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Predictive Correlations and Optimization of Atmospheric Long Residue Hydrotreating Process

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Abstract
Recently, the rising production of extra heavy crude oils has led to an increase in the production of atmospheric and vacuum residues associated with a decrease in light and middle distillate fractions. This has encouraged the design of processes to upgrade these heavy fractions to more useful lighter products. Hence, upgrading the heavy crude oil atmospheric residue (long residue) becomes an important solution for that challenge. Hydrotreating is considered as one of the most promising techniques used to upgrade long residue. The present work introduces predictive correlations to study the influence of atmospheric residue hydrotreating operating variables; temperature, pressure, and liquid hourly space velocity; on vacuum distillation yield. Response surface methodology was used to derive the required correlations. Results obtained were validated using experimental data available in the literature. In addition, hydrotreater optimum operating conditions to maximize light/middle products yield and minimum vacuum residue yield were specified. The yield obtained by hydrotreating (catalytic upgrading) was compared with that obtained from thermal upgrading using the derived correlations. Hydrotreating proved to be the best option with higher liquid yield and lower vacuum residue yield.

Keywords: *Optimization; Response surface methodology; Long residue hydrotreating; Thermal/catalytic upgrading.*

1. Introduction

The need to upgrade heavy residues is increasing day after day to meet the increasing demand for lighter petroleum fractions such as gasoline and middle distillates. Moreover, the quality of the supplied crude oil to refineries is getting heavier with high asphaltene content and high amount of impurities [1-2]. Therefore, maximizing the overall liquid yield and minimizing the heavy residue is an important target that refineries need to meet through upgrading technologies [3-4]. Traditional upgrading technologies [5] is not sufficient, so, the integration of various process technologies is proposed in the literature for residue upgrading [6-9]. Such integration may include hydrotreating coupled with coking or visbreaking [6], or deasphalting followed by hydrotreating.

Coupling of the hydrotreating process with vacuum distillation is proposed here as a potential upgrading methodology that could be applied by refineries instead of the traditional distillation route, see Figure 1. Through this new route the long residue will be introduced to the hydrotreating process immediately after leaving the atmospheric distillation unit, after which it will enter the vacuum distillation unit. As shown in Figure 1, more lighter products (naphtha and kerosene) are produced compared to the traditional route.

Deriving correlations and models of the proposed processes are important steps that must be investigated. In this study, correlations were used to investigate the amount of yield and the suitability of the proposed process combination without the need for high investment.
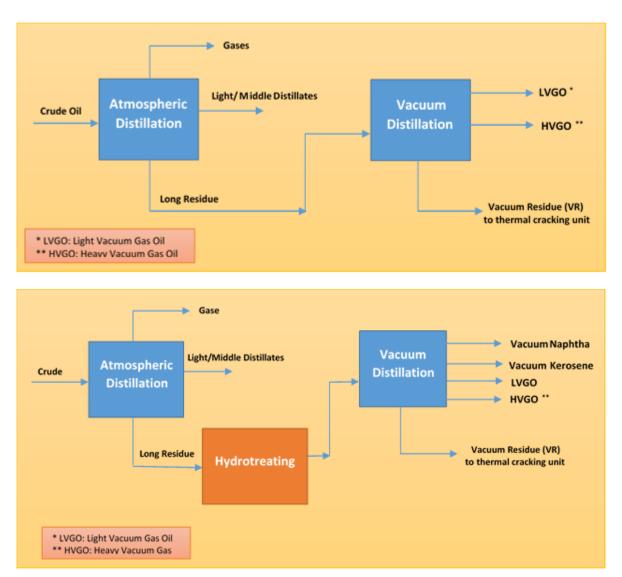
Figure 1. (a) Typical block flow diagram for a refinery process plant, (b) Proposed block flow diagram with the hydrotreating unit for a refinery process plant.

