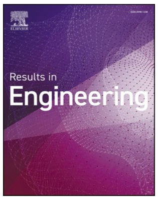
Results in Engineering 19 (2023) 101224

Contents lists available at ScienceDirect

Results in Engineering

journal homepage: www.sciencedirect.com/journal/results-in-engineering



# Effect of catalyst-to-oil ratio and catalyst temperature on determining the yield of gasoline in the riser reactor

Olubunmi G. Abatan [a], Olaosebikan A. Olafadehan [b], Vincent E. Efeovbokhan [a], Olagoke Oladokun [a,*], Augustine O. Ayeni [a]

[a] *Department of Chemical Engineering, Covenant University, Ota, Ogun State, Nigeria*
[b] *Department of Chemical and Petroleum Engineering, University of Lagos, Akoka-Yaba, Lagos 101017 Nigeria*

ARTICLE INFO

*Keywords:*
Kinetics
Heavy oil
Model
Simulation
Sensitivity analysis

ABSTRACT

Increasing the yield of Gasoline has been the desire of every crude oil refining process in the oil industry. The principal unit that has significantly contributed to increasing the yield of Gasoline is the Fluid Catalytic Cracking (FCC) unit. The performance of the FCC unit is dependent on many parameters, substantively the catalyst-to-oil ratio (COR) and the temperature of the catalyst ($t_{cat}$) when entering the riser reactor. To understand the effect of COR and $t_{cat}$, a five-lump kinetics model was developed, and the simulated result was further plugged into MINITAB 7.0 software in order to generate a set of empirical equation models. The empirical equation models predicted the optimal yield of gasoline to be 56.83%, with corresponding optimal parameters of COR and temperature of catalyst as 3.35 and 900 K, respectively. The actual yield of gasoline at 3.35 COR and 900 K catalyst temperature was 56.78%, with a 0.09% error compared to the predicted yield of gasoline. The two parameters were varied with the values from previous studies, and the predicted result compared to the actual is 7.8648 root mean square error (RMSE). Therefore, the empirical equation model is reliable in predicting the yield of gasoline with respect to the COR and temperature of catalyst.

## 1. Introduction

The Fluid Catalytic Cracking Unit (FCCU) is a major unit that evolved in the refinery to increase gasoline production based on its demand [1]. It is also essential for the production of high-grade gasoline to match the continuous upgrade in technology. Fluid Catalytic Cracking (FCC) is one of the most effective subordinate processes in the refinery used to boost gross refinery margin (GRM) [2] also one of the most significant processes in the petroleum refining industry [3] as a lot of money is spent on refining [4]. The fluid catalytic cracking unit has increased profitability as it transforms cheap heavy feedstock into lighter, more treasured hydrocarbons such as liquefied petroleum gas (LPG) and gasoline at extremely high temperatures and restrained pressure in the presence of a catalyst which is finely divided and silica/alumina based.

The FCCU can be described presently as the core of refineries. The feedstock used in the riser a reactor of the FCC unit determines the quality of the product obtained from the unit [5] (see Fig. 1).

A cracking process was introduced due to the large amount of high boiling materials after the process of crude oil distillation which is the first unit with the highest output in the refinery [7]. This process involved the conversion of heavy crude into compounds of lower boiling points and molecular weight [8]. The fixed catalyst was initially used for the process, but this process was not so efficient due to the local variation in the temperature of the bed. Due to the deposition on the surface of the catalyst, carbon could not be burnt off, so it had to be taken out of the bed from time to time. However, all these shortcomings led to the introduction of fluidized catalysts. The fluidized systems possess high heat transfer coefficients, enabling uniform temperatures within the reactors and easy control of the conditions. The major disadvantage of the fluid bed catalytic cracking is the number of side reactions due to some longitudinal mixing [9].

