Exergy and Energy Analysis of Fluid Catalytic Cracking Unit in Kaduna Refining and Petrochemical Company

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***Abstract*—The energy and exergy analysis of FCCU of Kaduna Refining and Petrochemical Company (KRPC) Nigeria is presented. The primary objectives of this work were to analyze the system components separately and to identify and quantify the sites having largest energy and exergy losses. The performance of the plant was estimated by a component wise simulation using Aspen Hysys software and a detailed break-up of energy and exergy losses for the considered plant has been presented. The ideal work was calculated to be (- 74.169 MW) which characterized the system as work producing. Energy losses mainly occurred in the fractionator column where 46.6MW is lost to the environment while only 3.69, 1.77 and 0.68 MW was lost from the condensers, other equipment and absorbers respectively. The percentage exergy and second law efficiencies of the system was found to be 61.20 and 24.77 %.**

***Index Terms*—Exergy analysis, ideal work, efficiency, exergy destruction, FCCU, KRPC.**

I. Introduction

Kaduna Refining and Petrochemical Company (KRPC) location Kaduna Nigeria was designed and constructed by a Japanese Chemical Engineering Company (CHIYODA). It was commissioned in 1980 as NNPC Refinery Kaduna. Its initial capacity was 100,000 barrels per stream day [BPSD]. As the third Refinery in the country, it was established to cope with the growing demand for petroleum products, especially in the Northern part of the country. The Refinery was designed to process both Nigerian and imported crude oils into fuels and lubes products. The purpose of fluid catalytic cracking unit (FCCU) is to convert heavy distillates into lighter ones. The distillates used are normally heavy gas oil coming from atmospheric and vacuum distillation units. The most widely used cracking units are the catalytic type with a moving catalyst bed of Zeolite – Y as this gives a higher conversion and above all a higher selectivity. The selectivity of the process is due to the particular characteristics of the catalyst. Actual design depends on refiner's operating conditions and product priority.

Analysis of energy losses are of scientific interest and also essential for the efficient utilization of energy resources. The most commonly-used method for analysis of an energy-conversion process is the first law of thermodynamics. However, there is increasing interest in the combined utilization of the first and second laws of thermodynamics, using such concepts as exergy and exergy destruction in order to evaluate the efficiency with which the available energy is consumed. Exergy analysis provides the tool for a clear distinction between unavoidable energy losses to the environment and internal irreversibility in the process (Kopac, 2007).

Exergy analysis is a methodology for the evaluation of the performance of devices and processes, these involves examining the exergy at different points in a series of energy-conversion steps. With this, efficiencies can be evaluated, and the process steps having the largest losses (i.e., the greatest margin for improvement) can be identified (Rosen, 2004).

For these reasons, the modern approach to process analysis uses the exergy analysis, which provides a more realistic view of the process and a useful tool for engineering evaluation (Utlu, 2007). As a matter of fact, many researchers (Szargut et al, 1988)have recommended that exergy analysis be used to aid decision making regarding the allocation of resources (capital, research and development effort, optimization, life cycle analysis, materials, etc.) in place of or in addition to energy analysis (Rosen, 2004). Due to the relatively high energy cost as a component of a unit production cost, it is necessary for any plant to carry out analysis of energy utilization.

The objective of this work is to analyze FCCU of Kaduna Refining and Petrochemical Company (KRPC) through energy and exergy perspective. Sites of primary energy loss and exergy destruction will be determined. The second law and exergy efficiencies will also be determined.