Number of correlations have been suggested in the literature for the hydrotreating processes to correlate the degree of impurities removal by hydrodesulphurization with feed properties and process variables [11-18]. Martínez et al. [11], tested eighteen different correlations from the literature, optimized their parameters and developed new correlations. He found that the polynomial equations type show the best prediction accuracy, when comparing the predicted results with the experimental ones. Other researchers presented models to predict catalyst deactivation with different catalyst systems [19-20]. Ferreira et al. [21], proposed a model to predict the trend of the different yields obtained when changing only the physical properties of the catalyst. Lababidi and AlHumaidan [10], studied the consequence of hydrocracking associated with hydrotreatment of atmospheric residue feedstock and developed a kinetic model describing the cracking reactions taking place, using three different catalysts. Furthermore, Castañeda et al. [22] studied hydrogen consumption during the hydrotreating process and found that there is no correlation in the literature that could predict hydrogen consumption with high accuracy. Only, correlations of up to 15% error are used.

Up-to-date, there are no reliable correlations could be found in the literature to predict the main vacuum products yield as a result of long residue hydrotreating. Thus, our present work

here focuses on developing correlations that will accurately estimate the yield of vacuum distillation fractions based on the long residue hydrotreater operating variables (temperature, hydrogen pressure and liquid hourly space velocity). Response surface methodology (RSM) was applied, it is an efficient mathematical statistics method useful for the developing, improving and optimizing of processes [23]. The main advantage of RSM is the reduced number of experiments needed to evaluate multiple parameters and to understand the interactions between factors, resulting in saving time and experimentation cost [24].

Additionally, the optimum operating condition for the long residue hydrotreating process were identified using Lingo software, at such condition maximum liquid petroleum fractions yield is reached while minimizing the vacuum residue yield. The present study also provided a comparison between the long residue thermal upgrading option and the hydrotreating option. In this comparison, the derived correlations in this work was used to model the hydrotreating process (catalytic upgrading) while Ghashghaee [25], correlation was applied for the thermal upgrading process.

2. Long residue hydrotreating process correlation

In our work here, Response surface methodology (RSM) was applied using Design Experts software to generate correlations between the long residue hydrotreating operating variables and the yield of five vacuum petroleum fractions; namely vacuum naphtha, vacuum kerosene, light vacuum gas oil (LVGO), heavy vacuum gas oil (HVGO), and vacuum residue (VR) from the vacuum distillation unit.

The present study is based on the experimental data presented in the research work of Esmaeel *et al.* [26]. They studied experimentally the hydrotreating process of atmospheric long residue in a continuous trickle bed reactor. The catalyst used was Ni–Mo supported on alumina. The feed to the hydrotreating process was an atmospheric residue derived from Kirkuk crude oil. Refer to Esmaeel *et. al.* [26] for feedstock properties, true boiling point (TBP) ranges of the produced vacuum petroleum fractions and catalyst characteristics.

The derived correlations helped in building up a mixed integer non-linear program (MINLP) aiming at finding the optimum operating conditions for the hydrotreater. ***Lingo software version 14*** was used to obtain the optimum operating variables that will maximize the produced vacuum naphtha, vacuum kerosene, LVGO, and HVGO, and will minimize the produced vacuum residue. Three different pressures; 60, 80 and 100 bar, three different temperatures of the hydrotreating process; 380, 400 and 420°C, and three liquid hourly space velocity (LHSV) values of 0.3, 0.7 and 1 h^{-1} combinations were studied same as that listed in [26]. The hydrogen to oil ratio (H$_2$/oil) was maintained at constant value of 1000 L/L.

Then, a comparison between thermal upgrading products yield (using correlations derived by Ghashghaee [25], and catalytic upgrading products yield (using the proposed statistical validated models) was held. Finally, the best option for residue upgrading technique has been investigated.

3. Results and discussion

The yield of the five vacuum distillation petroleum products was calculated by using *Equation (1).*

$$Product(i)\ yield\ (wt\%) = \frac{Amount\ of\ product\ (i)}{Total\ amount\ of\ the\ products}\ x\ 100 \qquad (1)$$

