RESEARCH ARTICLE

Lessons Learned from 10 Years H-Oil Exploitation

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Abstract

The ebulled bed hydrocracking technology of petroleum residues, called H-Oil, was invented in the 1950s. The first patent was issued in 1961. A demonstration unit was started up in 1963, and the first large-scale commercial unit was started up in 1968. There are currently 21 vacuum residue hydrocracking units operating worldwide using the ebulled bed reactor technology. Since 2015, the ebulated bed vacuum residue (VR) hydrocracking has been operated at the LUKOIL Neftohim Burgas (LNB) refinery. Performance of LNB ebullated bed vacuum residue H-Oil hydrocracker for a period of 10 years during processing 39 different vacuum residues at reactor temperatures between 408 and 434°C, and liquid hourly space velocity (LHSV) between 0.12 and 0.22 h-1 is discussed in this study. The feasible co-processing of renewable feedstocks in the H-Oil hydrocracker is also outlined.

Keywords: hydrocracking, vacuum residue, conversion, sedimentation, co-processing.

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1 Introduction

The modern petroleum refining is a rather complex enterprise in which science, technology and business act together to provide its successful functioning. The adequate processing scheme of oil refining technologies applied in an oil refinery ensure the required flexibility needed to adapt to the ever changing conditions (market demand changing, regulation alteration, environment protection norm amendment, geopolitics variation) that is the foundation of surviving and prospering of the petroleum refining activity. The proper utilization of capabilities of existing refining technologies by means of using diverse scientific approaches and techniques gives a competitive advantage of the refinery, which reasonably squeezes the priming of its facilities. The adequate and timely business decisions which take into account all technological and political constraints is the other factor contributing to the surviving and prospering the oil refining enterprises.

Considering all these aspects 20 years ago the selection of the most appropriate technology to convert the bottom of the barrel in LUKOIL Neftohim Burgas (LNB) refinery was initiated. At that time the residue conversion technology applied in the LNB refinery was the vacuum residue visbreaking. It provided about 30% conversion of the vacuum residue that was not sufficient to ensure long term competitiveness

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of the LNB refinery in the light of continually decreasing demand of heavy fuel oil and increasing demand of light automotive fuels and feeds for the petrochemicals. After evaluation of seven residue conversion technologies the H-Oil vacuum residue hydrocracking was selected as the most suitable technology to apply in the LNB refinery to convert efficiently the bottom of the barrel of petroleum. The H-Oil complex has been constructed for 36 months and was put into commission in July 2015. The initial operations were painful, since the control of the H-Oil process was much different from that of the visbreaker, the vacuum residue technology the LNB personnel knew at that time [1]. It turned out the H-Oil was much more sensitive to the different crude oils, which were processed as blends at that time. Crude blends containing El Bouri, Kazakh Heavy, and imported atmospheric residue mixed with Urals crude oil were found to contribute to significant sediment formation in the H-Oil unit [1]. The same crude oils have not created any problems during their processing when LNB converted their vacuum residues by using the visbreaking technology [2].The intermittent start up and shut down of H-Oil hydroracker for cleaning of the accumulated sediments which blocked heat exchangers and rectification columns and the associated start up and shut down of the visbreaker at that time turned it to contribute to the production of residual oils which were incompatible [3]. Both unconverted residual oils from the visbreaker and the H-Oil hydrocracker stored in different reservoirs when blended was found to be incompatible [4]. At that time LNB felt for the first time in its history the burden of oil incompatibility in the refining process. Since then the incompatibility of oil constituents mainly observed in the hydrocracked residual oils has become the main concern when the severity of H-Oil hydro cracker was controlled. The variation of operating conditions of LNB H-Oil hydrocracker and its processing scheme are presented in [1, 5].

The aim of this work is to extract the most useful lessons learned from the 10 years exploitation experience with the respected H-Oil technology.