II. Theory

The FCCU of KRPC has an installed capacity of(500 kmol/h), located at 16 km Kaduna-Kachia road. It products are gasoline, liquefied petroleum gas, heavy and light naphtha, gases etc. The unit uses (VGO, HGO, and Waxy distillates) as its feed. FCCU feed components are obtained from Crude Distillation Unit (area 1) and Vacuum Distillation Unit (area 2) of KRPC. The feed is heated by a series of heat exchangers. The temperature is further increased by passing it through a furnace to temperature (300-330 ^{0}C) before the riser. This is an arrangement where the feed and the catalyst mixes at the bottom and rises up to the disengager. About 80% of the reaction takes place in the riser. Cracking temperature is between 515-535 ^{0}C depending on unit design and the catalyst being used. The disengager is the final part of the reactor and has the purpose of separating vapours from the catalyst. A group of cyclones are installed inside the disengager (Open system). The vapour flows through the rough cut, smooth cut cyclones and finally to the main fractionator column. The fractionator column receives the superheated vapours from disengager

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top, quenches it and fractionates the products in accordance with the required specifications by means of boiling point differentials. The working principles are that of the fractional distillation. The bottom product is sent to the vapour recovery section where gasoline is separated from the liquefied petroleum gas (LPG).

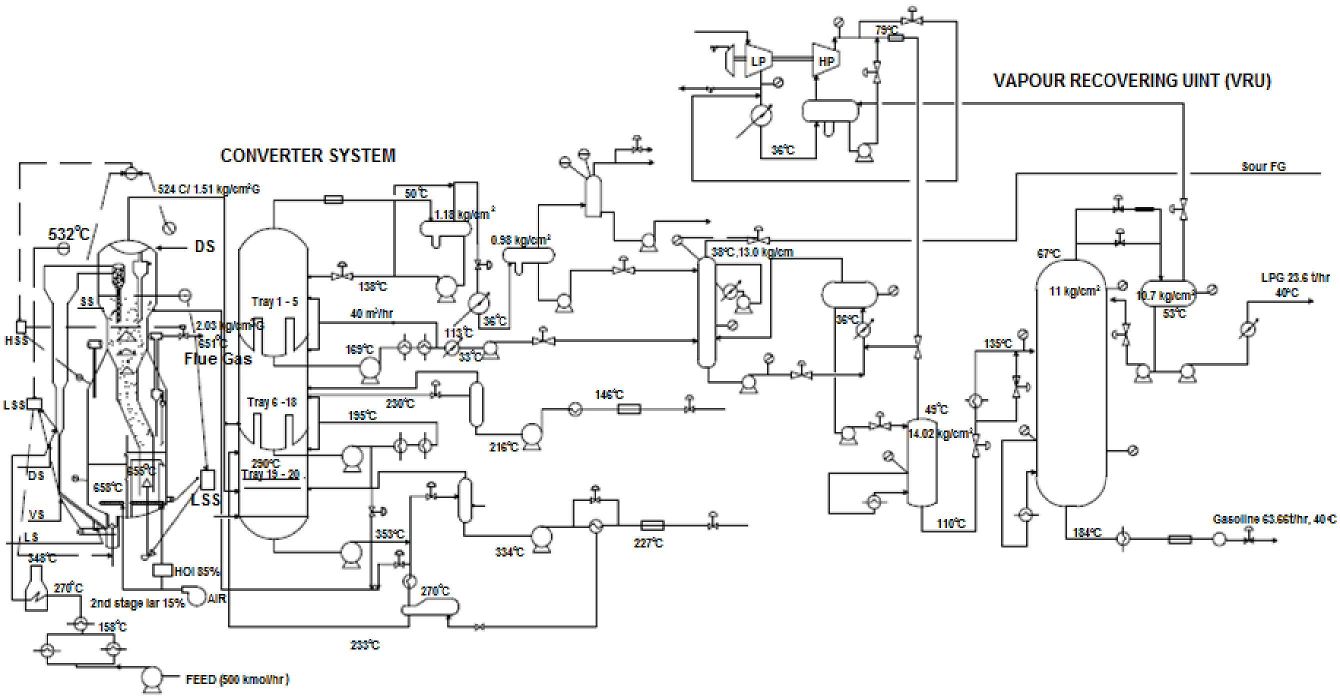

Fig. 1. Schematic diagram of KRPC, FCCU.