3.1. New correlations and validation

Response surface methodology (RSM) was used to generate correlations of a quadratic-polynomial type that relate hydrotreater process variables to vacuum yield. By applying the design expert software on the experimental data given in Esmaeel *et al.* [26], the best regression models obtained was quadratic correlations those relating the vacuum distillation products yield to the long residue hydrotreating process operating conditions as shown below:

$$Vacuum\ Naphtha\% = -14.1425 + 5.7839 * LHSV - 0.0338 * P + 0.0399 * T - 9.2951 * e^{-3} * LHSV * P - 0.021 * LHSV * T + 1.3396 * e^{-4} * P * T + 1.2892\ (LHSV)^2 \tag{2}$$

$$Vacuum\ Kerosene\% = 73.99 + 2.9675 * LHSV - 0.0856 * P - 0.3775 * T - 0.01 * LHSV * P - 0.0126 * LHSV * T + 2.6437 * e^{-4} * P * T + 1.2646\ (LHSV)^2 + 4.8694 * e^{-4} * T^2 \tag{3}$$

$$LVGO\% = 179.1 - 1.7403 * LHSV + 0.01124 * P - 0.9331 * T - 0.0238 * LHSV * T + 4.3942\ (LHSV)^2 + 1.2824 * e^{-3} * T^2 \tag{4}$$

$$HVGO\% = 25.6557 + 1.8774 * LHSV - 0.1415 * P + 0.0806 * T - 0.02608 * LHSV * T + 4.3938 * e^{-4} * P * T + 3.3041\ (LHSV)^2 \tag{5}$$

$$VR\% = -212.4184 - 7.3673 * LHSV + 0.2562 * P + 1.4257 * T + 0.0835 * LHSV * T - 8.2187 * e^{-4} * P * T - 10.2493(LHSV)^2 - 2.0654 * e^{-3} * T^2 \tag{6}$$

$$Total\ Liquid\ Yield\% = Vacuum\ Naphtha\% + Vacuum\ Kerosene\% + LVGO\% + HVGO\% \tag{7}$$

where: vacuum naphtha, vacuum kerosene, LVGO, HVGO, VR, and total liquid yield are in wt.%; T, P and $LHSV$ correspond to temperature (°C), pressure (bar), and liquid hourly space velocity (h^{-1}), respectively. Equations 2 to 7 are valid within the limits of the studied operating conditions.

The response surface models were statistically validated for adequacy by analysis of variance (ANOVA). The tests of significance (F-test) results for each factor and interaction for the yield of each species are shown in Table 1. According to the results shown in Table 1, it could be confirmed that each of the three chosen factors has a significant effect on vacuum distillation yield for each product. This is because the magnitudes of the P-value for all the studied factors are less than 0.05. All the terms that have high P-value will be forbidden from its corresponding correlation, since its effect is insignificant. It can also be noticed that the term (B^2) does not exist in all of the proposed correlations and this means that the influence of temperature and LHSV are more significant than that of pressure.

Table 1. Results of factors and their interactions for the vacuum distillation products yield (ANOVA Analysis)

Factors or interactions	P-Value of factors or interactions				
	Vacuum Naphtha	Vacuum Kerosene	LVGO	HVGO	VR
A-LHSV	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
B-P	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
C-T	< 0.0001	< 0.0001	< 0.0001	< 0.0001	< 0.0001
AB	0.0017	0.0011	0.0125	0.2581	0.2112
AC	< 0.0001	0.0001	< 0.0001	0.0369	< 0.0001
BC	0.0073	< 0.0001	0.8485	0.0442	0.0036
A^2	< 0.0001	< 0.0001	< 0.0001	0.0030	< 0.0001
B^2	0.8621	0.8635	0.5267	0.1287	0.1612
C^2	0.1923	< 0.0001	< 0.0001	0.2000	< 0.0001

Figure 2 represents parity plots used to compare the experimental results done by Esmaeel et al. [26] to the corresponding predicted values by the developed correlations in this study; it is clear that, there is a good agreement between experimental and predicted yields, where the average absolute errors are less than 5%. This in turn indicates that the developed correlations could be used effectively for estimating the yields of the considered products when hydrotreating process coupled with vacuum distillation take place within the studied operating conditions.