The core of several refineries is catalytic cracking. It transforms heavy feeds into lighter products with the aid of a catalyst by cracking large molecules into smaller molecules. In comparison to hydrocracking, which runs at high partial hydrogen pressures, catalytic cracking operates at low pressures without incorporating hydrogen. Catalytic cracking is inherently safe, as it actually operates during the cracking process with very little oil in inventory. It is an endothermic process

---

* Corresponding author.
*E-mail address:* olagoke.oladokun@covenantuniversity.edu.ng (O. Oladokun).

https://doi.org/10.1016/j.rineng.2023.101224
Received 5 April 2023; Received in revised form 24 May 2023; Accepted 4 June 2023

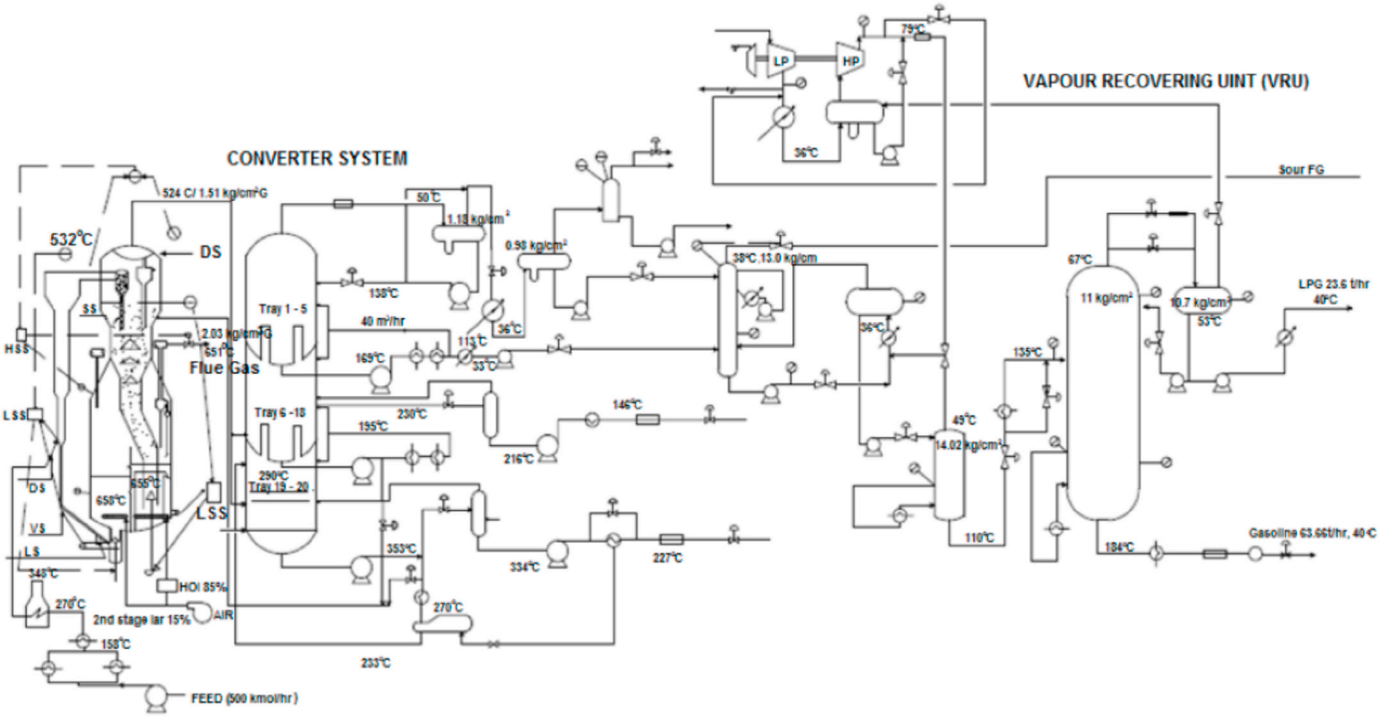


**Fig. 1.** Schematic diagram of KRPC's FCC [6].

**Table 1**
Statical Table of gasoline yield.

| Source | DF | Adj SS | Adj MS | F-Value | P-Value |
|---|---|---|---|---|---|
| Model | 5 | 1113.05 | 222.611 | 10925.74 | 0.000 |
| Linear | 2 | 1092.26 | 546.128 | 26803.97 | 0.000 |
| COR | 1 | 522.33 | 522.332 | 25636.07 | 0.000 |
| Tcat | 1 | 569.92 | 569.923 | 27971.88 | 0.000 |
| Square | 2 | 6.17 | 3.084 | 151.34 | 0.000 |
| COR*COR | 1 | 6.01 | 6.014 | 295.19 | 0.000 |
| Tcat*Tcat | 1 | 0.15 | 0.153 | 7.49 | 0.012 |
| 2-Way Interaction | 1 | 14.63 | 14.631 | 718.07 | 0.000 |
| COR*Tcat | 1 | 14.63 | 14.631 | 718.07 | 0.000 |
| Error | 24 | 0.49 | 0.020 |  | 0.000 |
| Total | 29 | 1113.54 |  |  |  |

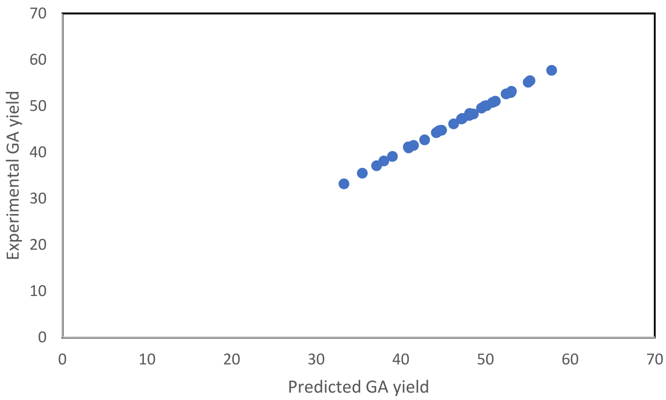