2 Results and Discussion

Figures 1(a) and 1(b) show the evolution of the operating conditions (WABT and LHSV) over the 10-year period and the resulting vacuum residue conversion level and ediment content in the hydrocracked atmospheric residue (atmospheric tower bottom product) in the LNB H-Oil hydrocracker.

From the data in Figure 1, it can be seen that both vacuum residue conversion and ATB sediment content demonstrate improvement and deterioration over the years. For the period 2015-2021, a significant improvement was recorded with a simultaneous increase in conversion from 43.4 to 86.3 wt.% and a decrease in the content of ATB sediments from 0.4 to 0.1 wt.%. Then, in 2022, an abatement in conversion to 74.7 wt.% was registered with an increase in ATB sediments to 0.28 wt.%. This deterioration in the LNB H-Oil hydrocracker performance was overcome by replacing the design cascade fresh catalyst addition system with a parallel one and optimizing the solid fresh catalyst and the liquid nanosized HCAT catalyst addition rate [6, 7]. In 2023, the vacuum residue conversion was reduced further to 72 wt. %, although the sediment content in the ATB was sufficiently low (0.11 wt%) to allow operation at higher reactor temperatures. This low-severity hydrocracking operation of H-Oil was practiced in 2023 due to low demand for naphtha. In 2024, the conversion of the vacuum residue increased to 79.4 wt.% with a very low sediment content in ATB (0.06 wt.%), which overall could allow further amplification of the reaction severity and achieving higher conversion. In 2025, an increase in ATB sediment content was observed from 0.06 wt. % in 2024 to 0.36 wt.% with a subsequent decline in conversion to 73-74 wt.% in May and July 2025. The reason for this performance degradation was the processing of mixtures of vacuum residues with slop heavy oils accumulated during the shutdown for repair work and the commissioning after the completion of the repair work. The most severe deterioration since the first start-up in July 2015 in the operation and performance of the LNB H-Oil hydrocracker was observed in July 2025 when Vasconia and Basrah Heavy vacuum residues were processed in amount between 67 and 72 wt.% in H-Oil VR blend feed (14 wt.% $<$ Vasconia VR $<$ 19 wt.%; 50 wt.% $<$ Basrah Heavy VR $<$ 60 wt.%) [8]. Fluidized bed loss of the catalyst at the bottom of the second reactor was observed, which was very close to activating the forced shutting down of the H-oil plant. An addition of about 2.5% fluid catalytic cracking (FCC) heavy cycle oil (HCO) to the feed in the second reactor allowed the fluidization of the lower catalyst bed to be restored. The reduced expansion of the catalyst bed during processing of the VR mixture by Vasconia and Basrah Heavy VR, which caused unstable operation of the second reactor, may have resulted from the formation

Table 1. Properties of vacuum residues derived from various crude oils processed at the LNB H-Oil plant for a period of 10 years.

