

Article

Effect of Crude Oil Quality on Properties of Hydrocracked Vacuum Residue and Its Blends with Cutter Stocks to Produce Fuel Oil

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Abstract: The production of heavy fuel oil from hydrocracked vacuum residue requires dilution of the residue with cutter stocks to reduce viscosity. The hydrocracked residue obtained from different vacuum residue blends originating from diverse crude oils may have divergent properties and interact with the variant cutter stocks in a dissimilar way leading to changeable values of density, sediment content, and viscosity of the obtained fuel oil. H-Oil hydrocracked vacuum residues (VTBs) obtained from different crude blends (Urals, Siberian Light (LSCO), and Basrah Heavy) were diluted with the high aromatic fluid catalytic cracking (FCC) light cycle, heavy cycle, and slurry oil, and the low aromatic fluid catalytic cracking feed hydrotreater diesel cutter stocks and their densities, sediment content, and viscosity of the mixtures were investigated. Intercriteria analysis evaluation of the data generated in this study was performed. It was found that the densities of the blends H-Oil VTB/cutter stocks deviate from the regular solution behavior because of the presence of attractive and repulsive forces between the molecules of the H-Oil VTB and the cutter stocks. Urals and Basrah Heavy crude oils were found to enhance the attractive forces, while the LSCO increases the repulsive forces between the molecules of H-Oil VTBs and those of the FCC gas oils. The viscosity of the H-Oil VTB obtained during hydrocracking of straight run vacuum residue blend was established to linearly depend on the viscosity of the H-Oil vacuum residue feed blend. The applied equations to predict viscosity of blends containing straight run and hydrocracked vacuum residues and cutter stocks proved their good prediction ability with an average relative absolute deviation (%AAD) of 8.8%. While the viscosity was found possible to predict, the sediment content of the blends H-Oil VTBs/cutter stocks was recalcitrant to forecast.

Keywords: petroleum; vacuum residue; hydrocracking; blending; sedimentation; viscosity modeling; intercriteria analysis



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1. Introduction

The vacuum residue is the lowest value product from petroleum refining, that if not converted is mostly used for production of road pavement bitumen and heavy fuel oil [1]. Among the vacuum residue conversion processes, slurry hydrocracking is reported to achieve the highest conversion level—95% [2], then followed by the ebullated bed vacuum residue hydrocracking (EBVRHC)—93% [3,4]. Despite the high conversion level achieved by the hydrocracking technologies, they still generate unconverted hydrocracked vacuum residues, which need to be utilized [5]. As with the straight run vacuum residues,