**Fig. 2.** Plot of simulated gasoline Yield versus Predicted gasoline yield by Minitab.

because it consumes heat [10].

In the riser reactor where cracking takes place, vaporised oil enters through the bottom simultaneously with the hot catalyst (fresh or regenerated), which is fluidized. The contact between the two brings about the cracking, which takes place between 2 and 10 s [11]. With this, some catalysts would have coke deposits on them and are then drawn off through the side valves in the reactor, while the products are then sent to the separator. The spent catalyst is being sent into the regenerator, where the coke deposits are burnt off with air to give the regenerated catalyst, CO, $CO_2$, and $H_2O$ [12] although all efforts are been made to reduce $CO_2$ as it is a byproduct of carbonaceous fuel [13]. Fresh catalysts are added intermittently even as the aged catalyst are removed from the process to keep a balanced system in terms of the amount of catalyst need per time.

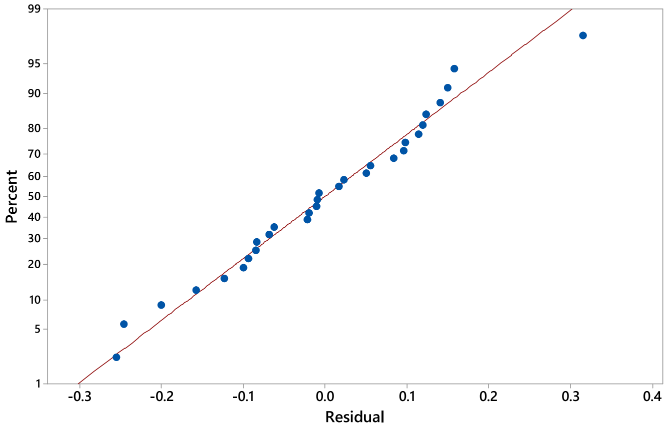


**Fig. 3.** Normplot of residuals for gasoline showing the justification of the model.

The yield of Gasoline of major interest as the demand is on the increase especially in places like Nigeria due to power outage and generators are powered majorly with it in both residential and business places especially growing ones [14]. The availability of gasoline as a source of energy is very critical to the sustainability for human activity [15]. Despite the effort to increase the yield by using the FCCU, the