No	VR	SG	MCR, wt,%	S, wt,%	N, wt.%	Vis at 100°C , cSt	Soft. Point, °C	C7-asp, wt,%	C5-asp, wt,%	MW, g/mol	Na, mg/kg	Ni, mg/kg	V, mg/kg	Fe, mg/kg	As, ppb	Ca, mg/kg
1	Arab Heavy	1.040	23.6	5.80	0.44	7150	51.2	8.8	15.8	791	3.4	20.6	82.0	8.8	84.2	2.5
2	Arab Light	1.029	18.7	4.90	0.28	2654	32.3	3.0	6.0	709	1.8	16.7	25.1	2.5	18.0	1.0
3	Arab Med.	1.031	20.7	5.40	0.36	2796	44.7	6.1	12.8	722	38.0	31.8	43.5	17.5	21.0	63.1
4	Aseng	0.984	14.2	0.60	0.67		51.5	3.0	6.3	707						
5	Azeri Light	0.967	9.5	0.50	0.44	358	30.2	0.2	1.1	675	15.0	12.0	18.5	22.5	60.0	1.4
6	Basrah H	1.071	28.9	7.10	0.42	20254	68.6	17.1	28.9	672	7.0	29.5	149.3	10.0	34.5	3.7
7	Basrah L	1.052	23.8	5.90	0.43	4001	50.3	8.9	17.8	721	7.4	21.1	77.0		17.0	
8	Basrah Medium	1.057	24.2	6.82	0.32	16019	60.1	11.5	22.2	708	6.9	22.4	114.3	17.7	5.6	2.5
9	Bonga	0.968	12.8	0.74		7150	51.8	0.2	0.9							
10	CPC	0.981	16.0	2.10	0.31	492	25.2	1.1	4.9	606	14.2	12.3	84.9	20.6	26.1	7.4
11	El Bouri	1.050	25.5	3.30	0.53	4450	45.0	12.0	21.2	636		81.6	92.1			
12	El Sharara	0.976	13.1	0.39	0.43	383	24.9	2.4	8.9	657						
13	Es Sider	0.999	13.8	1.10	0.73	724	49.0	3.6	10.8	727	55.1	35.5	12.0	6.8	29.7	18.6
14	Forties	0.990	14.8	2.50	0.45	621	28.9	4.7	10.1	752						
15	Gulf of Suez	1.024	19.7	3.30	0.38	2353	54.3	9.2	16.2	741	7.0	43.3	123.9	20.3	31.6	5.5
16	Helm	1.054	23.3	3.01	0.34	17045	44.3	11.2	17.1	710	30.8	56.1	177.0	21.1	24.0	8.4
17	Iranian H	1.050	23.9	5.20	0.68	11845	61.9	9.9	18.8		22.0	63.0	202.0		15.0	
18	Johan Sverdrup	1.023	18.3	1.77	0.70	4403	86.0	6.8	11.4	757	1.0	32.5	45.4	59.5	36.0	8.5
19	KEB	1.037	23.3	5.70	0.49	8018	47.8	9.3	17.6	769	4.3	23.7	81.1		9.8	
20	KEBCO	1.020	16.3	3.23	0.50	838		5.0	11.4	709	9.8	26.9	134.5	24.4	178.0	4.2
21	Kirkuk	1.054	25.2	5.90		3748	58.1			749	25.0	70.0	145.0	12.0	89.0	4.1
22	LSCO	0.993	14.0	1.58	0.42	526	28.9	3.0	6.9	620	7.9	18.2	33.2	10.9	55.3	20.5
23	Okwuibome	0.975	12.9	0.50	0.17	695	23.3	0.8	2.2	704						
24	Payara Gold	1.001	13.0	1.43	0.73	979		2.7	4.7	729	3.6	22.2	59.3	14.9	21.8	1.0
25	Prinos	1.108	32.8	9.14	0.11	83790	69.2	19.2	31.5	611	32.2	17.9	18.3	8.7	16.0	94.7
26	RasGharib	1.059	25.1	5.60	0.19	53103	75.8	18.5	31.9	727						
27	Rhemoura	1.041	23.7	1.80	0.50	1045	51.1	9.6	17.4	663	57.7	77.5	57.0	26.6	18.0	90.5
28	Sepia	0.998	13.8	0.75	0.92	1543	52.0	3.7	8.8	776	20.3	19.2	21.5	20.9	123.8	3.9
29	SGC	1.050	22.9	5.09	0.13	30471	58.4	12.3	21.5	689	23.6	105.0	265.0	30.2	146.0	43.7
30	Tartaruga	1.008	16.3	1.35	0.92	2174	56.0	6.7	14.1	746	75.3	10.0	20.3	35.3	10.0	13.5
31	Tempa rossa	1.120	34.3	9.30	0.54	3978283	100.0	23.8	36.5	758	22.7	116.0	65.4	8.2	73.1	9.7
32	TEN	0.981	11.6	1.06	0.62	321	39.0	0.6	2.0	730	5.5	27.2	14.8	6.3	24.3	4.1
33	Unity Gold	0.979	14.7	1.32	0.52	882	44.0	2.3	6.4	735	8.6	15.2	45.1	19.0	52.6	7.3
34	Urals	0.997	17.5	3.00	0.50	1212	40.1	7.7	15.8	739	16.2	10.8	89.8	11.4	21.0	5.6
35	Val'Dagri	1.052	21.4	6.00	0.30	2260	43.7	3.0	9.9	697		21.0	17.0		14.0	
36	Varandey	0.990	15.1	1.70	0.27	553	43.8			759						
37	Western Desert	1.052	19.0	1.31	0.35	1608	54.6	9.0	16.8	671	10.7	35.4	59.2	37.9	18.0	17.3
38	Mandji	1.017	19.6	2.73	0.53	9252	56.0	5.4	11.7		41.2	128.0	157.3	23.0	29.3	18.5
39	Vasconia	1.083	31.1	2.17	0.69	1141120	98.0	25.5	39.0	697	4.7	84.1	410.7	5.8	34.3	3.2