Simulation of FCCU was carried out in order to generate enough data for the analysis. Data such as (streams enthalpy, specific heat capacity, and entropy) were required. Fig. 1 was modified and simulated using Aspen Hysys software version 7.2 using KRPC, FCCU data log sheet (daily mass flow, temperature, and pressure readings). The temperature, pressure, molar flow rates, molar enthalpy, and molar entropy used for the exergy analysis were obtained from the simulation results. The modification involves truncating stripper and fractionator as a unit; heat exchangers are arranged in series as a unit while pumps and other auxiliary equipment were left out. This is presented in Fig. 2.

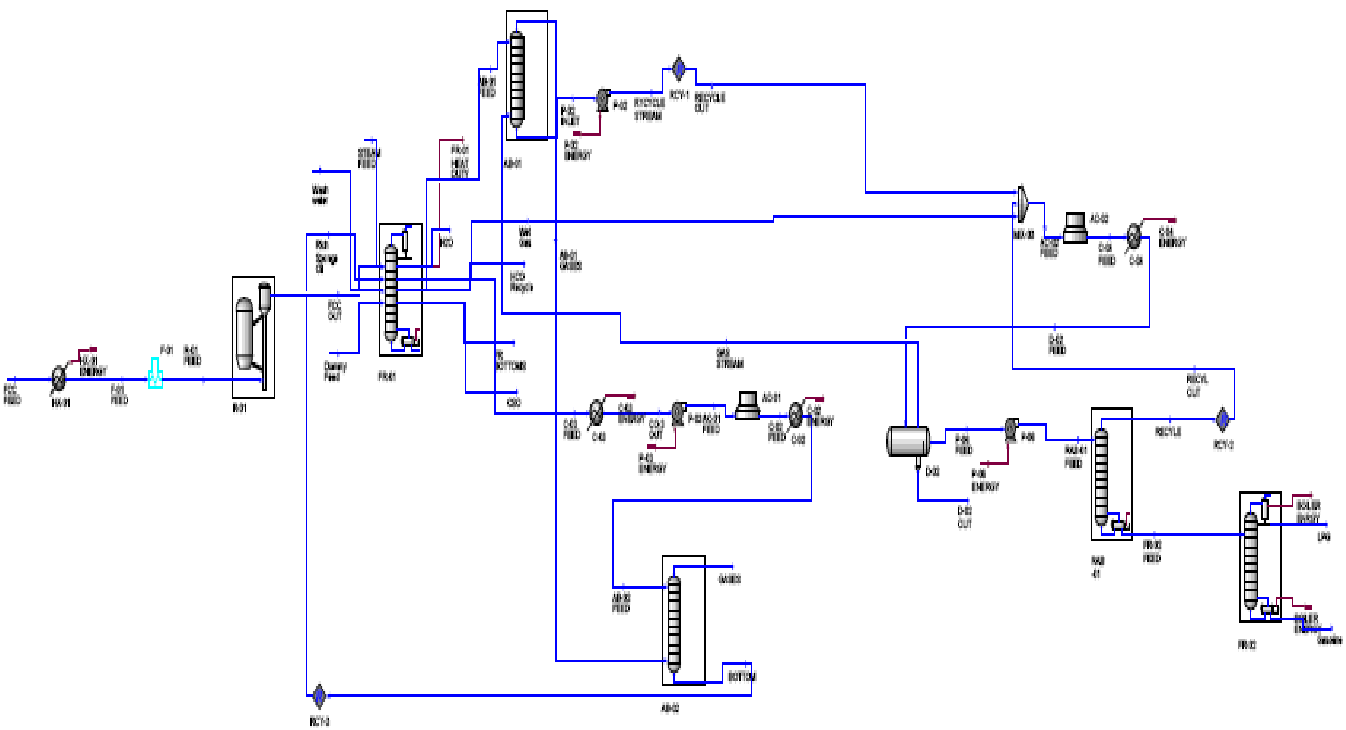

Fig. 2. Simulated FCCU Aspen HysyS

III. Analysis

Table I–II presents FCCU feed properties (obtained from the data log sheet), exergy destruction and efficiency equations.