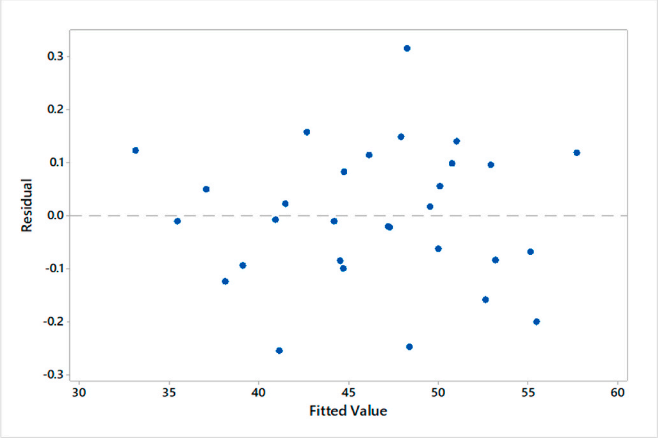


**Fig. 4.** Residual vs fits for gasoline showing the random fitting.

demand is still not met and the price is on the increase due to increase in the use of automobiles driven by factors such as economic growth, population growth, general inflation, and finally rise in the price of gasoline [16–18].

This has necessitated the reason for a sensitivity analysis determined based on the different factors obtained in production or a model which will help redirect and give possible changes that can be made to current process that bring about the increase of gasoline production.

## 2. Methodology

The sensitivity analysis was done using Minitab software where the simulation results obtained from the simulated results in MATLAB which followed Olafadehan et al. (2018) and Olafadehan et al. (2019) method of lumping. The DOA function was used at 95% confidence level, which is the most accurate of all. The linear factor, square factors and interactive factor were also used where COR is represented as $X_1$ and ($t_{cat}$) is represented as $X_2$ .

The best optimized condition was given at COR = 3.35 and $t_{cat} = 900$ K. At this condition the output of gasoline, the premium product, is 56.78%, which is more than what was obtained from the industry.

## 3. Discussion of results; GA yield with respect to variations in COR, tcat

The sensitivity test was done using the single, square and interactive factors. The p-value for the sensitivity of GA varying the temperature and catalyst to oil ratio of the riser reactor at confidence level of 95% were <0.000 from Table 1.

The lower the p-value with respect to the confidence level the better and reliability of the model. The uncoded model for GA was obtained from the minitab in Equation (1).

$$GA = 77.58 + 1.365X_1 + 0.0043X_2 + 0.1795X_1^2 - 0.000017X_2^2 - 0.005783X_1X_2 \qquad 1$$

From Fig. 2 we can see that the plot of experimental value that is the simulated value and the predicted value from Minitab is gives a straight-line graph with shows perfection and proper fitting of the 95% confidence level.

The summary regression obtained for GA are as follows; the standard error given is 0.1427. It reflects the variability around the estimated models which is very good based on the confidence level of 95% that was set. The $R^2$ value is 99.96%, $R^2$ (adjusted) is 99.95% and $R^2$ (predicted) was given as 99.91% which are all close to perfection. The $R^2$ value is clearly justified in Fig. 3 where data is seen almost fitting fully into the line of the normplot.

The residual fits Fig. 4 also show random fitting which justifies the validity of the normplot.

Equation (1) was used in Table 2 to test the validity of the empirical model equation using the COR and ($t_{cat}$) obtained from the MINITAB and Heydari et al. (2010). It can be seen that the result obtained in line one of the equations gave 0.09% error while the general Root mean square error (RMSE) gave 7.083. The result generated from the table may have given the RMSE of 7.8648 due to the different conditions involved in generating the models used.