Note. SG = specific gravity; MCR = micro carbon residue; S = sulfur; N = nitrogen; Vis = kinematic viscosity; MW = molecular weight; C5-asp = n-pentane asphaltenes; C7-asp = n-heptane asphaltenes.

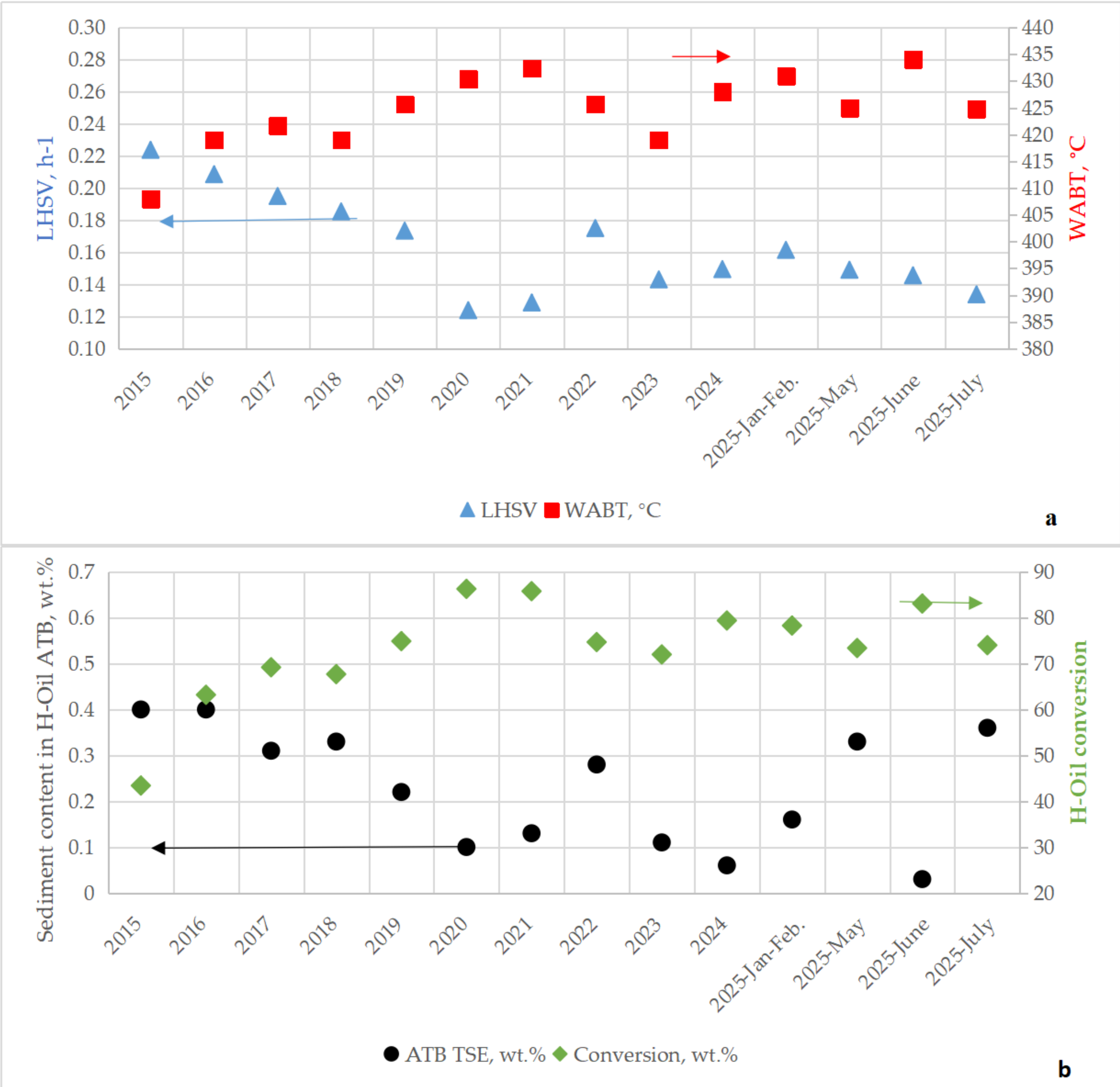

Figure 1. Variation of weigh average bed temperature (WABT) and liquid hourly space velocity (LHSV) (a), and conversion and sediment content in the atmospheric tower bottom product (ATB TSE) (b).

of a separate, asphaltene-rich phase inside the reactor, an event described in the study by Gray et al. [9]. This difficult-to-process VR mixture resulted in an increase in the sediment content in the ATB to 1.2 wt. %, which required a reduction in the reactor temperature by 17.5 °C, which in turn resulted in a decrease in conversion by 18 wt. %. The diminishing of Vasconia VR to 8 wt. % and Basrah Heavy to 31 wt.% and the addition of 45% Payara Gold to the H-Oil VR feed blend allowed to decrease sediment content down to 0.15 wt.% and increase reactor temperature to 430°C and augment conversion up to 79 wt.%. This practical example highlights the major impact that the quality of the H-Oil feedstock can have on both the operation and performance of an ebullated bed vacuum residue hydrocracker. Thirty-nine vacuum residues, whose properties are summarized in Table 1, have been hydrocracked in the LNB H-Oil hydrocracker for the period July 2015 - July 2025. The diverse vacuum residues exhibited both different reactivity (conversion under the same operating conditions) and