the hydrocracked ones can be employed as components for production of road pavement bitumen, heavy fuel oil, and feeds for delayed coking units [6,7]. The lower oxidative ageing resistance of the hydrocracked vacuum residues limits their application as a component for production of road pavement bitumen [8]. Therefore, the hydrocracked vacuum residues can be used either as a feedstock for coking units, or as a component for production of heavy fuel oil. Unfortunately, the hydrocracked residual oils are featured by a low colloidal stability and thus by a high sediment formation affinity [9–17]. This makes the users of the heavy oil hydrocracking technology add high aromatic oil fractions such as fluid catalytic cracking (FCC) gas oils to keep the hydrocracked asphaltenes solvated and suppress the sediment formation process [9,18–21]. Marques et al. [9] reported that the polycondensed tri-, tetra-, and penta-aromatics contained in the FCC slurry oil (SLO) suppressed sediment formation during hydrocracking of vacuum residue derived from Urals crude oil. Tirado and Ancheyta [19] reported that the di-aromatics from the FCC light cycle oil (LCO) suppressed to a higher extent the sediment formation during hydrocracking of heavy crude oil in comparison with the FCC heavy cycle oil (HCO) and SLO. Their experimental results showed that the FCC SLO made even more sediments than those obtained during the heavy crude oil hydrocracking without diluent [19]. Marafi et al. [18] studying the hydrocracking of Kuwait vacuum residue observed about 50% reduction of sediment content in the reactor liquid product when 10% FCC LCO and HCO were added to the vacuum residue feed. They reported that the FCC LCO was slightly less effective in sediment reduction compared with the HCO. Ortega-García et al. [20] reported that during hydrocracking of vacuum residue from a petroleum refinery with the addition of FCC SLO to the hydrocracked vacuum tower product (VTB) in the amount of 10%, the reduction of sediment content was 63%, 55%, and 47% at liquid hourly space velocity (LHSV) of 0.5, 0.4, and 0.3 h⁻¹, respectively. Stratiev et al. [21] in their study established that during processing of vacuum residual oil blends derived from the crude oils Urals, El Bouri, Kazakh, Arab medium, Arab heavy, Basrah light, and Val d'Agri in H-Oil hydrocracker, the addition of FCC LCO, HCO, and SLO in the concentration range 5–50% to the H-Oil vacuum residue feed led to continually decreasing the level of sediments in the hydrocracked residual oils with the cutter stock concentration enhancement. They determined that the three high aromatic FCC gas oils exhibited the same efficiency in sediment formation reduction. The published results suggest that the efficiency of the diverse FCC gas oils in the suppression of sediment formation in the hydrocracked residual oils can be different depending on the origin of the heavy oil, and the operating conditions in the hydrocracking unit. The immense diversity in the petroleum properties that can impact the whole performance of a petroleum refinery has been well documented in the references [22–27]. Moreover, crude oil blends instead of single crude oil are typically processed in the petroleum refineries which makes the evaluation of the effect of the crude origin on the specific interactions occurring in the heavy oil hydrocracking even more difficult [28]. Therefore, when blends of crude oils are processed in a refinery possessing an EBVRHC unit, the efficiency of the distinct FCC gas oils to suppress the sediment formation in the hydrocracked residual oils can be divergent. The FCC HCO, and SLO, however, have very high density, and the market of the heavy fuel oil shows that the fuel oil whose density is lower, for example, 991 kg/m³, has significantly higher value than that of the fuel oil with density of 1025 kg/m³. Therefore, cutter stocks with lower density which do not deteriorate the colloidal stability of the fuel oil based on the hydrocracked vacuum residue are desirable. Although the main hydroprocessing technology to treat vacuum residue was reported to be the EBVRHC [29], the information about the effect of the crude oils on the properties of the unconverted hydrocracked vacuum residue and its blends with different cutter stocks is insufficient. Additionally, there is no published report showing the relation of vacuum residue feed blend viscosity to the unconverted hydrocracked vacuum residue viscosity. That was the reason for us to perform this study investigating the performance of the EBVRHC H-Oil in the LUKOIL Neftohim Burgas refinery during processing three different crude oils: Urals, Siberian Light, and Basrah Heavy.

The aim of this research is to determine the effect of crude oil properties on the properties of the unconverted hydrocracked vacuum residue and its blends with the high aromatic FCC gas oils, and lower aromatic FCCPT diesel.

2. Materials and Methods

2.1. Materials

Three crude oils, Urals, Siberian Light, and Basrah Heavy, with properties summarized in Table 1, were used in this study. An additional case with processing of Kirkuk crude oil discussed in Section 3.4. requires inclusion of properties of Kirkuk crude oil in the data of Table 1. Properties of the vacuum residues extracted from the three investigated crude oils are presented in Table 2. The data in Table 2 also include characteristics of the vacuum residue derived from Kirkuk crude oil which are discussed in Section 3.4.

Table 1. Properties of crude oils under study.

Crude Origin		Urals	Basrah H	LSCO	Kirkuk
Crude density at 15 °C	kg/m ³	877.0	905.0	854.0	879.9
Crude sulphur	wt.%	1.53	3.86	0.57	2.88
Crude kin. viscosity at 40 °C	mm ² /s	12.6	37.2	10.8	11.8
Crude Sat.	wt.%	58.4	46.5	62.3	57.7
Crude Aro.	wt.%	35.2	38.7	31.4	34.2
Crude Res.	wt.%	2.6	5.1	3.1	2.2
Crude Asp(C ₇)	wt.%	3.8	9.7	3.2	6.0
Crude Asp(C ₅)	wt.%	6.3	14.8	6.3	8.1
IBP–180 °C	TBP, wt.%	15.0	15.7	20.0	20.9
180–240 °C	TBP, wt.%	8.7	7.8	9.1	9.0
240–360 °C	TBP, wt.%	21.0	17.7	23.1	19.5
360–550 °C	TBP, wt.%	30.3	25.9	29.6	24.5
>550 °C	TBP, wt.%	23.9	31.9	17.3	25.1

Table 2. Properties of vacuum residue (VR) fractions extracted from the crude oils under study.

