(RESEARCH ARTICLE)

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Catalyst deactivation and the effect of catalyst makeup on the FCC unit

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Abstract

One of the significant processes of the crude oil refining process is the fluid catalytic cracking (FCC) unit. This unit produces olefins and other feedstock for the petrochemical industry as well as high octane gasoline, naphtha, light cycle oil, and heavy cycle oil. Attrition is one of the forms of catalyst deactivation on FCC catalyst which affects its operation, thereby giving rise to a high amount of catalyst makeup to compensate for the losses in this unit. This study investigated the effect of catalyst attrition on a commercial FCC unit through an analysis of its technical data from 4-run operations. The catalyst loss profile was evaluated while the scanning electron microscopy (SEM) showed abrasion as the dominant attrition type in the unit, hence resulting in many catalyst particles being lost as micro fines through elutriation. A simulation study was carried out using ASPEN HYSYS version 8.8 to assess the effects of reduction and increment of fresh catalyst makeup on the product yield while a cost analysis was done to evaluate the economic implication. The results showed that a 2% reduction of the current daily catalyst makeup gave the same yield as that of the reference value. The products also had similar qualities showing that $117,000.00/annum could be saved by a 2% reduction of the current catalyst makeup.

Keywords: FCC unit; Refinery; Simulation; Catalyst; Attrition

1. Introduction

Over the years, catalyst deactivation is one of the challenges of the fluid catalytic cracking (FCC) unit operation. Deactivation in heterogeneous catalysts could be physical or chemical. Whereas chemical deactivation involves the reaction of the catalytic phase of these catalysts with other compounds thereby leading to their destruction, physical deactivation such as attrition involves the physical degradation of these catalysts (Cerqueira *et al.*, 2008). Attrition is a major concern in the FCC process and is responsible for most of the material and economic losses encountered in this unit. It occurs as a result of catalyst particle motion and inter-particle collision arising from the gas flow and bed-to-wall impact during the reaction process. As much as these collisions are necessary for the operation of fluidized-bed reactors, the consequent attrition leading to the generation of fines which pass as dust and the loss of valuable materials is a significant drawback in the operation of the FCC unit (Wu *et al.*, 2016; Wei *et al.*, 1977). These losses have both operational and economic implications for the running of these units. This is because the loss of these catalyst particles results in the need for addition of makeup catalyst to keep the system at a level required for optimum performance (Kramp *et al.*, 2011; Wether and Reppenhagen, 1999). Moreover, whereas increased coarseness of the fluid bed is undesirable, a bed whose particle size distribution comprises of extremely fine particles might also not achieve the desired result. Sources of attrition include activities inside the cyclone, particle motion and collisions in the fluid bed (bubble phase) and grid jet (transport phase). Studies have also been carried out on attrition in these regions (Werther and Hartge, 2003). Wei *et al.* (1977) attributed reasons for catalyst losses to the possible existence of catalyst attrition

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in all FCC units knowing that there are many channels through which attrited catalysts could be lost in the process. As much as some of these channels could be controlled e.g., withdrawal from the bottom of the regenerator, others like the loss of microfine particles through the regenerator exhaust system cannot be controlled. Besides, catalysts leaving through these routes usually contain more micro-fines than those circulating within the main unit (Wu *et al.*, 2010).

Attrition in fluidized beds could be influenced by catalyst particle properties, fluidization conditions, and bed structure parameters (Wu *et al.*, 2015). Catalyst particle properties include material and textural properties, mechanical strength, catalyst shape, particle size, surface roughness, hardness, microcracks etc. Fluidization conditions are gas velocity, pressure, temperature, density, humidity etc., whereas fluidized bed structure parameters describe orifice number for multi-orifice distributor plates among others (Wu *et al.*, 2010). Particle size has been studied as a factor of attrition using a jet-cup apparatus for several FCC catalysts (Wu *et al.*, 2015), while Chen *et al.* (2008) studied the attrition of catalyst particles in a high-velocity air-jet apparatus. Particle morphology, system composition, and operating conditions are other key factors reported to affect the attrition of catalyst particles (Hao *et al.*, 2016; Fiske, 2013). Attrition modes range between abrasion and fragmentation resulting in the production of elutriate fines which do not alter the composition of the mother particle as well as particle breakage, respectively (Arrington *et al.*, 2017).

Although catalyst makeup is done during industrial FCC operation to compensate for catalyst losses, this operation increases the cost of this process. Furthermore, the catalyst makeup level could impact the product yield and process conditions. This study, therefore, investigates the effect of catalyst makeup through a simulation study of an industrial FCC process.

2. Material and methods

The FCC unit of a commercial refinery was considered in this study while the commercial-grade catalyst used for its operation was characterized. The methods used in this work were technical evaluation, plant simulation and cost analysis.

2.1. Technical Evaluation

The technical evaluation of the design and operation of the FCC unit was done. Data from 4 continuous run operations were used to study the effect of attrition on the commercial-grade catalyst used in this unit. In line with the work of Fernandes *et al* (2008), the catalyst level was evaluated from the pressure exerted by the catalyst at each point in time and recorded on a 6 hr interval while the amount of the catalyst makeup was deducted to evaluate the catalyst loss in the process.

2.2. Simulation Procedure

Aspen HYSYS version 8.8 software was used to simulate the operation of the FCC unit to evaluate the effect of catalyst makeup on product yield and composition. Design and operating data obtained from the technical evaluation were used to model the operation of this unit using this software.

2.3. Process Description

The FCC design used to model the operation of the commercial unit considered in this study is shown in Figure 1. The modelling and optimization were performed using Aspen HYSYS version 8.8. Simulations were performed using the data to validate the whole simulation procedure and optimize it. The simulation procedure involved the definition of the chemical components (feed assay), selection of a thermodynamic model, determination of plant capacity, choice of a proper operating unit, and setting up of input conditions of the process such as flow rate, temperature, pressure, catalyst information etc. Data on components such as water, hydrocarbons, oxygen, CO, CO_2, NO_2, and SO_2 are available in the HYSYS component library. A Process-flow of a built-in simulation basic management fluid package was set up with the components of the input stream. Peng Robinson was selected as the fluid package because of its ability to handle hypothetical components (pseudo-components). The main process units considered include a riser, reactor, regenerator, main column, valves, heat exchangers etc. The steady-state process simulation was executed by the HYSYS software to obtain the mass and energy balance of each unit as well as the operating conditions and model for the FCC unit after the input information and operating unit models had been set up. The FCC design and process flow diagram of the modelled process are shown in Figures 1 and 2, respectively.
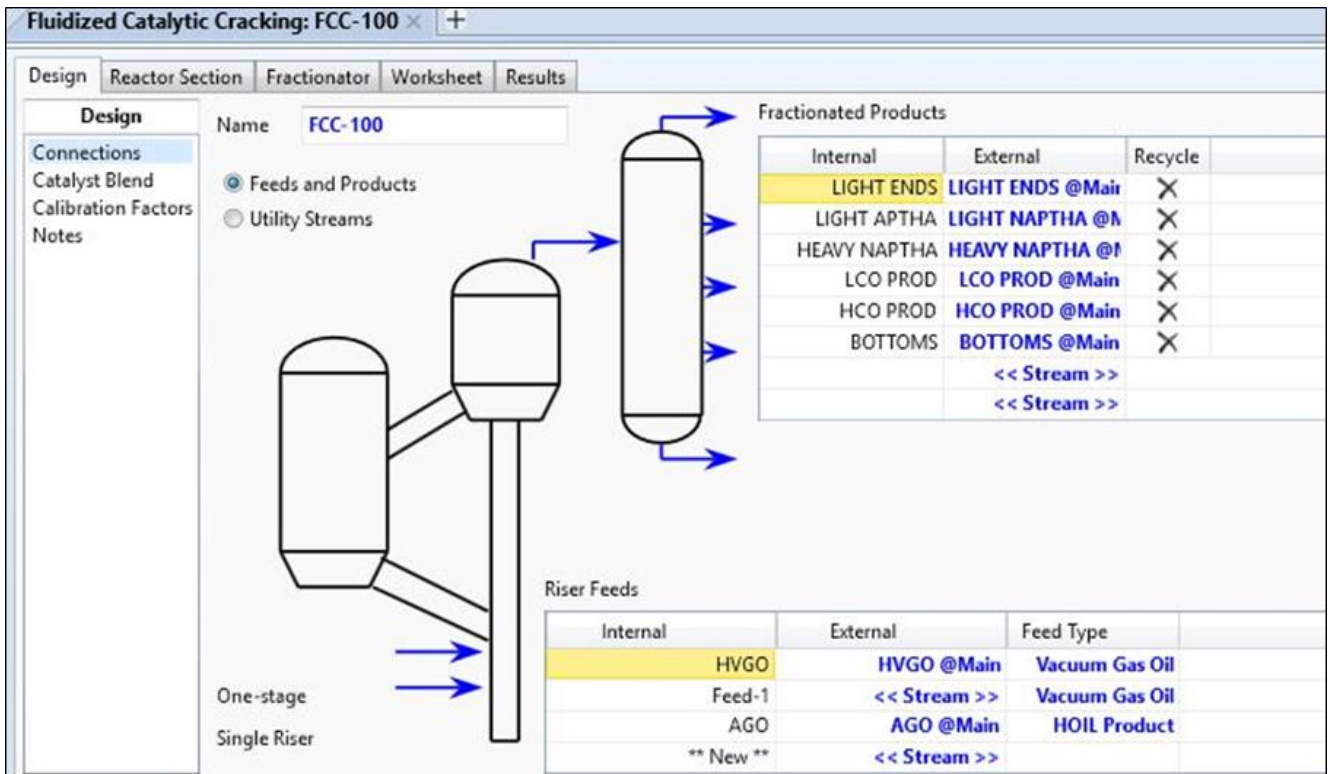
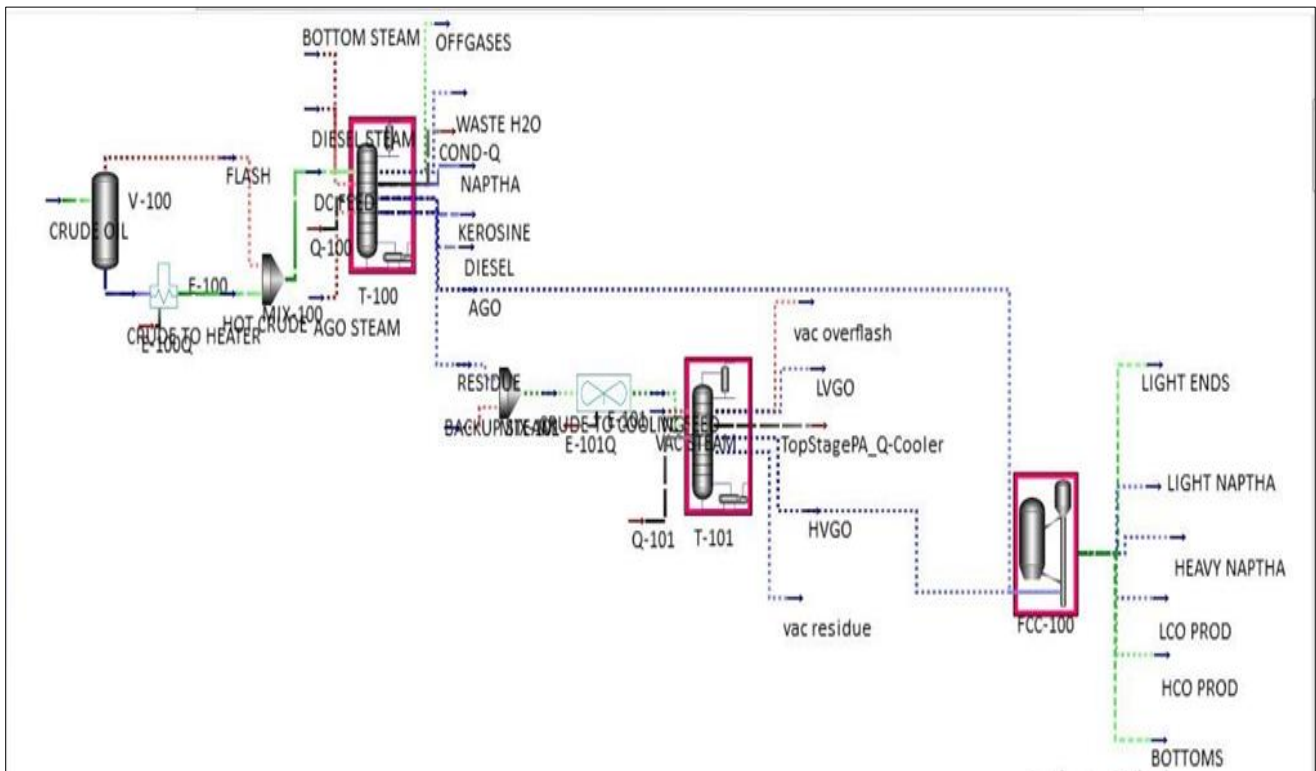**Figure 1** Modelled Fluid Catalytic Cracking Unit Design