distinct propensity to form sediments. The vacuum residues, which discerned in their inclination to form sediments in descending order, were found to be: Vasconia > Sepia = Tartaruga ≥ Rhemoura >Johan Sverdrup > El Bouri. The increasing tendency to form sediments by the vacuum residues from crude oils Sepia, Tartaruga and Johan Sverdrup is discussed in [10], that of El Bouri is discussed in [11, 12]. Rhemoura VR processed in a blend with 56% Urals and 33% Arab Medium VRS in amount of 11 wt.% at 425.5°C and LHSV of 0.196 h-1 increased the ATB sediment content from 0.2 to 0.5 wt.% relative to the blend 70% Urals/30% Arab Medium. It is worth noting here that the correlation developed on the base of pilot plant results from hydrocracking of eight different vacuum residues for the conversion achieved at the same sediment content [13] shown as equation 1 demonstrates the same descending order for the VRs from the crude oils Vasconia, Sepia, Tartaruga, Rhemoura, Johan Sverdrup and El Bouri (see Figure 2).

$$\begin{aligned} VR\ conversion^{\text{constant ATB sediment}} \\ = 87.1306 - 0.01306 \times (V + Ni) - 13.3068 \times N \\ - 0.92045 \times MCR + 5.9613 \times S \\ - 0.83468 \times C_{7asp} \end{aligned} \tag{1}$$

Therefore, one may conclude that the sediment formation propensity of a VR could be quantified by using equation 1. Another important observation related to the reactivity of the different VRs, expressed by the conversion at the same operating conditions revealed following:

