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# A Precise Mathematical Correlation to Estimate Product Yield of Delayed Coking Units

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**ABSTRACT**

Typical models are employed to estimate the product yields of delayed coking units using complicated and multistep calculations. In the current study, a new first-order mathematical model has been proposed to estimate delayed coking products yield utilizing Volk’s model as the baseline. The modified coefficients of Volk's model for the industrial level are 0.634, 0.589, 1, and 1.116 for gas, gasoline, gasoil, and coke yield prediction, respectively. In Compare to other models, the proposed model showed a very close and similar trend with industrial data in yield prediction, and the average error for gas production was 0.25%. For gasoline, almost all of the other models have overestimated efficiency. However, the current model prediction was obtained close to the industrial data with an average error of 14 % which is almost three times better than Volk’s model prediction (which was the most accurate model previously). The industrial data for the gasoil was underestimated by all previous models. However, the average error of the proposed model for the prediction of gasoil yield was 13% while other models’ estimation error is much higher. For coke production, this newly developed model is the most accurate one compared to other predictive models.

## Introduction

Regarding the highly growing demand for light and intermediate petroleum distillates and the reduction of light petroleum reservoirs, methods that increase the production of light petroleum products from the heaviest reservoirs have significant profitability. Delayed coking is one of these approaches. Due to the fluctuations in the price of oil and final petroleum products, refineries are facing new challenges in order to seek as many new opportunities for profit as possible while providing optimal conditions [1]. Updated heavy and extra-heavy oil

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technologies are one of the effective methods to enhance benefits in these plants [2]. A 0.7% increase in conversion in a vis-breaker unit with 25000 barrels per day has led to an increase $7 million more profit per year [3]. Considering higher demand for light crudes with low sulfur and metal content, such as Brent, has caused a decline in resources and an increment in prices. Heavy crude oil resources whose reserves exceed 6 trillion barrels and are cheaper, will shape the future of the energy source [4]. Therefore, heavy crude oils and other heavy energy containers must be managed appropriately to meet the world's increasing fuel demands. Refinery of the heavy petroleum and residues must take place using catalytic cracking or thermal cracking procedures. As the metal content and high molecular weight compounds of these heavy crudes are considerable, catalytic methods are not suitable due to the contribution of the mentioned components in poisoning the expensive catalysts and coke formation. The thermal cracking approach is the precedent route to upgrade the residues and heavy crude oils [5]. In recent years, due to the vast market for intermediate petroleum distillates, the production of these materials has increased, which has simultaneously caused more residues [6-8]. The residues such as fuel oils, and atmospheric and vacuum residues have created extensive problems for both producers and consumers. Due to their high viscosity and sulfuric materials, which require a significant amount of energy for their combustion, they also have a low price. Hence, these heavy materials are neither profitable for refiners, nor meet the environmental regulations [9, 10]. As the crude oil resources become heavier with more sulfur and metal impurities, worldwide demand for cleaner and more qualified fuels has gotten greater than ever [11]. The conflict becomes more serious when paying attention to the design of these energy industry plants. Old refineries which are designed and equipped to process light and medium crudes are not able to handle such heavy or extra heavy feedstocks. Considering the expense of the sweet and light feedstocks, the basic decision to change the regular feed from light to heavy, such as vacuum residues and barrel bottoms, is with refineries. According to the availability of residues for refineries, the selection of a suitable process for upgrading these residues also must consider. To achieve this goal, hydrogen addition and carbon rejection are the most common technologies. Both of them developed to increase the hydrogen to carbon ratio. Regarding the whole plant condition, one of the approaches must be chosen. Many factors need to be evaluated, such as characterization and type of crude to be refined, energy consumption, desired products, equipment price, etc. In the case of new refineries, they can be planned to handle heavy feedstocks, attaining as much benefit as possible by manufacturing valuable products from the cheapest feedstocks [10]. Residues not only have negative effects on the environment but also need high costs for storage.

One of the most common methods for conversion of residues into valuable products is delayed coking [12, 13]. The delayed coking process has been used as a method for the upgradation of heavy feedstocks, since its earlier application in 1930. The delayed coking process consists of thermal decomposition, polymerization, and condensation steps. So, residues are converted to the overhead gases, intermediate distillates, and green petroleum coke. Delayed coking units significantly affect the net profit of the entire system. A small increment in the yield of delayed coking can bring tremendous economic benefit. Because of this fact, increasing the yield was always one of the most interesting subjects in developing and improving delayed coking units [14]. A schematic of this process has been shown in Fig. 1 [15]. In this semi-batch process, vacuum residue after the primary separation in the fractionator, has entered the furnace. The furnace outlet temperature range is 450-500°C. After the feed passed through the furnace, it has been pumped to the coking drums where the thermal cracking reactions take place. Then, crack products have been come out within the upside of the drum, and green coke accumulated on the surface of the drums. It is worth mentioning that, this process has done utilizing two drums. One of them is for coking, and the other is for decoking.