The R^2 statistical test was employed to determine the correlations' accuracy in representing the experimental data. It is important to note that R^2 may be high; close to 1, while the predictive power of the model does not improve, due to the addition of insignificant factor. Thus, adjusted R^2 should be considered to evaluate the accuracy of the developed correlations, considering that adjusted R^2 only increases when the newly added factor is significant. Another

important quantity is the predicted R^2, so it is better to look at adjusted and predicted R^2 in addition to R^2 [5].
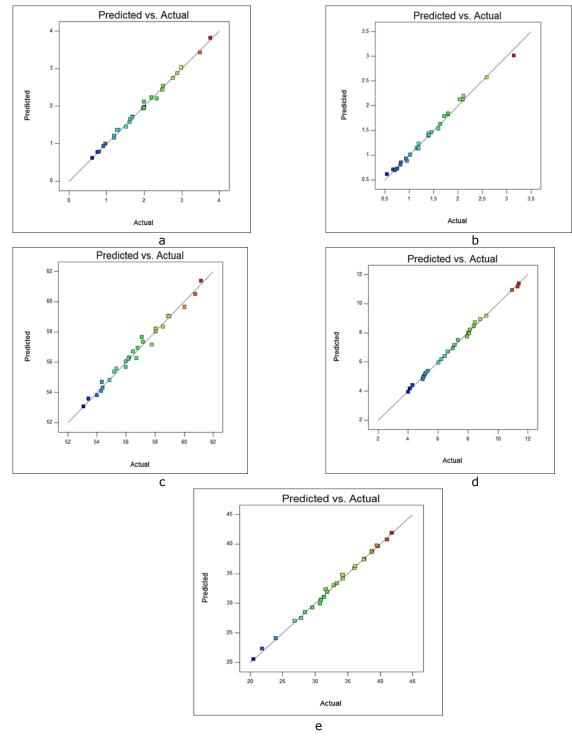

Figure 2. Parity plot comparing actual yield given by Esmaeel *et al.* [26] and predicted yield calculated using the developed correlation for: (a) vacuum naphtha, (b) vacuum kerosene, (c) HVGO, (d) LVGO and (e) VR

Table 2 includes R-squared test results of the produced yield of the five vacuum distillation products. According to the results shown in Table 2, the ranges of R^2, adjusted R^2, predicted R^2 are high with low standard errors. This demonstrates that all the developed correlations fit

the experimental data with standard errors less than 0.4. It is clear also that there is a good agreement between the predicted R^2 values and the adjusted statistics (adjusted R^2) according to Table 2. This reflects that significant terms have been included in the empirical model.

Table 2. R-Squared statistics for the developed models for vacuum naphtha, vacuum kerosene, LVGO, HVGO and VR yields

Model	R^2	Adjusted R^2	Predicted R^2	Standard error
Vacuum Naphtha	0.9961	0.9946	0.9914	0.061
Vacuum Kerosene	0.9933	0.9903	0.9816	0.061
LVGO	0.9976	0.9969	0.9956	0.12
HVGO	0.9855	0.9812	0.9741	0.30
VR	0.9971	0.9961	0.9947	0.35

The response surface models were validated statistically for adequacy by analysis of variance (ANOVA) as illustrated before. The proposed correlations have been further validated through their application on the results introduced by Alhumaidan *et al.* [27]. In their work, they used Kuwait atmospheric residue as a feedstock to the hydrotreating unit. They studied the effect of hydrotreating operating conditions on the vacuum distillation petroleum fractions. They assumed that four vacuum fractions are produced (naphtha, middle distillates, gas oil and vacuum residue). The data for each petroleum fraction can be obtained from AlHumaidan *et al.* [27].

By comparing the lumps in Esmaeel *et al.* [26] with those presented in AlHumaidan [27], see Table 3, it was noticed that the boiling ranges for naphtha and vacuum residue in both references are close to each other. While, the middle distillates boiling range in AlHumaidan [27] spread over the boiling range of kerosene and light gas oil lumps in Esmaeel *et al.* [26]. This consequently leads to predicted violation in correlation yields as the comparison will not be fair for the middle distillates and gas oil lumps. The developed correlation was applicable only for naphtha and vacuum residue (see Table 4). Hydrotreating process of Kuwait atmospheric residue (used as hydrotreating feed for the work of AlHumaidan) was carried out at pressure of 12 MPa; temperatures of 390 and 410^0C and LHSV of 0.5 and 1 h^{-1}.