Figure 2 Process Flow Diagram as Modelled on HYSYS

2.4. Product Yield and Composition

The modelled process was used to evaluate the effect of varying fresh catalyst makeup on the product yield. The composition of the light end product was equally observed. The results from the modelled process were validated by

comparison with plant data from the Commercial unit. The fresh catalyst makeup rate of 3000kg/day on the commercial unit considered in this study was used as a baseline to analyze the effect of fresh catalyst makeup on product yield from where the effects of reduction and increment of the catalyst on the product yield and composition were equally assessed. Analysis was done based on the yields of the light ends, LCO and bottom products whereas other products were considered as pump-around in the unit. Propane, i-Butane, n-Butane, i-Pentane and n-Pentane were the fractions considered in the light end.

2.5. Cost Analysis

Cost analysis was carried out to evaluate the effect of reduction on the amount of fresh catalyst makeup used in this process. This analysis was done using the current consumption as the reference point to determine the cost-effective operation. In other words, the savings is given by Equation (1)

$$Savings = (CurrentConsumption - ProposedConsumption) * Cost \dots\dots\dots\dots\dots\dots(1)$$

3. Results and discussion

3.1. Technical Evaluation

Technical evaluation of the FCC Unit was carried out to determine some of the parameters necessary for its operation. These include the temperature and pressure of the regenerator, flow rate, temperature, and pressure of the fluidizing air, as well as speed of the main air blower. These data were obtained for both the design and operating conditions and presented (Table 1).

Table 1 Plant data for design and operating conditions

Parameter	Design	Run 1	Run 2	Run 3	Run 4
Regenerator Dense Bed Temp (oC)	680	681	695	723	710
Regenerator Pressure (KNm-2)	206.92	216.72	211.82	215.75	218.69
Air flowrate (KNm3/hr)	155.7	129.72	129.87	130.04	128.08
Blower air discharge Pressure (KNm-2)	350.09	294.2	196.13	294.2	294.2
Air Temperature (oC)	183.6	184	176	178	179
Air blower speed (rpm)	5800	6000	6000	6000	6000

NB: average values for the operating data has been provided

Compared to the design values, the Dense bed temperature of 723 ^{o}C for the 3rd run operation was the highest whereas the 681 ^{o}C for the 1st run operation was the least and closest to the design value which is 680 ^{o}C. The fluidizing air temperature for the 1st run operation was also the closest to the design value. Chen (2013) highlighted the effect of operating a high temperature catalytic fluidized bed system and its impact on the unit which include erosion of the primary and secondary cyclones and diplegs, corrosion and emission of Nitric Oxides. This study was corroborated by the work of Sadeghbeigi (2000) who also reported the possibility of a crack occurring in the internal plenum due to thermal stress which could lead to catalyst losses and attrition. The study further reported that abrupt changes in some process conditions such as broken fluidized air supply, an increase in stripping and feed atomizing steam supply, could lead to catalyst attrition and the generation of catalyst microfines. Other factors which the study identified that could lead to attrition are the malfunction of trickle valves and overloading of the cyclones. In this study, however, Temperature was not found to play a significant role in the catalyst loss and attrition process; although the work of Hao *et al.* (2016) reported that high temperatures could alter the attrition mechanism from abrasion to fragmentation. Hao *et al.* (2016) equally highlighted the significance of temperature in the attrition process and such, the need to maintain the dense phase temperature as close to the design value as possible so as not to expose the catalyst to undue thermal stress. Consequences of this high pressure on the unit include increased chances of collision among the catalyst particles (Hao *et al.*, 2016), mechanical malfunction of the unit (Sadeghbeigi, 2000) and effects on other operating conditions of the unit. The unit which was designed to operate at a pressure of 206.92 KNm^{-2} could, therefore, have more of the catalyst particles colliding with each other and hence giving rise to more losses. Cocco *et al.* (2014) highlighted the importance of fluidization in the FCC process and the function of the air blower in achieving a good fluidization scheme. According to the study, superb heat transfer, ease of transfer of solid particles as liquid and ease of material processing

with a wide range of particle size distribution are factors which favour the choice of fluidized beds over other reactor types. The air flowrates across the 4-run operations ranged between 128.08 KNm³/hr to 130.04 KNm³/hr, hence no significant variation was observed in the air flowrate of this unit. These flow rates were therefore adequate to impose a drag force to withstand the force of gravity of the catalyst thus resulting in fluidization in line with the recommendation of Cocco *et al.* (2014). However, it is important to increase this flowrate to attain the design value of 155.7 KNm³/hr, the fluidization mode within the dense bed is largely determined by this according to Fahim *et al.* (2010). More so, Kim *et al.* (2019) have identified a link between fluidization and properties of the catalyst particles, whereas Mustafa and Atilhan (2015) and Wei *et al.* (1977) also identified a link between catalyst attrition and fluidization characteristics.