Typically delayed coking units' operational pressure is between 1 to 4 bar, and temperature varies between 410-450°C. A minimum of 24 hours of residence time is required for each drum [16, 17]. Depending on the feed type, operating conditions, and other effective parameters, the delayed coking process produces various quantities of gas, liquid, and coke [18]. Hydrogen, hydrogen sulfide, olefins, and light hydrocarbons like $C_1$-$C_5$, are major components in the gaseous product. Liquid products are cuts in the range of gasoline and gasoil. The solid deposits, in the form of coke, are fed into the downstream units for calcination and purification purposes, to meet the required standards.

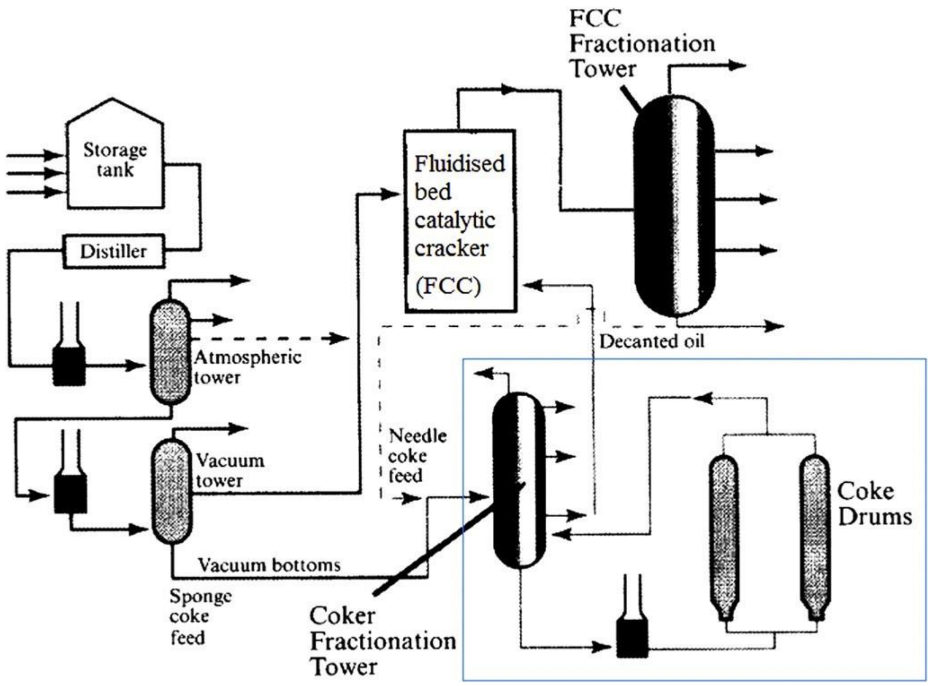


**Fig. 1**. The situation of the delayed coking unit, surrounded by a rectangle, in a typical refinery [19]

Delayed coking units have been the subject of many investigations including simulation, modeling [20, 21], optimization [22-24], system control [25-27], energy consumption [28, 29], and even the dynamic behavior of safety valves and relief systems [19, 30, 31]. As discussed, the process aims to maximize the intermediate distillates, minimizing the heavy residues, and simultaneously upholding the quality of the products. To estimate the product's yield, different correlations have been offered so far.

Zhou et al., [32] proposed a predictive kinetic model that estimates six major groups, including soft resins, hard resins, heavy aromatics, light aromatics, asphaltenes, and saturated hydrocarbons. This model's rate coefficient does not depend on the feed type. Their presented model has been evaluated for three different feedstocks and developed only to predict the quantity of the components. But, their model cannot predict the yield of products.

In another study, a graphical model which estimates the product yields was proposed [33]. For each product, a three-step calculation is required. The proposed model consists of 5 variables that two of which are related to the feed properties and the rest considering the operating conditions. As the authors have mentioned, the model is not applicable for feedstocks with Conradson carbon residue (CCR) higher than 25 percent and operating pressures above 30 psig, which is a great limitation of this approach. Rent et al., [34] proposed a non-linear model consisting of 7 variables and 15 coefficients for estimating each product. If utilized with different feedstocks, the model will show a significant deviation. Gary and Handwerk proposed a set of correlations to predict the yields of gas, coke, gasoil, and gasoline [35]. Unfortunately, they ignored the effect of operating conditions and developed a model considering only the CCR value. Although the model exhibited low accuracy and high deviation from experimental data, however, it is user-friendly and can be easily applied.

Maples et al., [36] suggested correlations similar to the previous models considering the CCR content only. The approach is only suitable for feedstock with 1.4-21.5 API range and CCR of 2.84-25.5%. They have also introduced a set of correlations to estimate the sulfur content of each product.

Following the models given by Gary and Handwerk, another model have been suggested by Smith et al., [15]. Indeed, their proposed model evaluates the effects of pressure (p), temperature (T), and CCR content on the yield of the products.