Table 3. True boiling ranges of the vacuum fractions after atmospheric long residue hydrotreating process from the literature

Esmaeel *et al.* [26]		AlHumaidan *et al.* [27]	
5 lumps	TBP range (ºC)	4 lumps	TBP range (^{0}C)
Naphtha	IBP-160	Naphtha	IBP-160
Kerosene	160-255	Middle distillates	160-360
Light gas oil (LGO)	255-345		
Heavy gas oil (HGO)	345-540	Gas oil	360-525
Vacuum residue (VR)	>540	Vacuum residue	>525

Table 4. Comparison between yield for naphtha and vacuum residue by our correlation and by [27]

Lumps	Operating conditions		Yield given by [27]	Yield as calculated using the proposed cor-
	LHSV	Temp (ºC)		
Naphtha	0.5	390	0.71	2.2241839
		410	2.15	3.1351031
	1	390	0.93	1.4384784
		410	1.54	2.1398176
Residue	0.5	390	35.73	31.771418
		410	25.80	26.101158
	1	390	37.62	36.686408
		410	33.03	31.851308

According to results shown in Table 4, there is a good agreement between the yield of naphtha and vacuum residue calculated using the developed correlations and the experimental results of AlHumaidan *et al.* [27]. Hence, the proposed correlations could be applied for long residue hydrotreating of a wide range of heavy crude oils.

3.2. Interaction between operating variables of the hydrotreating process

Equations 2 to 6 do not show straightway dependence of vacuum naphtha, vacuum kerosene, LVGO, HVGO and VR yields on the hydrotreater operating variables. Furthermore, the interaction of variables and their effect on the lump's yields could not be predicted through the correlations only, hence, further illustration is needed.

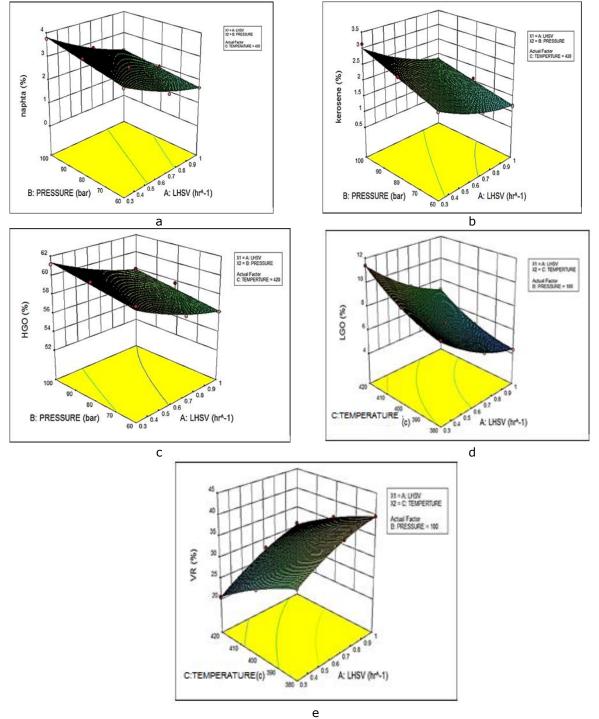Surface response plots were developed to illustrate this dependence as presented in Figure 3.

a

b

c

d

e

Figure 3. Surface response of the effect of temperature (ºC), pressure (bar), and LHSV (h^{-1}) on the yield of (a) vacuum naphtha, (b) vacuum kerosene, (c) HVGO, (d) LVGO and (e) VR