- Arab Heavy VR exhibits 6 wt.% lower conversion compared to Urals VR;
- 61% Basrah Heavy and 19% Vasconia VRs exhibit 6 wt.% lower conversion compared to Urals VR;
- 55% Basrah Heavy and 21% Johan Sverdrup display 1.5 wt.% lower conversion compared to Urals VR;
- 55% Urals and 18% Johan Sverdrup, 18% Sepia and 7% Tartaruga display 5 wt.% lower conversion compared to Urals VR;
- 67% Basrah Medium and 33% KEBCO demonstrate 2 wt. % higher conversion compared to Urals VR;
- 50% Urals and 50% (Arab Medium and Basrah Light) show 1 wt. % higher conversion compared to Urals VR.

The data above indicate that under the same operating conditions vacuum residue conversion can vary by 8 wt. % a fact already reported by Murray [14] during presenting pilot plant results of hydrocracking of six distinct VRs. The results reported by Murray indicate that Arab Medium VR exhibited 8% higher conversion than Urals VR, while Basrah Light VR demonstrated 10% higher conversion than Urals VR. However, at the H-Oil commercial plant, a 50/50 blend of Urals VR with Arab Medium and Basrah Light VR showed only 1% higher conversion than 100% Urals VR. If the linear mixing rule were valid, then the conversion of this VR

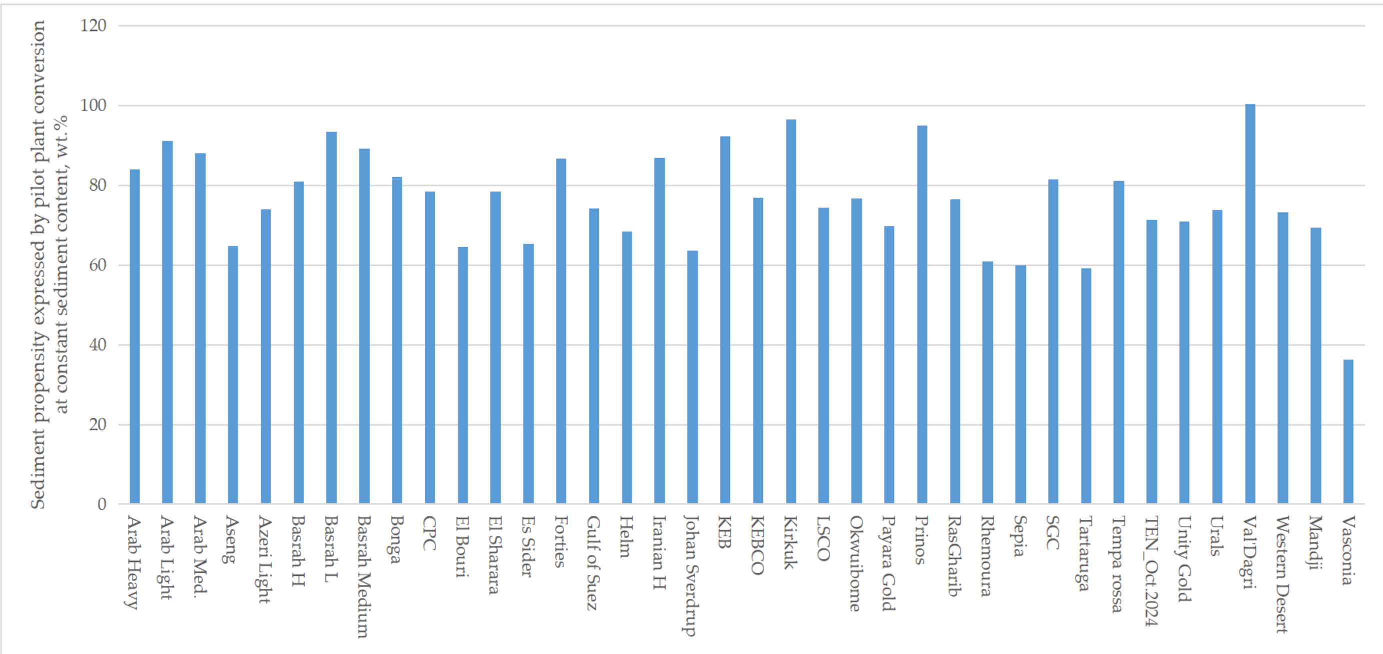

Figure 2. Calculated conversion at constant sediment content by correlation developed using pilot plant data.