3.2. Catalyst Loss on the System

The mass contained in the fluid-bed was evaluated from the pressure exerted by the catalyst inside the regenerator and monitored from the control unit. For the 4-run operations considered, the mass of the catalyst was recorded on a 6-hour interval for 114 hours across each run. With deductions made on the amount of makeup catalyst, the catalyst loss was evaluated for each operation (Figure 3).
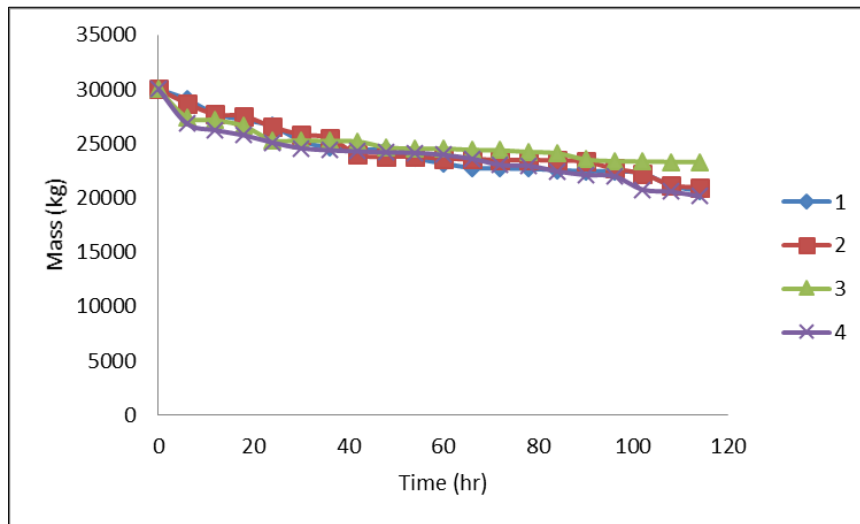

Figure 3 Catalyst level vs Time

Figure 3 shows a general decline in the mass of the catalyst bed inside the regenerator for the 4-run operations. Chiranjeevi *et al.* (2014) gave reasons for catalyst losses in FCC units to include the inherent characteristics of the catalyst and the operating condition of the unit. The gradual decline in the mass of the catalyst implies a steady loss of elutriate fines within this unit which Wu *et al.* (2016) ascribed to the characteristic loss of smaller fines in the catalyst bed leading to the increased coarseness of the fluid bed (Kramp *et al.*, 2011); although with continuous removal of the surface layer from the parent material, these coarse particles could undergo further attrition over time (Chiranjeevi *et al.*, 2014). The initial sharp decline could infer the unsteady state process described by Wu *et al.* (2016). Wei *et al.* (1977) outlined sources of the loss of these microfines to include regenerator exhaust pipes, transportations within the cyclones or even particles which escape with the products because of an inadequate separation. Catalyst particles could also be lost from the bottom of the regenerator in the process of withdrawal, although this is controllable. As stated earlier, changes in temperature did not show much impact on the observed losses as was the case with pressure. In other words, mechanical stress rather than thermal stress could be responsible for attrition in this unit; however, there is a need for further research in this area.
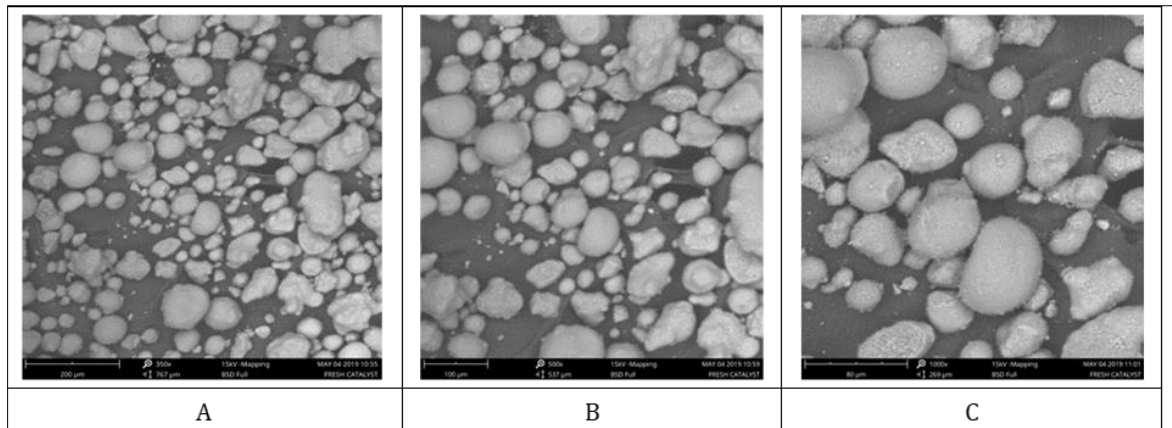
Figure 4 SEM micrograph for fresh catalyst with a magnification of (a.) 500, (b). 1000, (c).1500
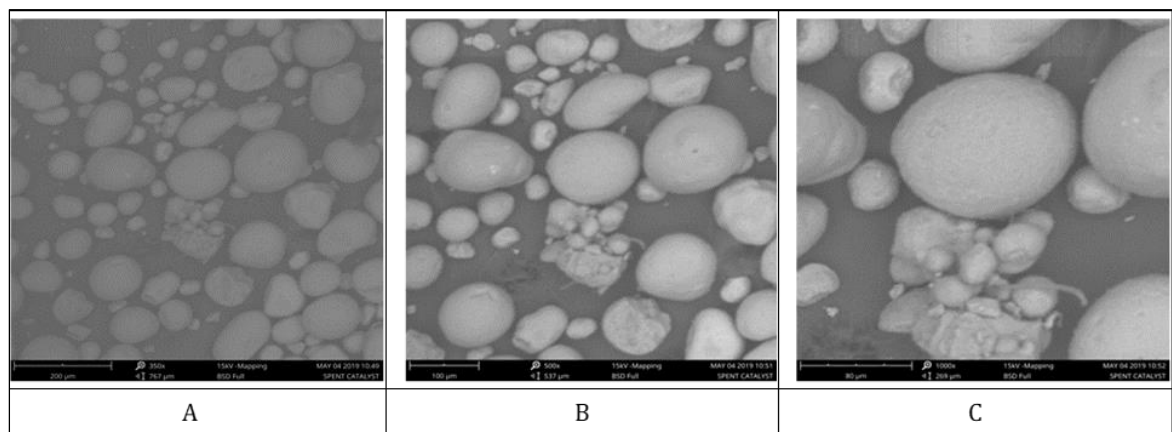

Figure 5 SEM micrograph of spent catalyst with a magnification of (a.) 500, (b). 1000, (c).1500

The morphology of the fresh and spent catalyst samples indicate that the fresh catalyst (Figure 4) contains more microfine particles compared to that of the spent catalyst (Figure 5). Also, these figures show that the smoothness of the surface of the latter over the former which also appears to become less smooth on further magnification is a confirmation of further loss of the microfines during this process. These observations corroborate the findings of Kukade *et al.* (2016) who carried out similar studies on commercial FCC catalyst using both the ASTM and Jet cup test methods. It could also be observed from the morphology that there were fewer protrusions on the spent catalyst particles compared to the fresh catalyst which is an indication of attrition occurring through the surface abrasion mechanism thereby leading to increased surface smoothness. Also, it is possible that the high speed of collision of these particles due to the regenerator pressure could have caused the breakage of some of these particles, hence the possibility of attrition due to fragmentation. The works of Hao *et al.* (2016) and Zhao *et al.* (2000) reported that where the dominant attrition mechanism is fragmentation, obvious cracks are visible in the morphology of the particles which was not the case in this study. The work of Liu *et al.* (2015) established a link between catalyst attrition and catalyst poisoning by unwanted materials which could damage its smoothness and shape thereby leading to increased chances of particle collision which ultimately results in attrition.

3.3. Process Simulation

The effect of catalyst makeup level on the process was investigated using 30000kg as the reference level. This procedure was repeated at different levels of the catalyst. The result obtained at this stage is shown in Table 2 while the volumetric flow rate is shown in Figure 6.

Table 2 Performance Evaluation of the products using 3000 kg/hr of the fresh catalyst makeup

| Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	36.48016	4.504552	19.87985	9.604184	6.422736	23.108524
Yield by Weight [%]	29.76969	4.491137	20.15838	9.496533	6.816194	29.268061
D86 5% [°C]	-33.2062	130.4014	163.5117	234.0997	276.8212	336.7841
D86 95% [°C]	114.2058	146.7908	210.4755	264.8173	300.4527	599.19343
Gap (D86) [°C]	16.19568	16.72092	23.62426	12.00391	36.33139	
RON (Clear)	97.14939	92.05856	89.70227	81.30415	76.4941	76.428607
MON (Clear)	88.99399	81.02	77.81497	70.81875	66.12647	66.060014
Cetane Index D976	-44.2247	5.304169	28.22457	62.17593	48.91439	21.386022
API	83.76675	44.69352	41.74157	46.16015	34.0285	7.1988635
SG (60/60)	0.657324	0.803094	0.816779	0.796464	0.854838	1.0201958
SulfurWtPct [%]	3.33E-02	6.76E-02	9.46E-02	0.234649	0.350992	0.6631516
Nitrogen Content [ppmwt]	6.692698	28.24524	41.08123	163.2457	299.2649	388.71708
Paraffins by Volume [%]	63.67043	29.4842	32.0005	19.98772	13.6401	11.666535
Naphthenes by Volume [%]	7.576051	12.14715	5.553808	18.30877	22.11593	12.549979
Aromatics by Volume [%]	3.406516	26.13399	47.38701	61.65362	64.24396	75.783486
Flash Point [°C]	0	20.80376	45.94096	91.5521	113.8012	138.92553
Cloud Point [°C]	-148.072	-108.962	-68.7383	-25.9339	-3.30986	98.147039
Conradson Carbon Content [%]	8.04E-03	3.44E-02	4.42E-02	8.18E-02	8.57E-02	0.2656815
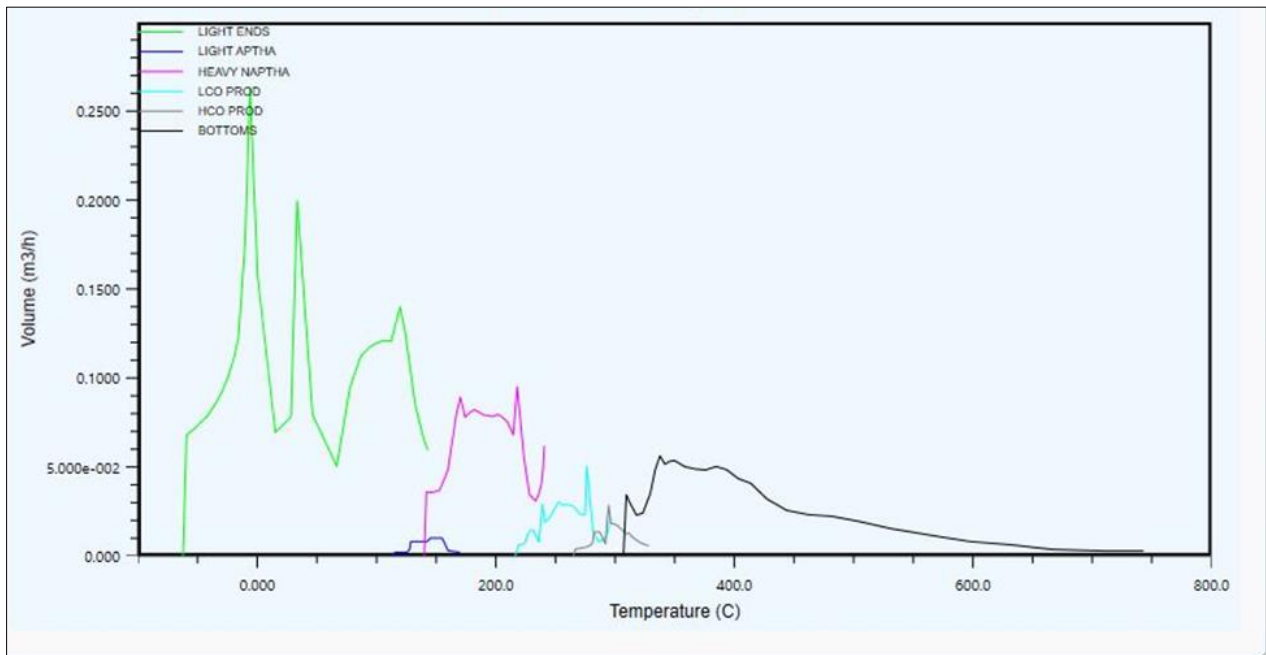
Figure 6 Volumetric flowrate vs temperature with 3000 kg/hr of the fresh catalyst makeup