This figure shows that increasing pressure and temperature and lowering LHSV increases the vacuum naphtha, vacuum kerosene, LVGO, and HVGO yield, and decreases the yield of the VR. The perturbation plots for the effect of operating variables on the yield of vacuum naphtha, vacuum kerosene, and LVGO, HVGO and VR are also introduced as presented in Figure 4. This represents a simple way of comparing the relative influences of hydrotreater operating variables on the vacuum distillation yields.
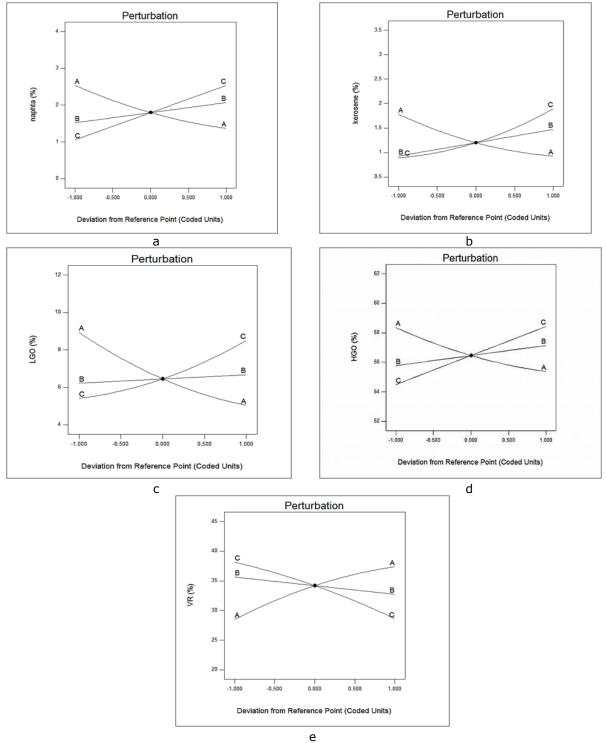

Figure 4. Perturbation plots for yields of: (a) vacuum naphtha, (b) vacuum kerosene, (c) HVGO, (d) LVGO and (e) VR versus operating conditions: LHSV (A), pressure (B), and Temperature (C)

The effect of each individual variable on the yield of each product are studied by a perturbation plot while the other variables are held constant. From Figure 4, it is clear that the effects of temperature, pressure, and LHSV are noticeably significant. Increasing the temperature and the pressure and decreasing the LHSV raises the yield of vacuum naphtha, vacuum kerosene, LVGO, and HVGO products but adversely affects the VR yield. Additionally, it is clear that the effect of LHSV is slightly greater than that of temperature and pressure for the yield of vacuum naphtha and LVGO, while the effect of temperature is greater for the vacuum kerosene yield. Generally, the impact of temperature and LHSV on the hydrotreating process are more significant than that of pressure.

3.3. Optimization of the hydrotreating process

Lingo software version 14 was used to optimize the different operating conditions of the atmospheric residue hydrotreating process under investigation. The optimization program constructed based on the above developed correlations, could be formulated as follows:
Maximize yield of product i (8)
Where i represents the specified product. If it is required to find the optimum operating hydrotreating conditions that maximize a specified product; such as vacuum naphtha, then the objective function would be as in Equation (8). In some cases, it may be required to get the operating variables, which minimize a specified product; such as vacuum residue, in such case, the objective function would be a minimization function.

Constraints for upper and lower limits of each affecting variable are formulated as follows:

$$T^L \leq T \leq T^U \qquad (9)$$
$$P^L \leq P \leq P^U \qquad (10)$$
$$LHSV^L \leq LHSV \leq LHSV^U \qquad (11)$$

Equations 8 to 11 form a non-linear program (NLP), it aims to find the optimum operating conditions which maximizes light and middle distillates, while minimizes heavy residue. Equations 9 to 11 represent the lower and upper limits for the considered operating variables (T, P, and LHSV) in which the introduced model is valid.

By applying this optimization program using the investigated atmospheric residue hydrotreating correlations, the optimum operating condition; T, P, and LHSV, can be determined. The achieved optimum yields are 3.76, 3.02, 11.38, 61.24, and 20.54 % for vacuum naphtha, vacuum kerosene, LVGO, HVGO, and VR respectively, as listed in Table 5.

The optimum operating conditions obtained for the hydrotreating process under investigation are 100 bar, 420 °C, and 0.3 h^{-1} for P, T and LHSV respectively as shown in Table 5. These results are in good agreement with the literature. Trejo and Ancheyta [28] noticed that the asphaltene content in the hydrotreated products diminishes as temperature, and pressure were increased and LHSV was decreased. This action can be attributed to the higher hydrocracking of those asphaltenes and this in turn leads to an increase in vacuum naphtha, vacuum kerosene, LVGO, HVGO yields and a decrease in the produced residue (VR). The effect of lowering LHSV on increasing the yield could be ascribed to the increasing in contact time between the reactants and the catalyst, so more reactions continue to proceed [29-30]. In addition, it is noticed that there is no effect for lowering the LHSV less than 0.3 h^{-1} on improving the atmospheric residue hydrotreating process.