## 4. Conclusion

The exquisiteness of this study is that the empirical model equation obtained from MINITAB can be used in predicting the yield of gasoline when the COR and catalyst temperature is to change at any point in time. This equation was obtained from a five lumps kinetic model which incorporated mass and heat transfer, catalyst deactivation, pressure drop and heat capacity of each component of the lumps. Therefore, the empirical equation model is reliable in predicting the yield of gasoline with respect to COR and temperature of catalyst.

## CRediT authorship contribution statement

**Olubunmi G. Abatan:** Data curation, Writing – original draft, Methodology, Investigation, Validation. **A. Olaosebikan Olafadehan:** Supervision, Conceptualization. **E. Vincent Efeovbokhan:** Supervision, Methodology, Writing - review & editing. **A. Olagoke Oladokun:** Software, Visualization, Investigation, Validation. **O. Augustine Ayeni:** Methodology, Writing – review & editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Table 2**
Evaluation of gasoline yield equation using results from other work.

| COR | Tcat | References | Predicted(P) Yield of GA | Observed(O)Yield of GA | P–O | %Error | (P–O)ˆ2 |
|---|---|---|---|---|---|---|---|
| 3.35 | 900 | | 56.83144 | 56.78 | −0.05144 | −0.0906 | 0.002646 |
| 6.75 | 868 | [3] | 52.01381 | 41 | −11.0138 | −26.863 | 121.3041 |
| 8.75 | 910 | [3] | 47.05488 | 43 | −4.05488 | −9.42996 | 16.44206 |
| 10.75 | 890 | [3] | 48.02967 | 41 | −7.02967 | −17.1455 | 49.41621 |
| 11.75 | 925 | [3] | 44.97886 | 37 | −7.97886 | −21.5645 | 63.66225 |
| 4.9 | 845 | [19] | 56.12886 | 49 | −7.12886 | −14.5487 | 50.82062 |
| 6.88 | 930 | [20] | 47.76148 | 45 | −2.76148 | −6.13662 | 7.625759 |
| | | | | | | ∑(P–O)ˆ2 | 309.2736 |
| | | | | | | (∑ (P–O) ˆ2)/n | 61.85473 |
| | | | | | **RMSE** | **√[(∑ (P–O) ˆ2)/n]** | 7.864778 |

## Data availability

Data will be made available on request.

## Acknowledgement

We would like to appreciate Covenant University, Ota, Nigeria for their support in attending this conference.

## References

[1] R. Palos, A. Gutiérrez, J.M. Arandes, J. Bilbao, Catalyst used in fluid catalytic cracking (FCC) unit as a support of NiMoP catalyst for light cycle oil hydroprocessing, Fuel 216 (2018) 142–152, https://doi.org/10.1016/j.fuel.2017.11.148. June 2017.

[2] J.S. Ahari, et al., Thermal conductivity of pure silica MEL and MFI zeolite thin films, Nanoscale Microscale Thermophys. Eng. 10 (4) (2010) 321–331, https://doi.org/10.1080/15567260601009171.

[3] M. Heydari, H.A. Ebrahim, B. Dabir, Modeling of an industrial riser in the fluid catalytic cracking unit, Am. J. Appl. Sci. 7 (2) (2010) 221–226, https://doi.org/10.3844/ajassp.2010.221.226.

[4] A.O. Mamudu, G.J. Igwe, E. Okonkwo, Process design evaluation of an optimum modular topping refinery for Nigeria crude oil using hysys® aspen software, Cogent Eng 6 (1) (2019), https://doi.org/10.1080/23311916.2019.1659123.

[5] E. Ivanchina, E. Ivashkina, G. Nazarova, Mathematical modelling of catalytic cracking riser reactor, Chem. Eng. J. 329 (2017) 262–274, https://doi.org/10.1016/j.cej.2017.04.098.