The properties and performance evaluation of products obtained using 3000 kg/hr of the fresh catalyst makeup indicate that the molecular weight of the light end, LCO and HCO products were 71.55, 205.93 and 302.57 respectively with a mass density of 2.60 kgm^{-3}, 615.89 kgm^{-3} and 755.42 kgm^{-3} respectively. Other parameters obtained include heat capacity, Watson K factor, surface tension, vapour pressure and viscosity index and these were adequate to produce the products whose properties have been reported in this work. The actual volumetric flow rate of 15033.2 m^3/hr, 20.27 m^3/hr and 50.94 m^3/hr for the light ends, LCO and bottom products indicate the performance of this unit using 3000 kg/day of fresh catalyst makeup. This is proof of the effectiveness of this unit in converting the feed to these products at this makeup rate. The profile of the flowrate which is shown in Figure 6 also confirms the performance of this unit.

The total yield of light ends to be 36 %, yield of LCO was 9.60 % whereas the yield of the bottom product was 23.1 %. The physicochemical properties of these products such as research octane number (RON) and motor octane number (MON), which are the octane ratings of these products at this level of catalyst makeup, were used to express their performance in numerical terms. Whereas RON describes the behaviour of these fuels in an engine at low temperature and speed, MON describes their behaviour at high temperature and speed. The light-end products had the highest values of 97.14 and 88.99 compared to other products and this is indicative of their performance. These values were also similar to the range specified by ASTM D4814 standard and therefore indicate that these products were comparable to the commercial grade. Flash Point and Cloud Point of these products were consistent with the ASTM standard of D92-18. The specific gravity (ASTM D-1298), conradson carbon content (ASTM D 1298), aromatic content (ASTM D2007), Vapour Pressure and viscosity profile of these products were comparable to that of the commercial-grade products and corroborates the works of Olafadehan *et al.* (2018) and Ahmed *et al.* (2013) who also carried out similar studies on other FCC Units, although there were slight differences with their observations on yield, paraffin and sulphur contents.

Furthermore, the result and the volumetric flowrate obtained with 2% reduction of the fresh catalyst make up is shown in Table 3 and Figure 7, respectively.

Table 3 Performance evaluation with 2 % reduction of the fresh catalyst makeup

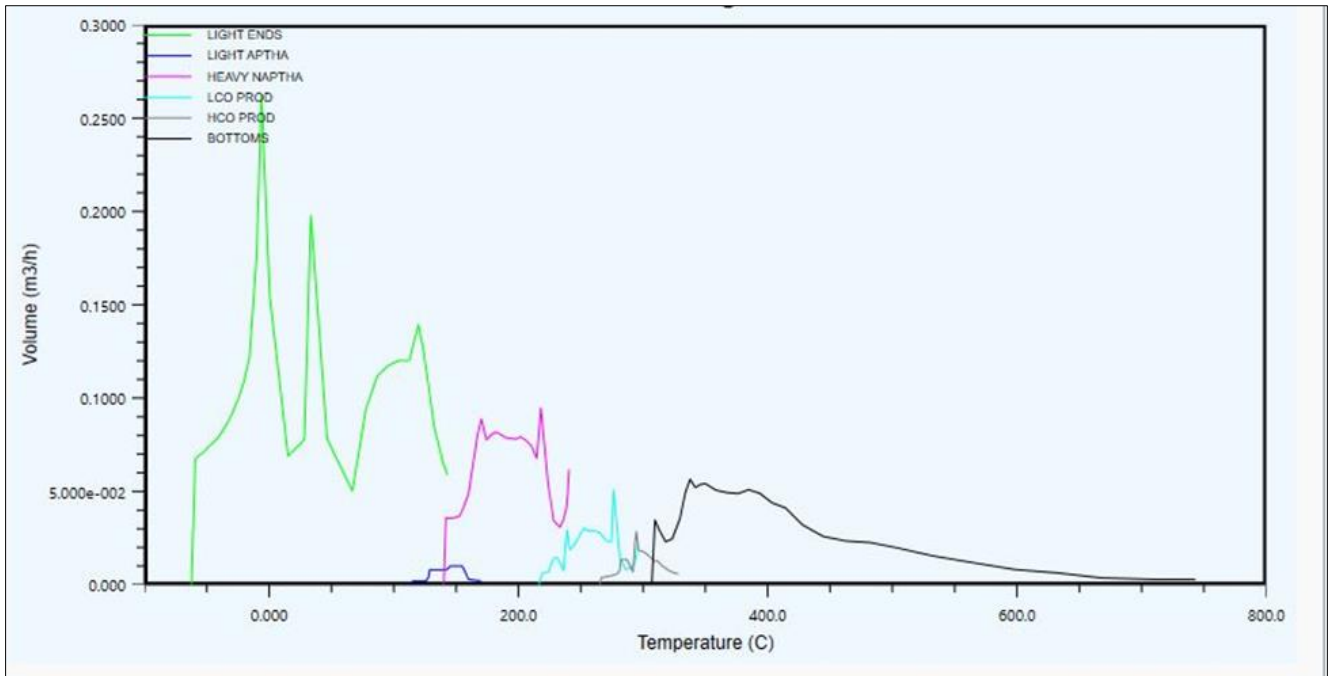| Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	36.35743	4.493375	19.83937	9.616573	6.432459	23.26079
Yield by Weight [%]	29.65683	4.477416	20.10727	9.501263	6.820878	29.43634
D86 5% [°C]	-33.2136	130.4016	163.5184	234.1116	276.8212	336.884
D86 95% [°C]	114.2105	146.7912	210.4927	264.819	300.452	599.754
Gap (D86) [°C]	16.19107	16.72726	23.61886	12.00217	36.432	
RON (Clear)	97.15543	92.04672	89.67672	81.29945	76.4941	76.42861
MON (Clear)	88.98239	80.99071	77.78527	70.81381	66.12647	66.06001
Cetane Index D976	-43.9797	5.412856	28.31036	62.36874	49.06815	21.43136
API	83.805	44.75072	41.78478	46.25618	34.12368	7.279868
SG (60/60)	0.657207	0.802834	0.816575	0.796034	0.854346	1.0196
Sulfur Wt Pct [%]	3.34E-02	6.77E-02	9.45E-02	0.233826	0.349688	0.660066
Nitrogen Content [ppmwt]	6.719937	28.34743	41.20864	163.2678	299.2202	386.5791
Paraffins by Volume [%]	63.52881	29.38532	32.18563	20.12948	13.76789	11.74501
Naphthenes by Volume [%]	7.614477	12.14324	5.535499	18.4193	22.25183	12.63542
Aromatics by Volume [%]	3.412808	26.10167	47.19851	61.40155	63.98028	75.61957
Flash Point [°C]	0	20.80385	45.94604	91.55872	113.8012	138.9657
Cloud Point [°C]	-148.065	-108.962	-68.6799	-25.8381	-3.20918	98.21988
Conradson Carbon Content [%]	7.99E-03	3.42E-02	4.40E-02	8.15E-02	8.53E-02	0.264649

Figure 7 Volumetric flowrate vs temperature with 2 % reduction of the fresh catalyst makeup