Table 5. The optimum conditions for producing maximum yields of vacuum naphtha, vacuum kerosene, HVGO and, LVGO, and minimum yield of VR after hydrotreating of the atmospheric residue

Product	Yield (wt%)	LHSV (hr^{-1})	P (bar)	T (°C)
Vacuum naphtha	3.76	0.3	100	418.8
Vacuum kerosene	3.02	0.3	100	420
LVGO	11.38	0.3	100	420
HVGO	61.24	0.3	99	419.5
VR	20.54	0.3	100	420

Increasing the temperature significantly enhances the thermal cracking reactions. The effect of temperature is nonlinear; more effect on conversion is shown above 390°C where the production of middle distillates increases. This is because the conversion is due to both thermal and catalytic cracking. Similarly, the catalytic reactions are enhanced by increasing temperature as it increases the rate of diffusion inside the active site of the catalyst as a result of decreasing residue viscosity, which agree with published work [31-33]. The more complex the feed is, the higher pressure is required to cause these molecules to react [34]. Consequently, long residue hydrotreating requires high pressure; that leads to a good contact between hydrogen, residue and the catalyst [5]. However, there are limitations on increasing temperature and pressure higher than 420 °C and 10 MPa, respectively, Higher temperature (>425°C) may cause thermodynamic equilibrium limitations that leads to decreasing in conversions. Moreover, the activity of the catalyst used will decrease due to coke formation that deposits on the catalyst [35]. The effect of pressure above 100 bar can be neglected, because the diffusivity and mass transfer coefficient will decrease with increasing the pressure [5].

3.4. Comparison between thermal and catalytic upgrading processes

Long residue upgrading could be achieved either by hydrotreating (catalytic upgrading) where our current study and developed correlation are based on, or by thermal upgrading. In this section we focus on the comparison between thermal upgrading and catalytic upgrading (hydrotreating) technologies used as a pretreatment of long residue for maximizing liquid products yields as well as for purification of some impurities. This comparison is based on the above-mentioned case study of atmospheric crude residue derived from Iraqi crude oil, Esmaeel et al. [26]. The reactor temperature for the thermal and hydrotreating upgrading processes varied from 380 to 420°C, the pressure ranged from 18 to 100 bar and the liquid hourly space velocity varied from 0.5 to 1 h^{-1} in the reactor (residence time of 60 to 120 min.). The introduced correlations as indicated in Equations 2-7 are used for the hydrotreating process to predict the yield of the total liquid and residue produced from the catalytic upgrading process, while the correlation presented by Ghashghaee [25], are used to predict the yield of the total liquid and residue produced from the thermal upgrading as presented in Equations 12-13.

$$L = -13.723 + (0.0142 + 0.0041 * API + 0.0045 * Sf + 0.0014 * CCR) * (335.4731 + T) * LN(0.0965 * T^{0.6748} * (0.8101 + t)^{1.1476} * P^{0.1941}$$
(12)

$$R = 113.541 + (0.0663 - 0.0204 * API - 0.0193 * Sf - 0.0063 * CCR) * (-343.807 + T) * LN(0.0296 * T^{0.5958} * (2.3027 + t)^{0.643} * P^{0.0495}$$
(13)

where L and R are total liquid and residue yields in wt.%; T, P and t are temperature (°C), pressure (bar) and time (min) respectively; feed characteristics are given in Esmaeel et al. [26], assuming that the Conradson carbon residue (CCR) is 10%.

Figures 5-8 show the liquid and residue yields from the vacuum distillation unit after the pretreatment of the atmospheric residue by either catalytic cracking or thermal cracking at different operating conditions. As shown in Figures 5 and 6, at fixed operating conditions, the liquid yield produced from the hydrotreating process is more than that produced from the thermal upgrading technology. It could be noticed that the yield at the lowest operating temperature (380°C) for catalytic upgrading is equal to the yield at the highest temperature of thermal upgrading (420°C), and it is even higher at low residence time.