[6] M. Nuhu, A.S. Olawale, N. Salahudeen, A.Z. Yusuf, Y. Mustapha, Exergy and energy analysis of fluid catalytic cracking unit in kaduna refining and petrochemical company, Int. J. Chem. Eng. Appl. 3 (6) (2012) 441–445, https://doi.org/10.7763/ijcea.2012.v3.239.

[7] S. Kumar, A.S. Mhetre, Comparative techno-economic evaluation of potential processing schemes for petroleum crude oil distillation, Results Eng 14 (April) (2022), 100480, https://doi.org/10.1016/j.rineng.2022.100480.

[8] Y. Xue, X. Wei, H. Zhao, T. Wang, Y. Xiao, Interaction of spent FCC catalyst and asphalt binder: rheological properties, emission of VOCs and immobilization of metals, J. Clean. Prod. 259 (2020), 120830, https://doi.org/10.1016/j.jclepro.2020.120830.

[9] J. Coulson, J. Richardson, Fluidisation, fifth ed., vol. 2, Elsevier Ltd, Oxford, 2002.

[10] United States of America patent No. 5,372,707, 1994 - google search. https://www.google.com/search?q=United+States+of+America+Patent+No.+5%2C372%2C707%2C+1994&oq=United+States+of+America+Patent+No.+5%2C372%2C707%2C+1994&aqs=edge..69i57.1060j0j4&sourceid=chrome&ie=UTF-8. (Accessed 13 September 2021).

[11] A. Corma, et al., Crude oil to chemicals: light olefins from crude oil, Catal. Sci. Technol. 7 (1) (2017) 12–46, https://doi.org/10.1039/c6cy01886f.

[12] K. Dagde, Y. Puyate, Six-lump kinetic modelling of adiabatic plug-flow riser-reactor in an industrial FCC unit, Int. J. Eng. Res. Afr. 2 (6) (2012) 557–568.

[13] O.A. Odunlami, D.A. Vershima, T.E. Oladimeji, S. Nkongho, S.K. Ogunlade, B. S. Fakinle, Advanced techniques for the capturing and separation of CO2 – a review, Results Eng 15 (April) (2022), 100512, https://doi.org/10.1016/j.rineng.2022.100512.

[14] U.K. Elinwa, J.E. Ogbeba, O.P. Agboola, Cleaner energy in Nigeria residential housing, Results Eng 9 (2021), 100103, https://doi.org/10.1016/j.rineng.2020.100103. January 2020.

[15] S.O. Oyedepo, On energy for sustainable development in Nigeria, Renew. Sustain. Energy Rev. 16 (5) (2012) 2583–2598, https://doi.org/10.1016/j.rser.2012.02.010.

[16] M. Salimi, M.A. Moradi, M. Amidpour, Modeling and outlook analysis of gasoline supply and demand and sensitivity analysis of main economic and social drivers, Energy 256 (2022), 124686, https://doi.org/10.1016/j.energy.2022.124686.

[17] N. Kamyabi, B. Chidmi, Gasoline demand in the United States: an asymmetric economic analysis, J. Econ. Asymmetries 26 (2022), e00275, https://doi.org/10.1016/j.jeca.2022.e00275. September.

[18] L. Levin, M.S. Lewis, F.A. Wolak, Reference dependence in the demand for gasoline, J. Econ. Behav. Organ. 197 (2022) 561–578, https://doi.org/10.1016/j.jebo.2022.03.003.

[19] O. M. Daramola Olafadehan, O.P. Sunmola, G.O. Abatan, Modelling and simulation of riser reactor of a commercial fluid catalytic cracking unit using 6-lump kinetics of vacuum gas oil, Pet. Petrochemical Eng. J. 3 (3) (2019), https://doi.org/10.23880/ppej-16000194.

[20] W. Zhu, S. Li, and Y. Zheng, “Modeling and Parameter Estimation for MIP-CGP Riser Reactor of FCCU.”.