TABLE I: FCCU Feed Properties.

Properties	Values
Specific gravity	0.89
Viscosity, Cst	190
Nitrogen, ppm	590
Sulphur, wt%	0.1
CCR, wt%	0.1
Nickel, ppm	0.2
K factor	12
Molecular weight, wt	371
API	20-26
Distillation	
IBP, ^{0}C	284
10%	351
30%	380
50%	409
70%	445
90%	490

FCCU Refresher Course Programme, 2004

TABLE II: Exergy Destruction and Efficiency

Equipments	Exergy destruction rate	Exergy efficiency
Fractionators	$I_{\Pr actionator} = X_{in} - X_{out}$	$\eta_{Fractionators} = \frac{I_{Fractionators}}{X_{in}}$
Absorbers	$I_{Absorber} = X_{in} - X_{out}$	$\eta_{Absorbers} = \frac{I_{Absorbers}}{X_{in}}$
Coolers	$I_{Cooler} = X_{in} - X_{out}$	$\eta_{Cooler} = \frac{I_{Cooler}}{X_{in}}$
Separator	$I_{Separator} = X_{in} - X_{out}$	$\eta_{Separator} = \frac{I_{Separator}}{X_{in}}$
Regenerator	$I_{\mathrm{Re}\,generator} = X_{in} - X_{out}$	$\eta_{\mathrm{Re}\,generator} = \frac{I_{\mathrm{Re}\,generator}}{X_{in}}$
Fumace	$I_{Fumace} = X_{in} - X_{out}$	$\eta_{Fumace} = \frac{I_{Fumace}}{X_{in}}$
Air coolers	$I_{Aircoolers} = X_{in} - X_{out}$	$\eta_{Aircoolers} = \frac{I_{Aircoolers}}{X_{in}}$
Pump	$I_{Pump} = X_{in} - X_{out}$	$\eta_{Pump} = \frac{I_{Pump}}{X_{in}}$
Mixer	$I_{Mixer} = X_{in} - X_{out}$	$\eta_{Mixer} = \frac{I_{Miser}}{X_{in}}$
Compressor	$I_{Compressor} = X_{in} - X_{out}$	$\eta_{Compressor} = \frac{I_{Compressor}}{X_{in}}$

The system ideal work is given by:

$$W_{ideal} = \Delta H - T_0 S_G \quad (1)$$

$$\Delta H = \sum n\, h_e - \sum n\, h_i \quad (2)$$

$$S_G = \sum n\, \Delta S - \sum \theta / T_0 \quad (3)$$

$$\eta' = \frac{W_s}{W_{ideal}} \quad (4)$$

$$\eta = 1 - \frac{I_{destruction}}{E_{in}} \quad (5)$$

$$I_{destruction} = T_0 S_G \quad (6)$$

$$E_{in} = m\left[h_{in} - h_0 - T_0\left(s_{in} - s_0\right)\right] \quad (7)$$

$$\psi = h - h_0 - T_0\left(s - s_0\right) \quad (8)$$

$$x = m\psi = m\left[h - h_0 - T_0\left(s - s_0\right)\right] \quad (9)$$

IV. Results and Discussion

Table III – V presents exergy analysis of FCCU, second law and exergy efficiency. Fig. 3and Fig. 4 represent pie chart of second law and exergy efficiencies respectively.

The FCCU of KRPC plant was analyzed using the above relations noting that the environment reference temperature and pressure are 25 ^{0}C and 101.3 kPa, respectively. The ideal work was calculated to be (- 74.169 MW) which characterized the system as a work producing.

