite, (b) matrix, (c) binder, and (d) filler. Zeolite is the primary active component and can range from about 15 to 50 weight percent of the catalyst. The zeolite used in FCC catalysts is referred to as *faujasite* or as *Type Y* and is composed of silica and alumina tetrahedra with each tetrahedron having either an Al or a Si atom at the center and four oxygen_atoms at the corners. It is a molecular sieve with a distinctive lattice structure that allows only a certain size range of hydrocarbon molecules to enter the lattice. In general, the zeolite does not allow molecules larger than 8 to 10 nm (i.e. 80 to 90 angstrom to enter the lattice (Jessica et al., 2006), Wen-Ching, (2003).

2.3 The AspenHysys Code (aspenONE)

AspenONE Engineering is a market leading suite of products focused on process engineering and optimization. In aspenONE, process modelling analysis and design tools are integrated and accessible through process simulators Aspen HYSYS and Aspen Plus copyright. Optimize process designs for energy use, capital and operating costs, and product yield through the use of activated energy, economics, and equipment design during the modelling process. Other applications of AspenHysys are: acid gas cleaning uses rigorous rate-based calculations and new property packages to deliver unprecedented accuracy and predictive results to gas absorption processes, petroleum refining layers powerful features onto the Aspen HYSYS process simulator to simplify and improve petroleum refining simulations, hydrocarbon optimisation: Aspen HYSYS is the energy industry's leading process simulation software that is used by top oil and gas producers, refineries and engineering companies for process optimization in design and operations, energy and utilities optimisation: Aspen Energy Analyser is an energy management software for performing optimal heat exchanger network design to minimize process energy etc. (AspenONE, 2016).

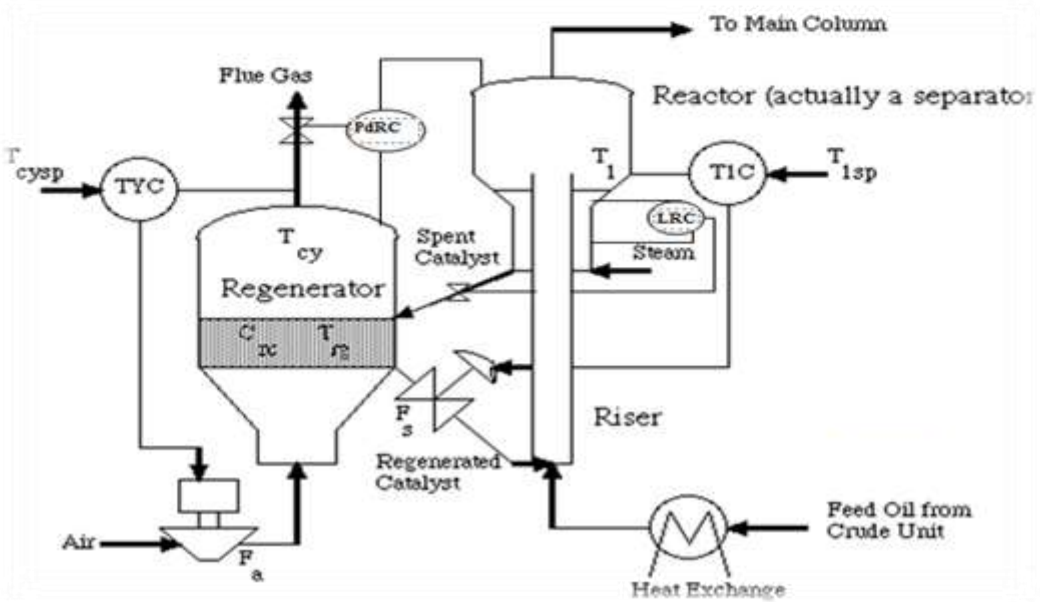

Figure 1: Process schematic and control systems of FCCU plant (Source: Speight (2006)

3.0 Materials and Methods

3.1 Materials

In this paper, the materials used are (i) a typical FCCU process flow scheme, and (ii) a licensed AspenHysys v8.4 version.

3.2 Methodology

Each of the unit operations was developed in the v8.4 code to generate the complete FCCU scheme in the AspenHysys version. Automatically, the materials and energy balance for each units and sub-units were generated as shown in Figure 2 below. The steps taken are as follows:

- **a)** The AspenHysys quickly accommodate the input data for the various unit operations, highlights any discrepancies and make suggestible corrections.
- **b)** Each materials and energy units were completely identified as correctly as possible.
- **c)** The operations were carried out in two-separate analysis to ascertain the capability of the AspenHysys code.
- **d)** Comparison of the results was conducted.

4.0 Results and Discussions

In this chapter, the discussions of the results were subdivided various subchapters as presented below:

4.1 Aspen Hysys v8.4 designed version of the FCCU process

Several simulations were conducted and a summary data is shown in Table 1 below.