Perhaps the most useful model has been given by Volk et al., [6]. In a detailed report, they proposed a new model that covered the operating conditions such as temperature, pressure, and liquid space velocity (LSV) as well as microcarbon residue (MCR) content of the feed. The model is applicable for units that operate in 6 to 40psig and 900-950°F. Also, the pilot and commercial-scale effects have been considered in their model. The key equations provided by the mentioned models are listed in Table 1.

**Table 1**. Equations provided by previous models extracted from literature

| Ref. | Equations | No. |
|---|---|---|
| [35] | $\text{Gas (wt\%)} = 7.8 + 0.144(\text{CCR, wt\%})$ | (1) |
| | $\text{Gasoline (wt\%)} = 11.29 + 0.343\,(\text{CCR, wt\%})$ | (2) |
| | $\text{Coke (wt\%)} = 1.6(\text{CCR, wt\%})$ | (3) |
| | $\text{Gasoil (wt\%)} = 100 - \text{Gas} - \text{Gasoline} - \text{Coke}$ | (4) |
| [36] | $\text{Gas (wt\%)} = 4.1264 + 0.2745(\text{CCR, wt\%})$ | (5) |
| | $\text{Gasoline (wt\%)} = 17.025 - 0.0082(\text{CCR, wt\%})$ | (6) |
| | $\text{Coke (wt\%)} = 1.6755(\text{CCR, wt\%}) - 0.3765$ | (7) |
| | $\text{Gasoil (wt\%)} = -1.9418(\text{CCR, wt\%}) + 79.225$ | (8) |
| [15] | $\text{Gas (wt\%)} = 7.4 + 0.1(\text{CCR, wt\%}) + 0.8\left(\frac{P-15}{20}\right)$ | (9) |
| | $\text{Gasoline (wt\%)} = 10.29 - 0.2(\text{CCR, wt\%}) + 2.5\left(\frac{P-15}{20}\right)$ | (10) |
| | $\text{Coke (wt\%)} = 1.5(\text{CCR, wt\%}) + 3\left(\frac{P-15}{20}\right)$ | (11) |
| | $\text{Gasoil (wt\%)} = 100 - \text{Gas} - \text{Gasoline} - \text{Coke}$ | (12) |
| [6] | $\text{Pilot Gas Yield (wt\%)} = 0.1729\text{MCR} + 0.0191\text{T} + 0.13646\text{P} - 786.319\text{LSV} - 6.762$ | (13) |
| | $\text{Pilot Gasoline Yield (wt\%)} = -0.3086\text{MCR} + 0.0137\text{T} + 0.1571\text{P} - 819.63\text{LSV} + 16.461$ | (14) |
| | $\text{Pilot Coke Yield (wt\%)} = 0.9407\text{MCR} - 0.0609\text{T} + 0.1529\text{P} - 319.759\text{LSV} + 65.075$ | (15) |
| | $\text{Pilot Gasoil Yield (wt\%)} = \text{gas}^* = -0.4714\text{MCR} + 0.0546\text{T} - 0.4076\text{P} + 1851.76\text{LSV} - 25.315$ | (16) |
| | $\text{Pilot diesel Yield (wt\%)} = -0.3339\text{MCR} - 0.02635\text{T} - 0.0392\text{P} + 70.957\text{LSV} + 50.452$ | (17) |
| | $\text{Commercial gas yield} = 0.82*(\text{Pilot gas yield})$ | (18) |
| | $\text{Commercial gasoline yield} = 0.75\text{gasoline}^*\left(\frac{\text{liquid}^*}{\text{liquid}}\right)$ | (19) |
| | $\text{Commercial coke yield} = \text{coke}^* = 0.91\,(\text{Pilot coke Yield})$ | (20) |
| | $\text{Commercial Gasoil yield (wt\%)} = \text{liquid}^* - (\text{gasoil}^* + \text{diesel}^*)$ | (21) |
| | $\text{liquid} = -1.1139\text{MCR} + 0.0419\text{T} - 0.2897\text{P} + 1103.08\text{LSV} + 41.59$ | (22) |
| | $\text{liquid}^* = 100 - (\text{coke}^* + \text{gas}^*)$ | (23) |
| | $\text{diesel}^* = 0.90\,\text{diesel} - \left(\frac{\text{liquid}^*}{\text{liquid}}\right)$ | (24) |

Since the Volk model considers 4 parameters, it showed relatively better results compared to other existing models. It is noteworthy that, the product distribution is also dependent upon the reaction conditions and feed type. In 2013, Munzo et al., [37] performed a study to evaluate and compare the most common proposed models. Their study indicated that the model proposed by Ren et al., exhibited quite high deviations predicting the product yields with different vacuum residues. The results showed that Volk et al., model has the lowest, and Gary et al., has the highest deviation from the commercial data. It should be noted that, for an appropriate separation and enhancing the quality of products, reflux flow applied in the design of almost every delayed coking unit around the world. In delayed coking equipment, a gasoil reflux stream is often introduced into the feed to prevent coke shot formation by reducing viscosity [38]. In general, literature review indicates that it is necessary to include the effects of the reflux ratio on the yield of the products as well. Therefore, the following equation can be considered to calculate the yield.

$$\text{Products Yield of Delayed Coking Unit} = F(\text{MCR, P, T, LSV, RF}) \tag{25}$$

where RF refers to the reflux flow or reflux ratio.