Table 4 Performance evaluation with 10% reduction of the fresh catalyst makeup

Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	35.76952	4.439543	19.64484	9.677523	6.480193	23.98838
Yield by Weight [%]	29.1182	4.411755	19.86306	9.525628	6.844612	30.23674
D86 5% [ºC]	-33.2495	130.4022	163.5514	234.1683	276.8213	337.3419
D86 95% [ºC]	114.233	146.7931	210.5774	264.8275	300.4488	601.7932
Gap (D86) [ºC]	16.16922	16.75828	23.59095	11.99379	36.89314	
RON (Clear)	97.18497	91.99171	89.55647	81.2773	76.49407	76.42861
MON (Clear)	88.92745	80.85229	77.64503	70.79046	66.12644	66.06001
Cetane Index D976	-42.8031	5.931575	28.72123	63.2947	49.80694	21.65358
API	83.98791	45.02296	41.99087	46.71527	34.5785	7.668264
SG (60/60)	0.656649	0.801595	0.815605	0.793984	0.852007	1.016755
Sulfur Wt Pct [%]	3.43E-02	6.82E-02	9.38E-02	0.229908	0.343487	0.645412
Nitrogen Content [ppm wt]	6.854857	28.85356	41.83748	163.3613	298.9829	376.8611
Paraffins by Volume [%]	62.85491	28.91735	33.0646	20.80406	14.37664	12.11886
Naphthenes by Volume [%]	7.796375	12.12189	5.447907	18.94547	22.89808	13.04234
Aromatics by Volume [%]	3.442955	25.9483	46.30358	60.20187	62.72527	74.8388
Flash Point [ºC]	0	20.80432	45.97093	91.59048	113.8012	139.1503
Cloud Point [ºC]	-148.034	-108.962	-68.3974	-25.3812	-2.72899	98.53739
Conradson Carbon Content [%]	7.79E-03	3.34E-02	4.31E-02	7.97E-02	8.35E-02	0.259705

Compared to the reference value of the catalyst makeup, there were no major changes in the properties of the product obtained with a 2% reduction of the catalyst. Although, there were slight changes in the product yield as follows: light ends 36.3%, LCO 9.6% and bottom 23.2% compared to the 36.4%, 9.6% and 23.1% respectively earlier reported for these products using the reference fresh catalyst makeup. Also, slight changes were observed for the values of the API and contents of paraffin, naphthenes and aromatics. These changes were however insignificant and therefore should not affect the choice of this process condition in any way. Furthermore, the flowrate of the products is shown in Figure 7 while the composition of the light end product comprised of similar profile as that of the reference value. This further confirms that 2% reduction of the fresh catalyst makeup will favour production in this unit.

The result and volumetric flowrates with 10% reduction of the fresh catalyst makeup is shown in Table 4 and Figure 8, respectively.
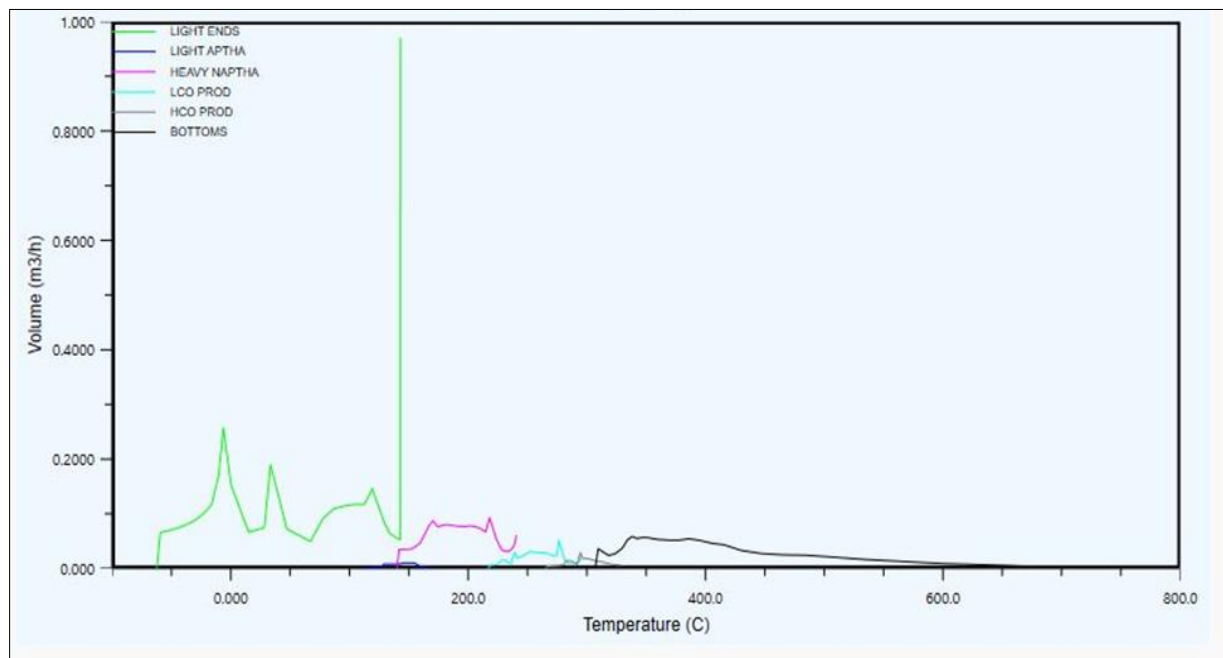

Figure 8 Volumetric flowrate vs temperature with 10 % reduction of the fresh catalyst makeup

The flowrate of the products, as well as the composition of the light ends using this amount of catalyst makeup, shows that there was a further reduction in the actual flow of the light ends to 14768.31 m³/hr with 2700 kg/day of the fresh catalyst makeup whereas the actual flow of LCO and the Bottom product were 20.51 m³/hr and 53.15 m³/hr, respectively. Furthermore, the heat of vaporization for the Light ends and LCO increased to 35628.36KJ/kgmol and 50797.76 KJ/kg mol, respectively whereas that of the Bottom product reduced to 195716 KJ/kg mol. Increase in yield of the Bottom product implies reduced efficiency and less conversion of these heavier ends which is further confirmed by the flowrate shown in Figure 8. Therefore, the yield, product properties, and composition all indicate that using this level of the fresh catalyst makeup might not be favourable to production in this unit.

The results and volumetric products of the products obtained with 30% reduction of the fresh catalyst makeup is shown in Table 5 and Figure 9, respectively. The properties and performance evaluation of products at 30% reduction of the fresh catalyst makeup indicate that there was a further reduction in the actual flow of the light ends to 13794.24 m³/hr whereas the actual flow of LCO and the Bottom product were 21.55 m³/hr and 61.22 m³/hr respectively. Furthermore, the heat of vapourization for the Light ends and LCO increased to 35777.18 KJ/kg mol and 50987.02 KJ/kg mol respectively whereas that of the Bottom product reduced to 197589.3 KJ/kg mol. Also, a further decline in the yield of the Light end to 33.2 % and an increase in the yield of LCO and bottom products to 9.9 % and 27.06 %, respectively with slight changes in the properties of these products was observed. Increase in yield of these heavier ends implies reduced efficiency and less conversion of these heavier ends which is further confirmed by the flowrate shown in Figure 9. Therefore, the yield, product properties, and composition all indicate that using this level of the fresh catalyst makeup might not be favourable to production in this unit.

Table 5 Performance evaluation with 30% reduction of the fresh catalyst makeup

| Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	33.29597	4.207001	18.8091	9.939201	6.68521	27.06351
Yield by Weight [%]	26.88471	4.135428	18.8383	9.634245	6.949053	33.55826
D86 5% [ºC]	-33.4412	130.4066	163.7025	234.4095	276.8217	339.0289
D86 95% [ºC]	114.3255	146.8038	210.966	264.8627	300.4349	603.6853
Gap (D86) [ºC]	16.08111	16.89867	23.44352	11.95901	38.59402	
RON (Clear)	97.32024	91.77933	89.07365	81.18912	76.49399	76.42861
MON (Clear)	88.70656	80.29168	77.07545	70.69689	66.12634	66.06001
Cetane Index D976	-37.8271	8.10368	30.47304	67.27932	52.99524	22.67899
API	84.77042	46.14907	42.85604	48.65428	36.49648	9.330131
SG (60/60)	0.654273	0.796514	0.811558	0.785438	0.84228	1.004757
Sulfur Wt Pct [%]	3.77E-02	7.00E-02	9.11E-02	0.213645	0.317827	0.584912
Nitrogen Content [ppm wt]	7.499109	31.26493	44.80733	164.0003	298.4277	342.8584
Paraffins by Volume [%]	60.08488	27.03041	36.69157	23.60993	16.91667	13.67727
Naphthenes by Volume [%]	8.534504	11.99206	5.079917	21.13334	25.5769	14.73542
Aromatics by Volume [%]	3.569379	25.30867	42.60889	55.21237	57.50642	71.58731
Flash Point [ºC]	0	20.80754	46.08501	91.72428	113.8014	139.84
Cloud Point [ºC]	-147.923	-108.958	-67.1444	-23.4582	-0.70812	99.55956
Conradson Carbon Content [%]	6.98E-03	2.99E-02	3.93E-02	7.25E-02	7.59E-02	0.238854
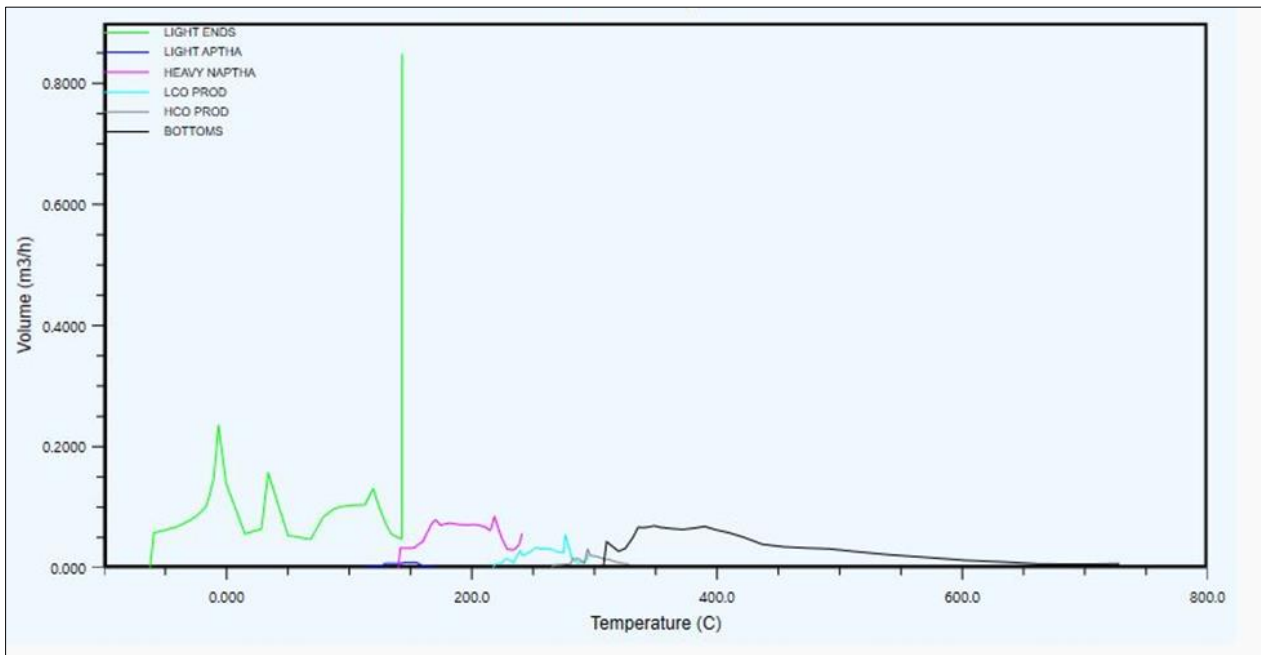
Figure 9 Volumetric flowrate vs temperature with 30% reduction of the fresh catalyst makeup