1. The PFD of FCCU designed using Aspen Hysys version 8.4. The inferences drawn from the re-development of the plant is as shown Figure 2.
2. FCCU workbook developed using Aspen Hysys version 8.4. The inferences from the AspenTech Hysys are shown in the workbook in Table 1.

4.2 Designs of the Relevant Controllers

1. The designs of all the relevant controllers for the FCCU
2. The suggested ways for the improvement of FCCU plant systems.

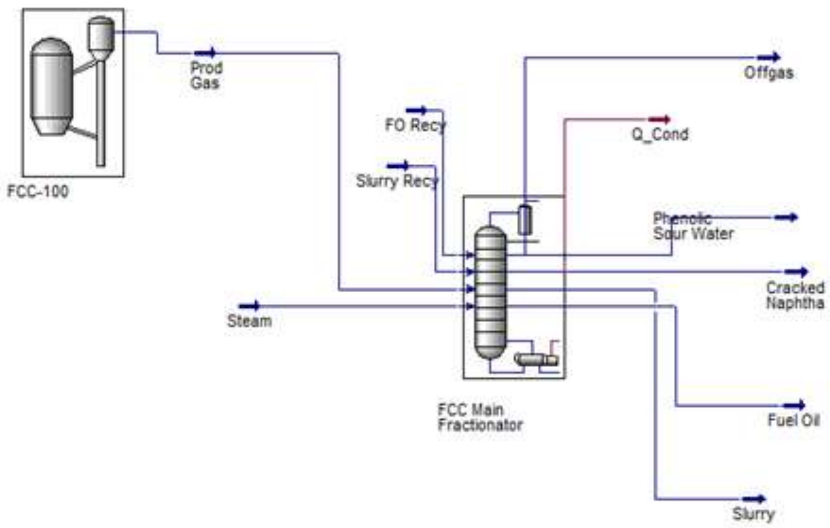

Figure 2: PFD of FCCU designed using Aspen Hysys V8.4 (Sources: AH v8.4 in 2015)

Table 1: FCCU workbook developed using Aspen Hysys V8.

aspentech — LEGENDS, Burlington, MA, USA

Case Name:	FCC Plant.hsc
Unit Set:	User Field2
Date/Time:	Thu Jun 04 12:02:47 2015

Workbook: Case (Main)

Material Streams — Fluid Pkg: All

Name		Prod Gas	Steam	Cracked Naphtha	Phenolic Sour Water	Slurry
Vapour Fraction		1.0000	1.0000	0.0000	0.0000	0.0001
Temperature	(F)	1013	464.0 *	105.8	103.5	652.2
Pressure	(psia)	49.31	196.0 *	36.99	36.99	43.76
Molar Flow	(lbmole/hr)	7699	673.1	1691	1283	69.25
Mass Flow	(lb/hr)	4.985e+005	1.213e+004 *	3.047e+004	1.146e+005	2.425e+004
Liquid Volume Flow	(USGPM)	1444	24.26	60.96	305.7	42.99
Heat Flow	(Btu/hr)	-1.785e+008	-6.801e+007	-2.072e+008	-9.855e+007	-1.660e+007
Name		**Offgas**	**FO Recy**	**Slurry Recy**	**Fuel Oil**	
Vapour Fraction		1.0000	0.0008	1.0000	0.0000	
Temperature	(F)	105.8	108.0 *	464.0 *	404.4	
Pressure	(psia)	36.99	183.1 *	196.0 *	39.53	
Molar Flow	(lbmole/hr)	4692	983.2 *	45.28	1665	
Mass Flow	(lb/hr)	1.972e+005	1.652e+005	815.7 *	3.101e+005	
Liquid Volume Flow	(USGPM)	746.9	376.5	1.632	689.9	
Heat Flow	(Btu/hr)	-1.192e+008	-1.507e+008	-4.575e+006	-2.417e+008	

(**Sources**: Spreadsheet developed from Aspen Hysys v8.4 2015)

4.3 The FCCU Controller Design

The selection of good inputs (manipulated variables) and outputs (measured variables) is an important issue, as is the pairing of chosen controlled and manipulated variables for decentralized control. In this case, the important measured variables are chosen to be the reactor temperature/riser outlet temperature (T_1), the regenerator gas temperature (T_{cy}) and the regenerator bed temperature (T_{rg}). The manipulated variables are the catalyst recirculation rate (F_s) and the regenerator air rate (F_a) Lee and Weekman (1976).

4.4 Challenges

Continuous catalyst regeneration makes it possible to manage the high catalyst coking rate. The constancy of the yields is achieved by catalyst cycling between reaction and regeneration, which ensures the reactor, is continuously supplied with freshly regenerated catalyst, and product yields are maintained at fresh catalyst levels. It's critical to control the regenerator temperature carefully to prevent catalyst deactivation by overheating and to provide the desired amount of burn-off. Reliable and accurate control is important for total process efficiency.