blend should exhibit a 4% higher conversion compared to 100% Urals. This finding suggests that inhibition or promotion of hydrocracking rates may occur when vacuum residues are hydrocracked as mixtures.

The 10 years experience with exploitation of the ebullated bed vacuum residue H-Oil hydrocracking revealed that both feedstock and catalyst condition have a profound effect on hydrocracker performance and operation. LHSV was also found to influence the rate of sediment formation, as shown in Figure 3, made based on the data from Figures 1(a) and 1(b).

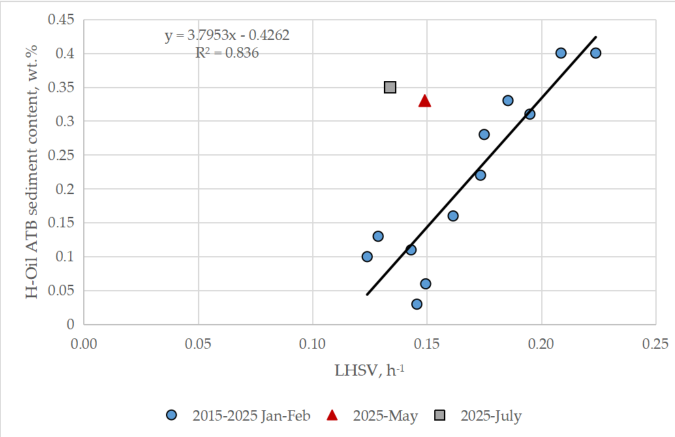

Figure 3. Relationship between sediment content in H-Oil ATB and LHSV.

As can be seen from the data in Figure 3, the sediment content in ATB decreases linearly with reducing LHSV, even though the reactor temperature for the data set that obeys the linear relationship varied between 408 and 432.4°C. The deviation of the data for May 2025 and July 2025 reflects substantial difference in the quality of feedstock and the catalyst condition. A feasibility assessment was carried out for co-processing of used cooking oil (UCO) and cashew nut shell liquid (CNSL) in the amount of 10% and 20%, respectively, along with the vacuum residue in the LNB H-Oil hydrocracker. The assessment, based on pilot plant tests under the conditions applied in the commercial H-Oil hydrocracker, indicated that hydrodeoxygenation (HDO) was about 90%, which was associated with a 10% increase in hydrogen consumption. Co-processing with UCO resulted in higher yields of C3, diesel, and water, while co- processing with CNSL showed higher yields of naphtha, diesel, and water. These increased yields should be considered when evaluating the equipment of the commercial H-Oil unit, and upgrades to critical pieces of equipment can be planned when renewable feedstocks are to be processed on an ongoing basis.

3 Conclusion

The H-Oil vacuum residue hydrocracker used for 10 years in the LNB refinery was found to be a valuable tool to decrease the production of low value heavy fuel oil and increase the production of automotive fuels, diesel and gasoline. The feedstock quality, catalyst condition, and LHSV proved to be the main variables controlling the level of conversion, the rate of sediment formation, and equipment fouling, and therefore the cycle length. There is still a lack of clarity about the characteristics affecting VR reactivity and how VR reactivity could be predicted especially when mixtures of vacuum residues are hydrocracked. Other important issues to be considered are the availability of renewable feedstock, the way of introducing sustainable feedstock into the H-Oil plant, considering its lower chemical stability and higher tendency to polymerization under H-Oil hydrocracking conditions, and the necessary changes to some parts of the process equipment to cope with the increased amount of C3, diesel and water generated during co-processing

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The author declares no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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