As there is no appropriate model considering the reflux ratio effect, in the current study, the purpose is to present a model that predict the product yields of delayed coking accurately. It also considers the reflux ratio as the other effective parameter, and has a low number of calculations. To this end, it has been tried to avoid any complications and a new term has been added to include the effects of reflux flow. So, in the proposed model, the coefficients of Volk's model have been modified in order to consider the impact of the reflux flow as well as other parameters.

## Methodology

In the current study, Volk correlations are considered as a base for further modification to achieve more comfortable and accurate model.

### Effect of Reflux Ratio

To explore effects of the reflux ratio, available data from different references were selected. These data have been presented in Table 2. In Table 2, information of feed A, B, and J were collected from Cold Lake, Arabian Heavy, and Alaska North Slope crudes processed in U.S refineries, respectively. Also, information of feeds D-I correspond to Maya-Isthmus crudes used in Mexico refineries. Feed C is a paraffinic crude, and K is a naphthenic crude. It worth mentioning that all these data are taken from references 37 to 40, except data no. 21 which obtained from Tabriz refinery Ltd, Iran.

According to previous studies, it is expected that adding heavy gasoil into the feed should increase the coke and reduce the liquid [38]. The ratio of consumption to non-consumption of reflux stream in the production of gasoline from Suncor residue has been calculated using the following equation:

$$\frac{\text{with reflux}}{\text{without reflux}} = \frac{16.8}{17.9} = 0.9385 \tag{26}$$

Through the same approach, this ratio for other products has obtained and presented in Table 3.

In the present study, 21 different feeds with different properties including Almerri data [37], were used to modify Volk's model and obtain more appropriate and accurate coefficients. Among these 21 feeds, 43% have API gravity less than 3.5 and the other 57% cases have API gravity more than 3.5. Considering the coefficients presented in Table 3 and the mentioned API ranges, the weighted average coefficients have obtained through Eqs 27 to 32, which presented in Table 4. In Tables 5 and 6 the obtained coefficients are summarized.

**Table 2**. Characteristics of the different feeds (residues).

| | Feed type | CCR (wt %) | API (deg) | Sulfur (wt %) |
|---|---|---|---|---|
| 1 | Feed A | 31 | 2.3 | 6.08 |
| 2 | Feed B | 29.00 | 3.7 | 5.3 |
| 3 | Feed C | 15.60 | 10.3 | 2.62 |
| 4 | Feed D | 31.00 | 0.1 | 5.15 |
| 5 | Feed E | 30.04 | 0.713 | 5.01 |
| 6 | Feed F | 29.05 | 0.778 | 4.97 |
| 7 | Feed G | 29.00 | 1.4 | 4.85 |
| 8 | Feed H | 26.13 | 2.27 | 4.61 |
| 9 | Feed I | 22.44 | 5.79 | 4.5 |
| 10 | Feed J | 22.44 | 7.9 | 2.34 |
| 11 | Feed k | 19.00 | 5.7 | 2.16 |
| 12 | Equilon resid | 29.4 | 1.1 | 4.9 |
| 13 | Suncor resid | 21.2 | 1.6 | 5.4 |
| 14 | Citgo resid | 25.7 | 3.3 | 3 |
| 15 | Chevron resid | 20.3 | 3.3 | 1.8 |
| 16 | Petrobras resid | 21.8 | 5.4 | 0.9 |
| 17 | Marathon resid | 16.3 | 9.7 | 2.1 |
| 18 | Karachi refinery resid | 13.2 | 9.03 | 3.85 |
| 19 | Kazakhstan resid | 7.15 | 19.85 | 0.26 |
| 20 | Russian resid | 10.01 | 18.55 | 17.86 |
| 21 | Tabriz refinery resid | 15.00 | 10.28 | 3.5 |

**Table 3**. Coefficient of reflux effect on the product yields

| Marathon Resid | | Suncor Resid | |
|---|---|---|---|
| Gas | 1.0098 | Gas | 1.0243 |
| Liquid | 0.9282 | Liquid | 0.9166 |
| Coke | 1.1900 | Coke | 1.1495 |
| Gasoline | 0.9838 | Gasoline | 0.9385 |
| Diesel | 0.9674 | Diesel | 1.0100 |
| Gasoil | 0.8582 | Gasoil | 0.8070 |