4.5 Major Controls

At one time or another, almost every operator of a fluid catalytic cracking unit has experienced problems with catalyst circulation. Usually, the problem is solved through adjustment of standpipe operating parameters, or change of catalyst physical properties. The following are the major controls on the FCCU itself, which maintain correct catalyst circulation rates Grosdidier, et al., (1993), Matsen, (1981).

4.6 The Stripper Level Control

The stripper level is controlled by a valve at the base of the spent catalyst standpipe. Stripper level control is important in order to provide sufficient residence time in the stripper for the stripping steam to displace strippable hydrocarbons for recovery downstream. The stripper level is also important to provide sufficient pressure to keep the air in the regenerator from reverse flow into the reaction system, thereby causing a hazard.

4.7 The Reactor/Regenerator Differential Pressure Controller

This controller operates the flue gas slide valve to maintain a safe differential pressure between the reactor and regenerator. When the pressure balance is proper, the differential pressure maintains about equal pressure drop across both the regenerated and spent catalyst control valves. The differential pressure may be adjusted to overcome small circulation difficulties from time to time. It may also be used to balance pressure drops across the two catalyst flow control valves.

4.8 Stripping Steam Flow Control

Remaining oil on the catalyst is removed by steam stripping before catalyst enters the regenerator. The steam supply to the reactor takes place at a temperature at dry saturated steam.

<u>Control valve Type</u>: Rotary plug valve

<u>Requirement:</u>

a. Control accuracy to optimize steam consumption
b. Reliable to ensure efficiency of oil stripping
c. Noise reduction capabilities

4.9 Air Flow Control

To maintain the catalyst activity at a useful level, it's necessary to regenerate the catalyst by burning off this coke with air. This is done by controlling the air flow. A typical air temperature is around 600 – 700°C.

<u>Control valve Type</u>: eccentric Disc valve

<u>Requirement</u>:

- Good control combined with long lasting tightness
- Economical control valve for low differential pressures

4.10 Catalyst Valve

Continuously catalyst regenerating makes it possible to manage the high catalyst coking rate. The constancy of the yields is achieved by catalyst cycling between reaction and regeneration, which ensures that the reactor is continuously supplied with freshly regenerated catalyst level.

<u>Requirement:</u>

- Leak free isolation to avoid waste or inefficient FCC performance.
- Reliable operation to avoid additional spent catalyst in regenerator, which may cause possible catalyst in flue gas and further emission problems.

4.11 Flue Gas Catalyst Separation Valve

Hot flue gases exit the regenerator through cyclones where catalyst is separated and recycled to reactor. A typical temperature here is 760^{o} Raterman, (1985).

4.12 Regenerator Extraction Valve

Catalyst handling valves play an important role in ensuring proper FCC performance. The feedstock is vaporized by the hot regenerated catalyst, the cracking begins, and the resultant vapor carries the catalyst upward through the riser. The heat of combustion raises the catalyst temperature to (620 – 845 °C), and most of this heat is transferred by the catalyst to the oil feed in the feed riser. The regenerator/reactor cycle continues until catalyst is spent and removed from process through extraction valve.

6.0 Conclusions

Within the limit of simulation error from the Aspen Hysys v8.4, it was determined that at the temperature of 464.0 °F the steam produced were about 6.801×10^7 Btu/hr. The production gas 1.787×10^8 Btu/hr was produced at the temperature of 1013 °F. It was also predicted from the code that the heat flown into the systems was 1.192×10^8 Btu/hr at 105.8 °F.
Of course the utmost importance about this simulation is on the improvement of the FCC unit as compared with the input data profile. From the Aspen predicted results, it was found that the cracked naphtha has a value of 3.047×10^4 Ib/hr or 1691 Ibmol/hr at 105.8 °F.

Abbreviations

Fa	-	*Regenerator rate*
Fs	-	*Catalyst recirculation rate*
FCCU	-	*Fluid catalytic cracking unit*
HGO	-	*Heavy gas oil*
HVGO	-	*Vacuum gas oil*
LRC	-	*Stripper level controller*
PdRC	-	*Regenerator/Reactor differential pressure controller*
PFD	-	*Process flow diagram*
T1	-	*Riser outlet/Reactor temperature*
Tcy	-	*Regenerator gas temperature*
Trg	-	*Regenerator bed temperature*
TYC	-	*Regenerator temperature controller*
USEIA	-	*United States Energy Information Administration*

Recommendations

1. An in-depth research studies should be carried out using a real life data from FCC refinery operations and the AspenHysys code.
2. Studies should be carried out on the possibility of debottlenecking and capacity increase to an existing FCCU process using AspenHysys code.

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