Further investigation showed that the process failed to converge beyond 35% reduction of the fresh catalyst makeup. This implies that the fresh catalyst makeup on this unit must not go below 1950 kg/day as this could have severe consequences on the operation of this unit. Sadeghbeigi (2000) stated that a low catalyst level could uncover the diplegs and allow a backflow of the catalyst. This backflow could occur as a result of an alteration in the pressure differential across the slide valves. Therefore, it is important to ensure that catalyst makeup is not altered to a point that the mass balance is lost. Fahim *et al.* (2010) and Pinheiro *et al.* (2012) have highlighted the need to maintain the mass balance across all sections of the FCC unit. Moreover, backflow due to alteration in pressure differential could result in severe consequences such as blow-out etc (Sadeghbeigi, 2000).

On the other hand, the effect of increments in the quantity of the fresh catalyst makeup on the product yield was also evaluated. Increments of 2%, 10% and 20% were considered. The result and volumetric flowrates of products obtained at 2% reduction of the fresh catalyst makeup are shown in Table 6 and Figure 10, respectively.

Table 6 Performance evaluation with 2 % Increment of the fresh catalyst makeup

Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottoms
Yield by Volume [%]	36.59447	4.514946	19.91752	9.592796	6.413788	22.96648
Yield by Weight [%]	29.87495	4.503925	20.20603	9.49229	6.811954	29.11085
D86 5% [ºC]	-33.1994	130.4013	163.5055	234.0887	276.8212	336.6895
D86 95% [ºC]	114.2013	146.7905	210.4596	264.8157	300.4533	598.6258
Gap (D86) [ºC]	16.19999	16.71505	23.62915	12.00552	36.23614	
RON (Clear)	97.14381	92.06973	89.72626	81.30856	76.49411	76.42861
MON (Clear)	89.00484	81.04744	77.8428	70.82338	66.12648	66.06001
Cetane Index D976	-44.4528	5.202723	28.14457	61.99631	48.77116	21.34408
API	83.73107	44.64007	41.70122	46.07056	33.93969	7.123368
SG (60/60)	0.657433	0.803338	0.816969	0.796866	0.855297	1.020751
SulfurWtPct [%]	3.31E-02	6.75E-02	9.47E-02	0.235419	0.35221	0.666037
Nitrogen Content [ppmwt]	6.667626	28.15119	40.9638	163.2238	299.3038	390.7473
Paraffins by Volume [%]	63.80272	29.57673	31.82735	19.85523	13.52075	11.59324
Naphthenes by Volume [%]	7.540079	12.15059	5.570876	18.20548	21.98891	12.47016
Aromatics by Volume [%]	3.400653	26.16423	47.56332	61.88918	64.49034	75.9366
Flash Point [ºC]	0	20.80369	45.93627	91.54594	113.8011	138.8875
Cloud Point [ºC]	-148.078	-108.963	-68.7925	-26.0233	-3.40389	98.07701
Conradson Carbon Content [%]	8.08E-03	3.46E-02	4.44E-02	8.22E-02	8.61E-02	0.266645

The properties and performance evaluation of products obtained using 2% increment of the fresh catalyst showed no significant changes at this makeup rate. However, although the yield of the light ends increased slightly to 36.5 % whereas the bottom product decreased to 22.9 %, the same composition of the light ends as that of the reference value (30000 kg) was observed at this makeup rate.

The result and volumetric flowrates of products obtained at 10% reduction of the fresh catalyst makeup are shown in Table 7 and Figure 11, respectively.
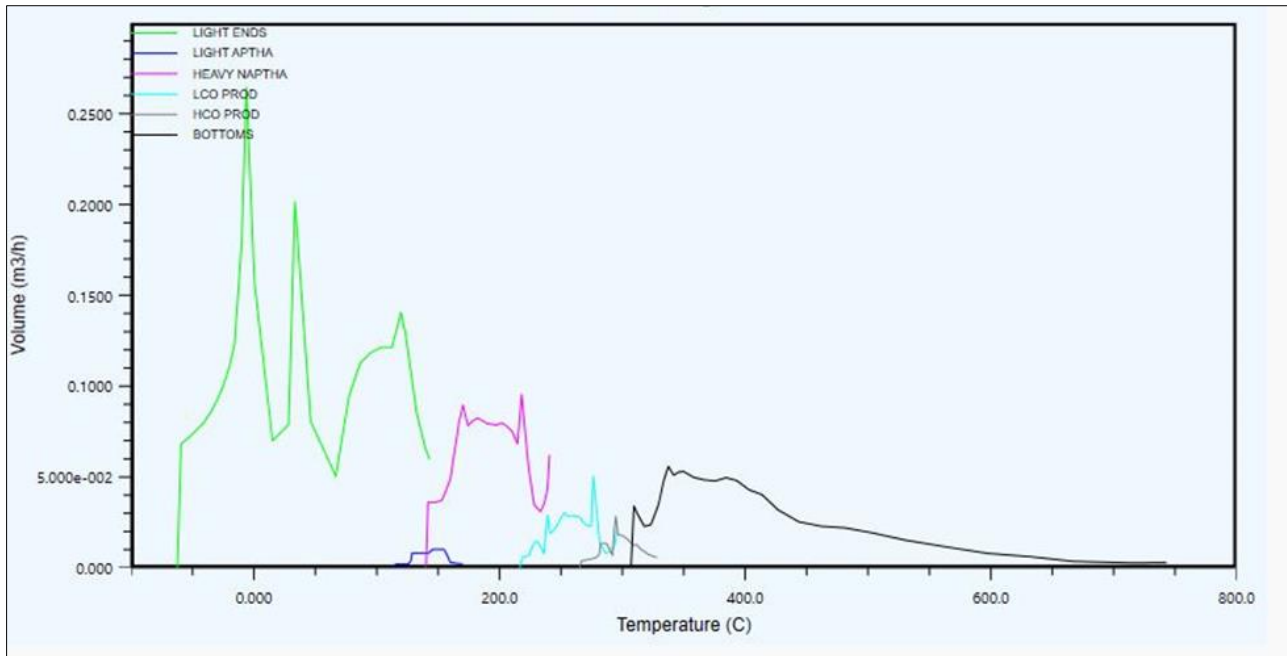
Figure 10 Volumetric Flowrate vs Temperature with 2 % Increment of the fresh catalyst makeup