**Table 4**. Current study suggested coefficients

| Equations Coefficients | | No. |
|---|---|---|
| Coefficient for gas: | 43%(1.0098)+57%(1.0243)=1.0180 | **(27)** |
| Coefficient for liquid: | 43%(0.9282)+57%(0.9166)=0.9215 | **(28)** |
| Coefficient for coke: | 43%(1.1900)+57%(1.1495)=1.1669 | **(29)** |
| Coefficient for gasoline: | 43%(0.9838)+57%(0.9385)=0.9579 | **(30)** |
| Coefficient for diesel: | 43%(0.9684)+57%(1.010)=0.9918 | **(31)** |
| Coefficient for gasoil: | 43%(0.8582)+57%(0.807)=0.8290 | **(32)** |

**Table 5**. Modified coefficients for considering the effect of the reflux ratio on the main products.

| Global Resides | |
|---|---|
| Gas | 1.018 |
| Liquid | 0.9215 |
| Coke | 1.1669 |

**Table 6**. Modified coefficients for considering effect of reflux ratio on liquid cuts production.

| Global Resides | |
|---|---|
| Gasoline | 0.9579 |
| Diesel | 0.9918 |
| Gasoil | 0.8290 |

Implementing the modified coefficients into Volk's model, modified correlations for estimating the product of pilot cokers have been listed in Table 7.

**Table 7**. Modified correlations in current study for estimating the product of pilot cokers

| | Equations | No. |
|---|---|---|
| Pilot gas yield | = (0.1729MCR+0.0191T+0.13646P-786.319LSV-6.762)1.018 | **(33)** |
| Pilot coke yield | = (0.9407MCR-0.0609T+0.1529P-319.759LSV+65.075)1.1669 | **(34)** |
| Pilot gasoline yield | = (-0.3086MCR+0.0137T+0.1571P-819.63LSV+16.461)0.9579 | **(35)** |
| Pilot gasoil yield | = (-0.4714MCR+0.0546T-0.4076P+1851.76LSV-25.315)0.829 | **(36)** |

Examining the commercial data indicates that the presented coefficients in Eqs 18 to 21 are not accurate and reliable for some reasons. One is that, in the case of coke production, industrial cokers are relatively more productive than what Volk's model estimates. So coefficient of 0.91 is not proper for industrial applications. The second one is that, for estimating the product yields via Volk's model, the user has to continue the calculations up to 4 steps which bring huge amount of error into calculations. For instance, to predict gasoline production yield, according to Eq. 19, amount of liquid, liquid*, and gasoline* should be calculated first. The third one is that, as Eqs. 21 and 23 are based on the mass balance, they predict too deviated yields. Therefore, after doing the modifications, the following correlations have been suggested to predict industrial cokers yields, which are presented in Table 8.

**Table 8**. Current study suggested finalized correlations to predict industrial cokers yields

| Equations | No. |
|---|---|
| Commercial Gas Yield = 0.634 (Pilot Gas Yield) | **(37)** |
| Commercial Coke Yield = 0.988 (Pilot Coke Yield) | **(38)** |
| Commercial Gasoline Yield = 0.589 (Pilot Gasoline Yield) | **(39)** |
| Commercial Gasoil Yield = Pilot Gasoil Yield | **(40)** |
| $\begin{cases} \text{Pilot yield} = (c_1MCR \pm c_2T \pm c_3P \pm c_4LSV \pm c_5)c' \\ \text{Commercial yield} = c''\ (\text{Pilot Yield}) \end{cases}$ | |
| Commersial yield $= c'c''c_1MCR \pm c'c''c_2T \pm c'c''c_3P \pm c'c''c_4LSV \pm c'c''c_5$ | **(41)** |
| where $C_1$ to $C_5$, C', and C" are the coefficient. By simplifying, the ultimate forms are as following: | |
| Commercial coke yield $= 1.084MCR - 0.070T + 0.1762P - 368.649LSV + 75.024$ | **(42)** |
| Commercial gas yield $= 0.111MCR - 0.012T + 0.088P - 507.499LSV + 4.364$ | **(43)** |
| Commercial gasoline yield $= 0.174MCR - 0.007T + 0.088P - 462.43LSV + 9.287$ | **(44)** |
| Commercial gasoil yield $= 0.390MCR - 0.045T + 0.337P - 1535.109LSV + 20.986$ | **(45)** |

It is worth mentioning that, the modified coefficients of the Eqs 37 to 40 are based on the same principles adopted by Volk's model. It should be considered that, as a direct result of considering reflux stream, the system has been approached to the equilibrium state where the large and heavy molecules have gained enough energy to transfer into the gas phase. In the existence of a reflux stream, these molecules transfer their energy content to the light molecules, thus cooling and returning to the liquid phase. This condensation process makes better separation and more valuable products.