The equipment lost work and percentage ideal work were also determined. It showed that the second law efficiency was (24.77%) appear to be low. This could be as a result of huge losses due to equipment age and inadequate maintenance. The lossesfrom the fractionator columnswas (49.66MW) which is 67% of the entire system lost work.Fractionators are known to be associated with low energy efficiency (Olakunle et al, 2011).

The calculated exergy efficiency of the FCCU was 61.2% compared to second law efficiency 24.77%. This is an indication that improvement in the quality of heat input would improve the second law efficiency of the unit. The analysis results were determined using equation (1)-(9).

TABLE VI: Second Law Efficiency.

Work		kW	% Ideal Work
Shaft Work (Ws)	Ws	18375	24.77
Lost Work	Components		
	Fractionators Column	49660	66.96
	Absorbers	676	0.91
	Coolers	3687	4.97
	Others	1771	2.39
Ideal Work		74169	100

TABLE III: EXERGY ANALYSIS OF FCCU FCCU FEED PROPERTIES.

Reference point	T_0 = 25 ^{0}C	P= 101 kPa		h_0 = -8.9E+05	s_0 = 894.6	h_0 **(kJ/kgmol)**	s_0**(kJ/kgmol C)**	
STREAM FLOW	**T (^{0}C)**	**P(kPa)**	**m,kgmol/h**	**h, kJ/kgmol**	**s, kJ/kgmol^{0}C**	**ψ, kJ/kgmol**	**χ (kJ/h)**	**χ (kW)**
WASH WATER	30	267	554	-285000	54.99	619490.3	3.43E+08	95332.67
RICH SPONGE OIL	50	1398	90.46	-403600	-18.03	502715.8	45475667	12632.13
FCC OUT	560	340	2414	-68570	390.1	827542.5	2E+09	554913.2
DUMMY FEED	250	300	5	6460	130.1	909072.5	4545363	1262.601
STEAM FEED	250	446	24.98	-233400	180.5	667952.5	16685453	4634.848
H20	38	265	931.9	-284400	56.94	620041.5	5.78E+08	160504.6
AB-01 FEED	38	265	1069	-239300	165.3	662432.5	7.08E+08	196705.7
WET GAS	38	265	874.1	-53680	166.1	848032.5	7.41E+08	205907
HCO RECYCLE	349	288	22.26	-429800	251.5	469777.5	10457247	2904.791
CSO	357	295	42.7	-54030	239.5	845847.5	36117688	10032.69
C-03 FEED	297	278	66.32	-394500	204.1	506262.5	33575329	9326.48
FR BOTTOMS	286	278	82.56	-413000	169.5	488627.5	40341086	11205.86
FR-02 FEED	128	1688	1489	-172100	196.6	728850	1.09E+09	301460.5
LPG	70	1101	913.7	-101900	103.7	801372.5	7.32E+08	203392.8
GASOLINE	296	1136	575.3	-230300	432.4	664755	3.82E+08	106231.5
AB-01 FEED	38	265	1069	-239300	165.3	662432.5	7.08E+08	196705.7
GAS STREAM	38	1550	718.4	-42090	155.7	859882.5	6.18E+08	171594.3
AB-02 FEED	43	1446	434.1	-47550	165.4	836679.2	3.63E+08	100889.6
P-02 INLET	50	1460	1353	-196100	160.8	705745	9.55E+08	265242.5
AB-01 GASES	43	1446	434.1	-47550	165.4	854180	3.71E+08	102999.9
GASES	48	1377	409.9	-45510	166.3	856197.5	3.51E+08	97487.6
BOTTOM	50	1398	90.46	-403600	-18.05	502716.3	45475712	12632.14
RAB-01 FEED	38	1653	1917	-160300	136.2	742160	1.42E+09	395200.2
RECYLE	52	1653	427.8	-38770	150.9	863322.5	382709.9	106.3083
FR-02 FEED	128	1688	1489	-172100	196.6	728850	1.09E+09	301460.5
D-02 FEED	38	1550	2654	-129200	140.9	773142.5	2.05E+09	569977.8
GAS STREAM	38	1550	718.4	-42090	155.7	859882.5	6.18E+08	171594.3
P-06 FEED	38	155	1917	-160300	136.2	742160	1.42E+09	395200.2
D-02 OUT	38	1550	19.18	-284400	56.96	620041	11892386	3303.441
R-01 FEED	348	148	500	-552600	1624	312665	1.56E+08	43425.69
FCC – OUT	560	340	2414	-68570	390.1	827542.5	2E+09	554913.2
F-01 FEED	270	101	500	-646700	1463	222590	1.11E+08	30915.28
R-01 FEED	348	148	500	-552600	1624	312665	1.56E+08	43425.69
AC-01 FEED	230	1385	66.32	-432500	132.8	470045	31173384	8659.273
C-02 FEED	66	1380	66.32	-510000	-51.64	397156	26339386	7316.496
AC-02 FEED	72	1584	2661	-121900	163.5	779877.5	2.08E+09	576459.5
C-03 OUT	297	278	66.32	-433000	132.6	469550	31140556	8650.154
C-04 FEED	57	1564	2661	-125200	153.8	776820	2.07E+09	574199.5
RECYCLE OUT	50	1584	1358	-196300	160.8	705545	9.58E+08	266147.3
RECYL OUT	52	1653	429.1	-38940	150.9	863152.5	3.7E+08	102883
CP-01 OUT	135	1584	874.2	-47130	170.2	854480	7.47E+08	207496.2
P-05 OUT	38	1584	1	-239000	165.5	662727.5	662727.5	184.091
MIX-03 FEED	38	1584	1	-284400	56.97	620040.8	620040.8	172.2335
AC-02 FEED	72	1584	2661	-121900	163.5	779877.5	2.08E+09	576459.5