Table 7 Performance evaluation with 10% increment of fresh catalyst makeup

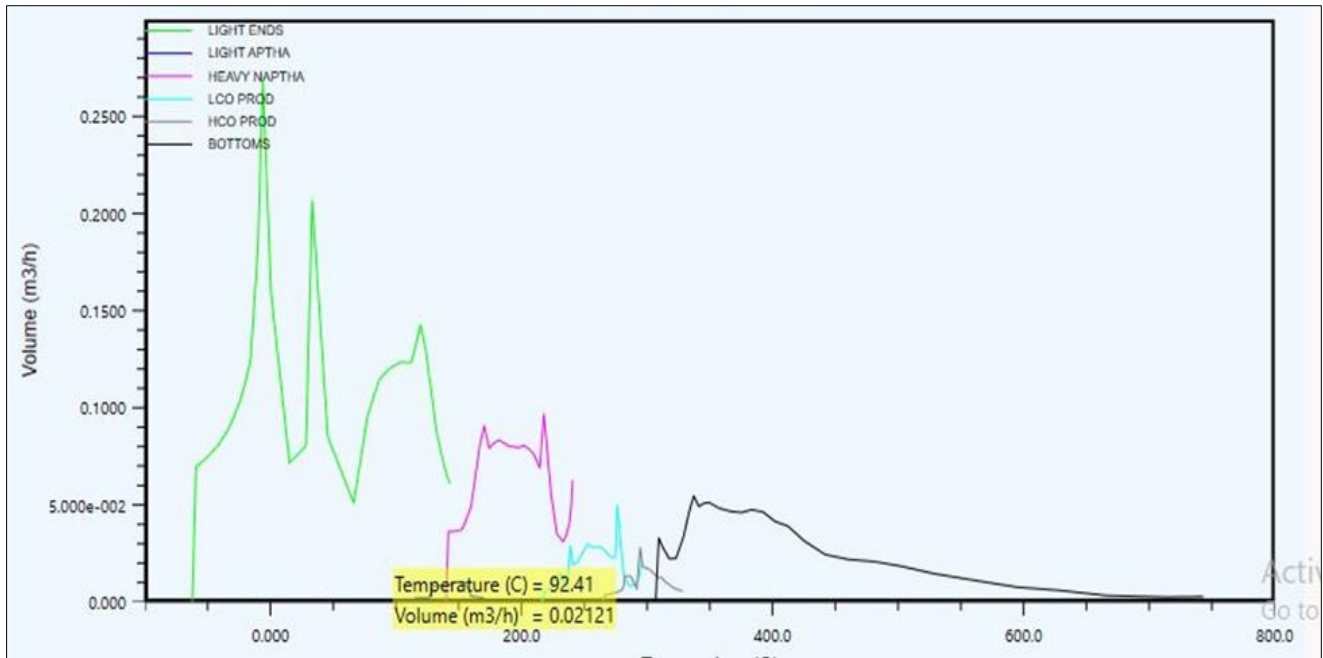| Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	36.98059	4.549943	20.04465	9.555771	6.384593	22.48445
Yield by Weight [%]	30.23152	4.547186	20.36752	9.479502	6.798801	28.57547
D86 5% [ºC]	-33.1762	130.401	163.4849	234.052	276.8211	336.3594
D86 95% [ºC]	114.1863	146.7894	210.4072	264.8102	300.4554	596.4232
Gap (D86) [ºC]	16.21467	16.69557	23.64475	12.01092	35.90399	
RON (Clear)	97.12526	92.10856	89.80874	81.32364	76.49412	76.42861
MON (Clear)	89.04185	81.14135	77.9382	70.83923	66.12649	66.06001
Cetane Index D976	-45.2216	4.858438	27.8736	61.38876	48.2868	21.20444
API	83.6099	44.45831	41.56407	45.76654	33.63816	6.867941
SG (60/60)	0.657803	0.804168	0.817616	0.798233	0.856858	1.022636
Sulfur Wt Pct [%]	3.25E-02	6.72E-02	9.51E-02	0.238038	0.35636	0.675879
Nitrogen Content [ppm wt]	6.585196	27.84204	40.57649	163.1347	299.4058	397.9094
Paraffins by Volume [%]	64.25235	29.89263	31.23675	19.40416	13.11487	11.34399
Naphthenes by Volume [%]	7.417179	12.16078	5.628659	17.85394	21.55618	12.19874
Aromatics by Volume [%]	3.380847	26.26756	48.1648	62.69108	65.32895	76.45726
Flash Point [ºC]	0	20.80346	45.92072	91.52532	113.8011	138.7556
Cloud Point [ºC]	-148.099	-108.963	-68.9745	-26.3272	-3.72351	97.82347
Conradson Carbon Content [%]	8.21E-03	3.51E-02	4.50E-02	8.33E-02	8.73E-02	0.269904

Figure 11 Volumetric Flowrate vs Temperature with 10% increment of the fresh catalyst makeup

Table 8 Performance evaluation of products with 20 % increment of fresh catalyst makeup

Property	Light Ends	Light Naphtha	Heavy Naphtha	LCO Prod	HCO Prod	Bottom
Yield by Volume [%]	37.33842	4.582248	20.16253	9.524548	6.359735	22.03252
Yield by Weight [%]	30.56353	4.587421	20.51822	9.470902	6.789081	28.07085
D86 5% [°C]	-33.1536	130.4008	163.4665	234.0189	276.821	336.0426
D86 95% [°C]	114.1723	146.7884	210.361	264.8053	300.4573	593.3618
Gap (D86) [°C]	16.22846	16.67807	23.65788	12.01578	35.58538	
RON (Clear)	97.10847	92.14652	89.88783	81.33794	76.49413	76.42861
MON (Clear)	89.07674	81.23063	78.02916	70.85423	66.12651	66.06001
Cetane Index D976	-45.9321	4.535859	27.62037	60.82448	47.83693	21.07924
API	83.49601	44.28747	41.43515	45.48277	33.35647	6.629537
SG (60/60)	0.658152	0.804949	0.818226	0.799513	0.858322	1.024401
SulfurWtPct [%]	3.20E-02	6.69E-02	9.55E-02	0.240497	0.360258	0.685185
Nitrogen Content [ppm wt]	6.512235	27.56887	40.23123	162.9982	299.3989	405.0634
Paraffins by Volume [%]	64.67414	30.19115	30.6783	18.97889	12.7331	11.10978
Naphthenes by Volume [%]	7.300736	12.16793	5.682538	17.52311	21.14825	11.94354
Aromatics by Volume [%]	3.362468	26.36562	48.73376	63.44652	66.11865	76.94668
Flash Point [°C]	0	20.80329	45.90678	91.50669	113.8011	138.6285
Cloud Point [°C]	-148.118	-108.963	-69.1425	-26.6134	-4.02498	97.5417
Conradson Carbon Content [%]	8.34E-03	3.57E-02	4.56E-02	8.44E-02	8.85E-02	0.272943

The properties and performance evaluation of products obtained with 10% increment of the fresh catalyst makeup are shown. The flowrate of the products and the composition of the light ends showed no significant changes in the

properties of the products obtained at this makeup rate. However, although the yield of the light ends increased to 36.9 % and that of the bottom product decreased to 22.5 %, the same composition of the light ends as that of the reference value was observed at this makeup rate. The volumetric flowrates of the products at this rate of makeup presented in Figure 11 also showed no significant change with what was observed using 3000 kg/day of the fresh catalyst makeup and as such will make no significant improvement in the operation of this unit.

The result and volumetric flowrates of products obtained at 20% reduction of the fresh catalyst makeup are shown in Table 8 and Figure 12, respectively.
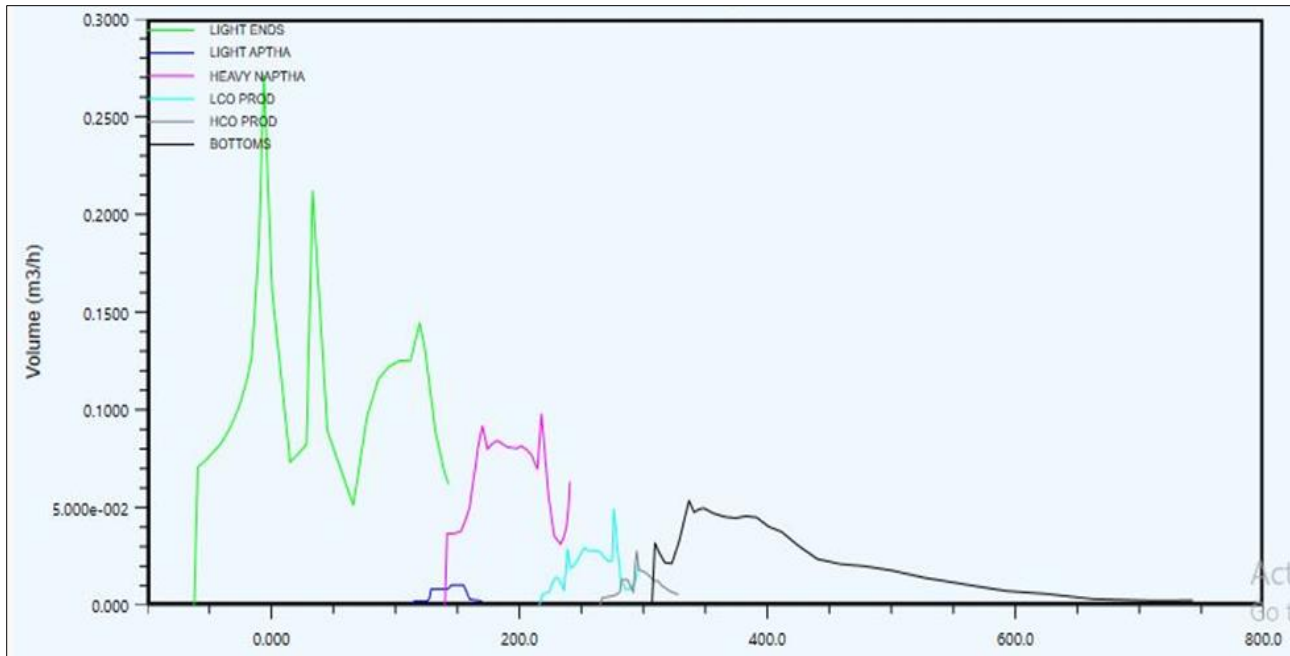

Figure 12 Volumetric flowrate vs temperature with 20% Increment of the fresh catalyst makeup

The properties and performance evaluation of products obtained using 20% increment of the fresh catalyst makeup are shown. Results showed no significant changes in the properties of the products obtained at this makeup rate. However, although the yields of the light ends increased to 37.3% whereas that of the bottom product decreased to 22 %, the same product composition of the light ends as that of the reference value was observed at this makeup rate. The volumetric flowrates of the products at this rate of makeup presented in Figure 12 also showed no significant change with what was observed using the reference catalyst makeup and as such will make no significant improvement in the operation of this unit.