## Results

In the current study, to evaluate the proposed model in comparison to the others, a vast database shown in Table 9 has been applied. This database consisted of commercial and operating information of 11 different refineries around the globe which consume various feedstocks and produce diverse quantities and qualities of the products. It is worth noting that some of these feedstocks have not been used for comparisons due to the unavailability of operating conditions. Although the delayed coking units handle a specific range of operating conditions and feed properties, however, it can be assumed that similar results will achieve for other cases.

**Table 9**. Operating conditions and characteristics of the industrial/commercial delayed coking used for comparison [37]

| Feed type | Operating Condition | | | | Products | | | |
|---|---|---|---|---|---|---|---|---|
| | Pressure (psig) | Temperature (F) | LSV ($min^{-1}$) | Reflux ratio | Gas (wt %) | Gasoline (wt %) | Gasoil (wt %) | Coke (wt %) |
| Feed A | 30 | 900 | 0.01 | 1.1 | 9.05 | 13.5 | 39.8 | 37.65 |
| Feed B | 30 | 900 | 0.01 | 1.1 | 9.00 | 12.5 | 35.51 | 42.99 |
| Feed C | 15 | 930 | 0.0073 | 1.10 | 8.20 | 17.20 | 56.83 | 17.77 |
| Feed D | 15 | 925 | 0.008 | 1.05 | 9.2 | 9.21 | 39.80 | 41.79 |
| Feed E | 15 | 925 | 0.008 | 1.05 | 9.02 | 9.04 | 36.57 | 45.37 |
| Feed F | 15 | 925 | 0.008 | 1.05 | 8.99 | 8.9 | 35.50 | 46.61 |
| Feed G | 15 | 925 | 0.008 | 1.05 | 9 | 8.81 | 35.51 | 46.68 |
| Feed H | 15 | 925 | 0.008 | 1.05 | 8.96 | 8.9 | 32.00 | 50.14 |
| Feed I | 15 | 925 | 0.008 | 1.05 | 8.6 | 9.06 | 30.00 | 52.34 |
| Feed J | 30 | 900 | 0.01 | 1.1 | 8.59 | 12.30 | 30.00 | 49.11 |

In Fig. 2 the gas yields predicted have been shown by different models. It is clear that, the proposed model not only has the best accuracy but also has very similar and close trend with the industrial data. The proposed model has an average error of 0.25%, which means the best performance compared to other models.

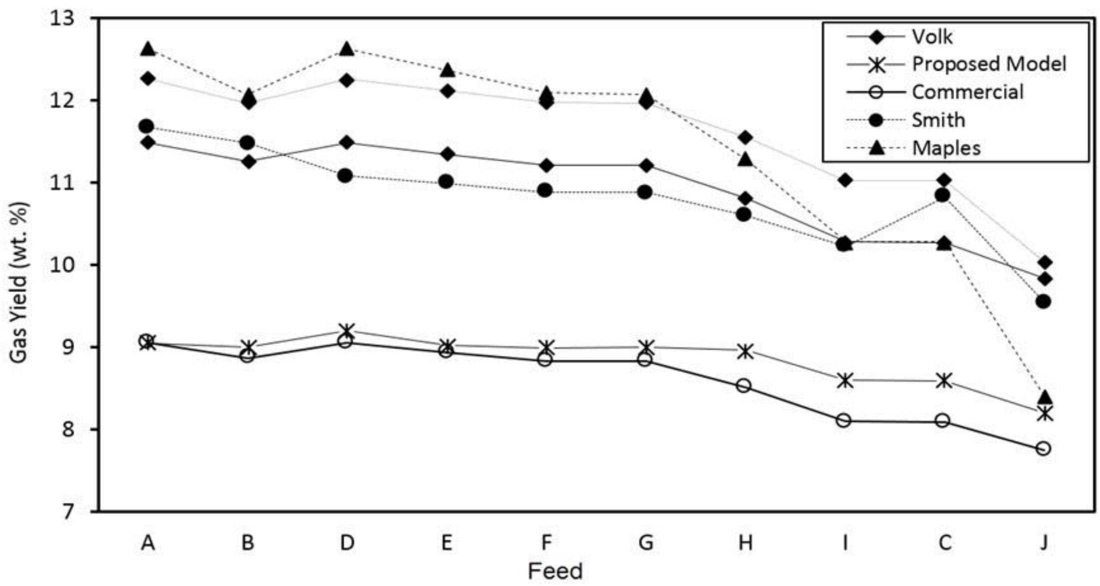


**Fig 2**. Commercial data and estimated gas yields by different models

Fig. 3 depicts the gasoline yields estimated by the models. Almost all other models overestimated the yield, except for the proposed model, which has predicted the product yield very closely. The average error of the proposed model is 14%, which is almost three times better than the prediction of Volk's model.