TABLE V: EXERGY EFFICIENCY .

Equipments	Exergy destruction (kW)	Exergy In (kW)	Exergy efficiency (%)
Fractionators	1089773	3327080	32.7546377
Absorbers	478692	1323611	36.16561059
Coolers	4580	590842	0.775164934
Others	531054	20220877	2.626265913

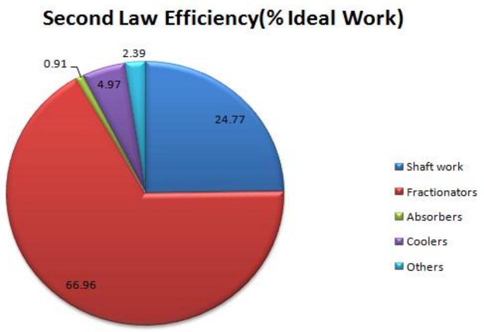

Fig. 3. Second law efficiency

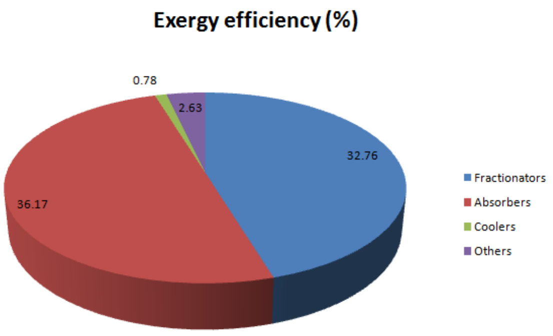

Fig. 4. Exergy efficiency

V. CONCLUSIONS AND RECOMMENDATION

In this study, exergy analysis of FCCU of KRPC has been presented. In the considered FCCU, the maximum energy lost was found in the fractionator columns where 67% of the input energy was lost to the environment. Next to it was the energy loss in the condensers where it was found to be 5%, 2.4% for all other components and less than 1% for absorbers. In addition, the calculated second law and exergy efficiencies of the system were 24.77 and 61.20% respectively. The effect of varying the reference environment state on the energy and exergy analysis is highly recommended for the next phase of research.

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