As shown in Figures 5 and Figure 6 increasing the temperature, pressure and residence time for either thermal or catalytic upgrading process, increases the liquid yield, however, increasing the temperature during thermal upgrading has high effect on increasing the liquid yield. In the meanwhile, the liquid yield by catalytic upgrading even at the lowest temperature of 380°C was higher when compared to thermal upgrading at the highest temperature of 420°C.

Figures 7 and 8 represent the vacuum residue yield at different operating conditions for both catalytic and thermal upgrading processes. It is clear that the residue yield when implementing the hydrotreating process (catalytic upgrading) at temperatures (380 and 400°C) was

less than that of thermal upgrading; which means that more liquid products are produced. On the other hand, at higher temperature of 420°C, the vacuum residue yield for thermal upgrading was less, but this does not mean more conversion to liquid products; this is related to higher yield of undesirable gases and coke as a result of increasing temperature.
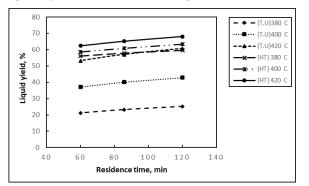

Figure 5. Comparison between liquid yields produced after thermal upgrading (T.U) or catalytic upgrading by hydrotreating (HT) of atmospheric residue at low pressure of 18 bar

Figure 6. Comparison between liquid yields produced after thermal upgrading (T.U) or catalytic upgrading by hydrotreating (HT) of atmospheric residue at high pressure of 100 bar
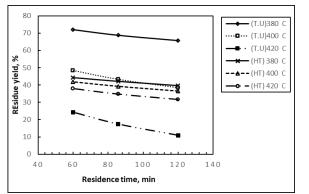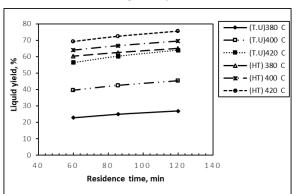

Figure 7. Comparison between vacuum residue yield after thermal upgrading (T.U) or catalytic upgrading by hydrotreating (HT) of atmospheric residue at low pressure of 8 bar
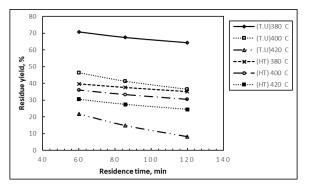

Figure 8. Comparison between vacuum residue yields thermal upgrading (T.U) or catalytic upgrading by hydrotreating (HT) of atmospheric residue at high pressure of 100 bar

4. Conclusion

Five correlations were developed for hydrotreating of atmospheric long residue before processing in the vacuum distillation unit. Data collected from the literature was used to develop and validate our correlations. By using the introduced correlations, the yield was related to the three operating variables; pressure, temperature and liquid hourly space velocity. Each of the three chosen factors has significant effect on hydrotreating process yield for each product. However, the influence of temperature and LHSV have more significant effect than pressure.

All the developed correlations fit the experimental data within the studied ranges of the operating conditions, with regression coefficients (R^2, predicted R^2 and adjusted R^2) for the proposed models close to 1. An average absolute error less than 5% was achieved. Hence, the developed correlations could be used effectively for estimating the yields of the considered products.

The optimization of the investigated hydrotreating process variables indicates that the most efficient process was achieved at high temperature and pressure and at low LHSV. The optimum operating conditions are at a reaction temperature of 420°C, LHSV of 0.3 h^{-1}, and pressure of 100 bar.

Surface response plots and perturbation plots show that increasing pressure and temperature and decreasing LHSV results in increased yield for vacuum naphtha, vacuum kerosene, LVGO, and HVGO, and decreased yield for the VR. In addition, the effect of LHSV is slightly greater than that of temperature and pressure for the yield of vacuum naphtha and LVGO, while the effect of temperature is greater for the vacuum kerosene yield.

The comparison between thermal upgrading and catalytic upgrading by hydrotreating options for the atmospheric long residue showed that hydrotreating of atmospheric residue is more convenient and produce more liquid yields.

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