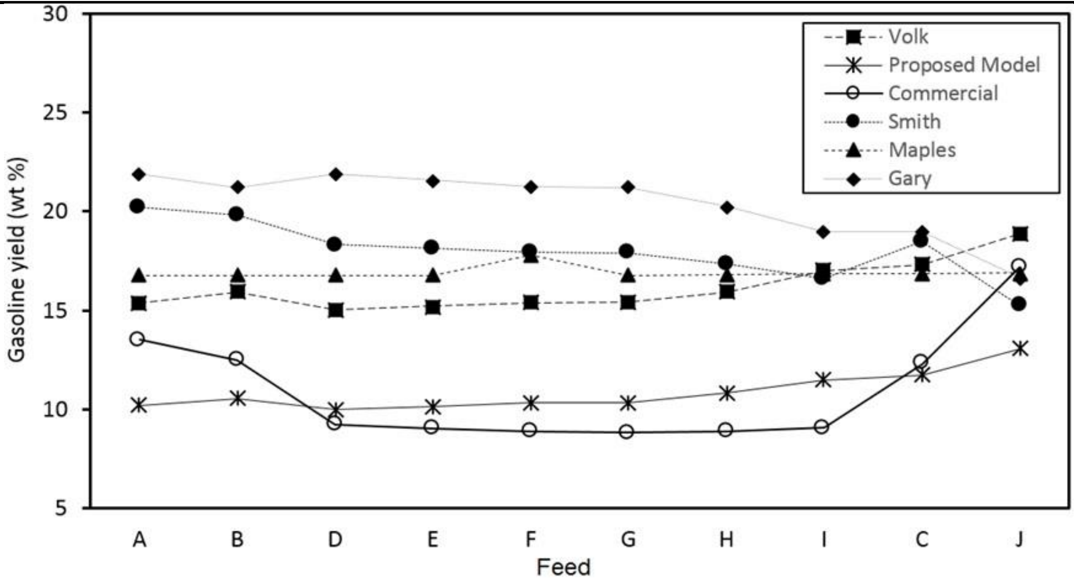


**Fig 3**. Commercial data and estimated gasoline yield by the models

Also, in Fig. 4, the gasoil yield estimation has been shown by using different models. As shown, all of the previous models have underestimated the yield, except the proposed model. In lots of cases, the proposed model predictions were very close to the industrial data. The average error is 13% while other models' estimation error was much higher than 20%.

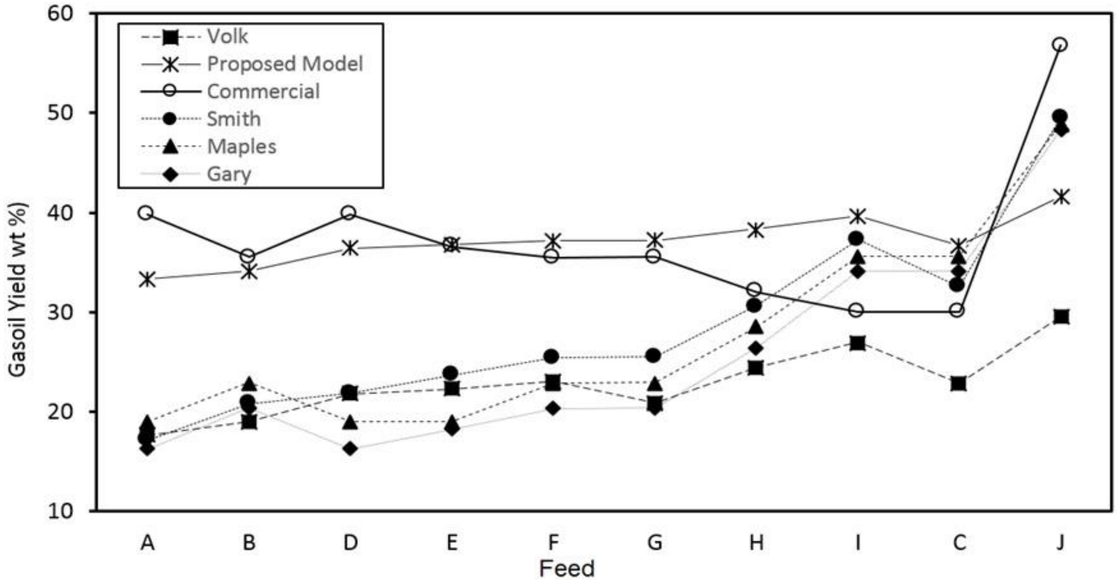


**Fig 4**. Commercial data and the estimated gasoil yield by the models

Finally, Fig. 5 shows the estimated coke yields by different models including the proposed one. Generally, all the models showed similar trends. The proposed model showed a closer prediction of the commercial data compared to the other models. The average error of the proposed model was 15%. On the other hand, as shown the Volk's model has the worst prediction. The ultimate form of the proposed model for each product has been presented in Table 10.