Further analysis indicates that the volumetric flowrates of the products with further increment of the fresh catalyst makeup showed no changes and as such will add no significant improvement in the operation of this unit compared to the cost of this increment to the process. Besides, this could also encourage more losses through attrition because these increments could contain more amounts of the least sized particles which might be lost as elutriate fines during operation. Moreover, Sadeghbeigi (2000) reported that high catalyst level could affect the effective operation of the primary cyclone by preventing it from draining properly. High catalyst level could also result in jamming of the cyclones which could interrupt the centrifugal action within the cyclones according to Wei *et al.* (1977).

Figure 13 gives a summary of the yield of all the products. Light Naphtha, Heavy Naphtha and HCO which served as pump-around on the commercial unit were not considered in the assessment of the performance of this unit.
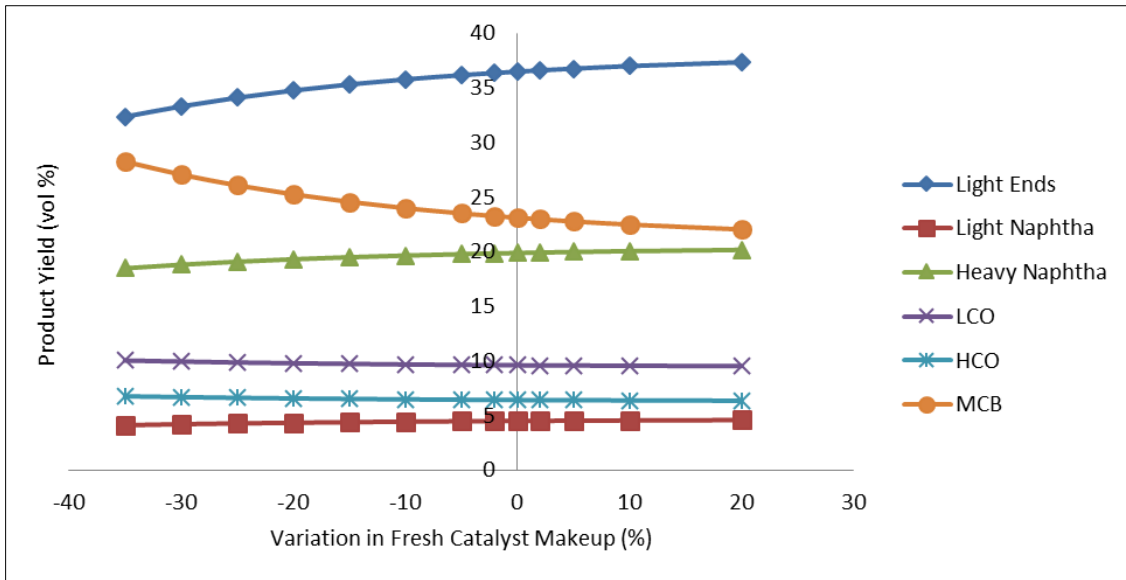
Figure 13 Product yield vs variation in fresh catalyst makeup

Hence the yield of the Light-ends, LCO and Bottom product have been considered in this study. Also, because of the greater demand for the light end products, its yield has been given a greater priority in this study.
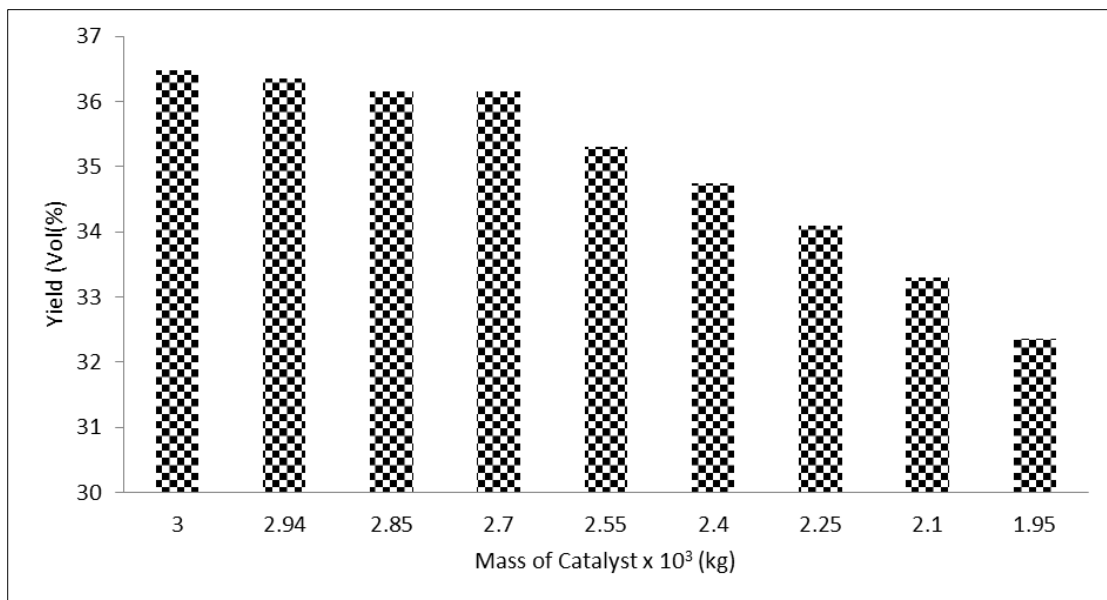

Figure 14 Variation of yield of light end products with reduction of the fresh catalyst makeup

Therefore, Figure 14 shows the yield of light-end products with a reduction of the fresh catalyst makeup. This shows that the 36.3% yield of the light end obtained with a 2 % reduction of the fresh catalyst was closest to the 36.4% obtained with the makeup rate of the baseline and as such this 2% reduction should be considered.

Moreover, this study has shown that beyond the 2% reduction of the fresh catalyst makeup rate, most of the bottom products were not converted. This resulted in an unusual flowrate of the yield of the light ends and therefore implies that a large amount of the feed was unconverted in line with the study of Vogt and Weckhuysen (2015). Also, a 2% reduction of the fresh catalyst makeup gave similar yield of the light end products as what was obtained using 30000 kg (reference value) as well as similar product composition including the flowrate. Recall that this study had earlier submitted that it is the particle size distribution rather than the quantity of the whole mass of catalyst that influences the attrition rate. As observed here, a 2 % reduction in the amount of the Fresh Catalyst makeup would not also alter

the product yield significantly. Hence a 2% reduction of the 30000 kg fresh catalyst makeup is therefore proposed in this work. Moreover, a reduction in the amount of makeup catalyst could have some economic implications.

From results presented in Figure 13, the yields of light end products with 30000kg (reference value) and with 2% reduction of the fresh catalyst makeup were 36.4% and 36.3 % respectively with the products having similar compositions. The cost implication of this reduction in the amount of fresh catalyst makeup has been evaluated.

3.4. Cost Analysis

From the findings in the previous section, this study proposes a 2 % reduction in the daily fresh catalyst makeup used in the commercial unit investigated. The breakdown of the Cost analysis is presented in Table 9

Recall that from the data obtained from the technical evaluation of the commercial FCC Unit

Current Fresh Catalyst Makeup = 3000kg/day

2% reduction of Fresh Catalyst makeup = 2940kg/day

But,

Cost of Fresh Catalyst = $6.5/kg

Table 9 Cost Analysis on the Reduction of Catalyst Makeup on the Unit

	Daily Consumption (kg)	Amount ($)
Current	3000	19,500.00
Proposed	2940	19,110.00
Difference	60	390

Hence daily saving with 2% reduction on the amount of fresh catalyst makeup= $390.00

If 1 year = 300 days (minus downtime)

The annual saving = 390 * 300

Savings = $117,000.00/ annum

As shown in Table 9, 2% reduction in the amount of fresh catalyst makeup implies reducing the quantity of Catalyst used in this unit by 60 kg which translates to saving $390 daily. Hence, over 300 days (minus downtime) $117, 000.00/annum would be saved on catalyst consumption. This isa huge economic benefit which shouldreduce the operating cost of running this unit thereby enhancing its profitability. Therefore, based on product yield and economic considerations, this study recommends a 2% reduction on the current consumption of fresh catalyst makeup used in this unit.

4. Conclusion

The FCC unit plays a vital role especially due to the high demand for its product. Increased demand for these products in recent times implies more pressure on the FCC units. Efficient operation of the FCC unit demands effective use of materials with little or no losses incurred in this process to achieve maximum yield of the desired products. This work has successfully undertaken a study on the effects of the reduction and increment of the fresh catalyst makeup on the product yield of a commercial FCC unit. The economic benefit of reducing the fresh catalyst makeup on this unit was evaluated through cost analysis. From this study, it was observed that attrition on this unit resulted from the loss of the attrited microfines through elutriation. An increment in the amount of fresh catalyst makeup showed no significant effect on the composition of the products. Besides, a high catalyst level could result in the jamming of the cyclones which could also interrupt the centrifugal action. On the other hand, a low catalyst level could uncover the diplegs thereby allowing backflow of the catalyst leading to an alteration in the pressure differential across the slide valves which could

result in unmitigated consequences such as blow-out etc. Moreover, the process failed to converge beyond the 35% reduction of the fresh catalyst makeup. A 2% reduction of the fresh catalyst makeup gave a similar yield to that of the reference value. Finally, the cost analysis from this study indicates that savings of $117,000.00/annum could be obtained from a 2 % reduction in the amount of fresh catalyst makeup used in this unit.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare they have no competing interests.

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