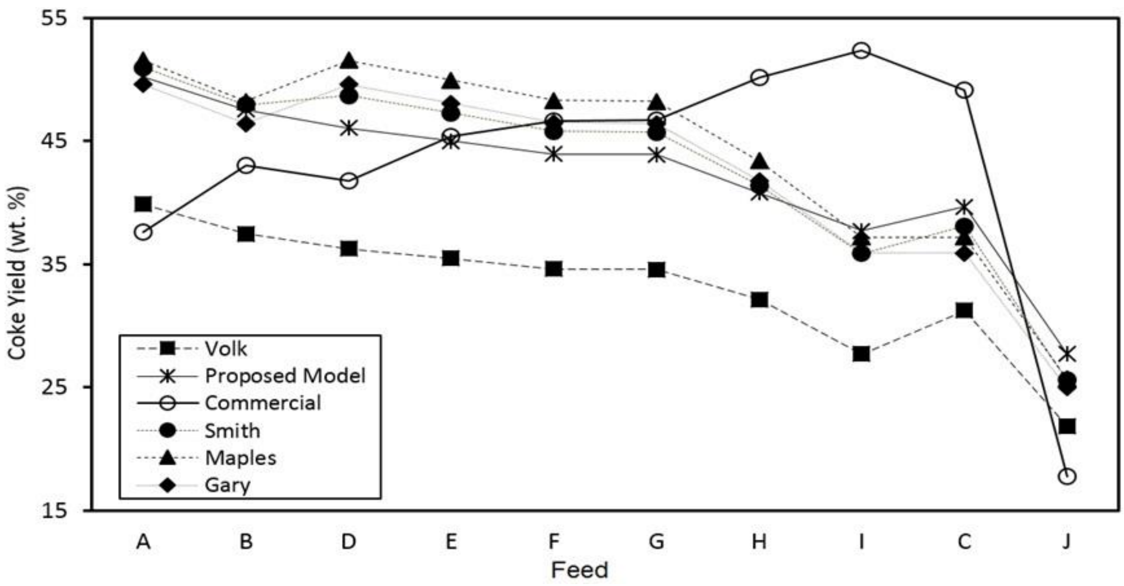


**Fig 5**. Commercial data and the estimated coke yields by the models

**Table 10**. The summary of the proposed model in current research

| Product | Correlation |
|---|---|
| Gas | yield=0.111MCR-0.012T+0.088P-507.499LSV+4.364 |
| Gasoline | yield=0.174MCR-0.007T+0.088P-462.43LSV+9.287 |
| Gasoil | yield=0.390MCR-0.045T+0.337P-1535.109LSV+20.986 |
| Coke | yield=1.084MCR-0.070T+0.1762P-368.649LSV+75.024 |

## Conclusions

Factors affecting product quantity and quality should be considered by refineries that decide to upgrade barrel bottoms to achieve higher profits through delayed coking unit design. In an attempt to optimize the coking units, some correlations to calculate the yields of the delayed coking unit products have been suggested. By applying these correlations and considering particular operating conditions and feedstock properties, it is possible to predict the amount of each product. Desirable predictions and appropriate actions can lead the system into the optimum situation. But high error and deviation of the available models in predicting the final product is a significant obstacle in design, optimization, and even in decision-making process. Ignorance of some effective parameters is the main reason for the failure estimation of such models. Previously, the Volk model, the approach with a generally more accurate prediction of product yields, was developed with 4 variables. Unfortunately, the effects of the reflux stream as one of the most important parameters has been ignored in the Volk's model as well as the other approaches. However, in the current study, the effect of reflux flow was considered. Utilizing Volk's model as the baseline, a new first-order mathematical model to estimate the delayed coking product yields was developed. In the proposed model, the modified coefficients are 1.018, 0.9579, 0.829, and 1.0341 for gas, gasoline, gasoil, and coke production at pilot level, respectively. To convert the pilot results into the industrial level, the user needs to multiply 0.634, 0.589, 1, and 1.116 as coefficients for estimating the gas, gasoline, gasoil, and coke product yields, respectively. For the gas yield prediction, the proposed model showed the best accuracy, and a very close and similar trend with the industrial data, so the average error was 0.25%. It is noteworthy that for the gasoline yields, almost all models overestimated the yields. However, the proposed model prediction was close to the available industrial data with an average error of 14% which is almost three times better than the Volk's model prediction.

Additionally, for the gasoil yield estimation, all of the previous models underestimated the industrial data. But the proposed model predictions were very close to the industrial data so the average error was 15% while other models' estimation error is much higher than 20%. Finally, for the coke yield estimation, models indicated a similar trend. However, the proposed model showed a closer prediction of the commercial data compared to the other models, so the average error was 15% for the proposed model while Volk's model had the worst prediction among the all models. Overall, ten different feedstocks were used for comparison purpose due to the unavailability of operating conditions for other data. Hence, as the delayed coking units handle a specific range of operating conditions and feed properties, it can be assumed that similar results will achieve for other cases.

## Declaration of 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.

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