		Urals	Basrah Heavy	Siberian Light	Recycle	Kirkuk
VR density at 15 °C	kg/m ³	997.0	1071	993.0	1035.9	10,540
VR Concarbon	wt.%	17.5	28.9	14	23.5	25.2
VR sulphur	wt.%	3.0	7.1	1.58	1.15	5.9
Sat (LNB)	wt.%	25.6	12.3	25.0		15.2
Aro (LNB)	wt.%	52.5	54.1	61.1		55.4
Res (LNB)	wt.%	7.8	5.8	6.1		5.0
C ₇ -asp (LNB)	wt.%	14.1	27.7	7.8	18.0	24.3
C ₅ -asp (LNB)	wt.%	17.6	37	15.5	25.7	33.1
Kin. vis. *	mm ² /s	220.9	731.9	149.1		308
Soft. point, °C	wt.%	40.1	68.6	28.9	38.9	58.1
Sat (SAR-AD)	wt.%	18.2	7.4	21.2	21.5	9.5
Aro 1 (SAR-AD)	wt.%	7.0	6.5	9.4	8.4	6.6
Aro 2 (SAR-AD)	wt.%	20.7	23.9	19.4	20.3	23.3
Aro 3 (SAR-AD)	wt.%	33.0	38.9	32.2	39.7	39.2
Resins (SAR-AD)	wt.%	14.0	13.4	13.4	4.2	10.2
CyC6 (SAR-AD)	wt.%	2.4	3.0	1.3	0.14	2.3
Toluene (SAR-AD)	wt.%	4.4	6.6	2.9	5.28	8.4
CH ₂ Cl ₂ (SAR-AD)	wt.%	0.1	0.3	0.1	0.53	0.5
Total Asp (SAR-AD)	wt.%	6.9	9.9	4.4	5.95	11.2

Note: * The kinematic viscosity is that of the blends 70%VR/30% FCC HCO at 80 °C.

The three crude oils were processed in the LUKOIL Neftohim Burgas (LNB) refinery in the following ratios: (1) 60% Urals/40% LSCO; (2) 72.5% Urals/14.1% LSCO/13.4% BH; (3) 63% Urals/31% LSCO/6% BH. The processing scheme of the LNB refinery is detailed in [2]. The vacuum residues obtained from the three crude oil blends were hydrocracked in the LNB H-Oil ebullated bed vacuum residue hydrocracking. The processing scheme of the LNB H-Oil unit is also presented in [6]. The operating conditions and product yields of the H-Oil hydrocracker during processing the three vacuum residue blends are shown in Table 3. Table 3 also includes data for the case where Kirkuk crude oil was processed together with Urals and Siberian light crude oil to be discussed in Section 3.4.

Table 3. Operating conditions and product yields of the H-Oil hydrocracker during processing the three vacuum residue blends.

Date	18 July 2022	29 August 2022	3 October 2022	5 May 2023
	60% Urals/ 40% LSCO	72.5% Urals/ 14.1% LSCO/13.4% BH	63% Urals/ 31% LSCO/6% BH	78% Urals/ 2.5% LSCO/19.5% Kirkuk
WABT of 1st reactor, °C	428	430	429	430
WABT of 2nd reactor, °C	428	432	431	430
ΔT 1st reactor	77	90	80	95
ΔT 2nd reactor	40	43	34	51
Residence time, h	5.47	5.3	5.12	7.96
VR in the H-Oil feed, wt. %	72.9	81.8	67.1	76.5
VGO in the feed, wt. %	13.14	4.6	14.9	1.7
Recycle, % of fresh feed	0	0	0	12.1
Gas yield, wt. %	6.37	7.05	5.64	8.86
Naphtha yield, wt. %	5.86	5.74	5.92	7.58
Diesel yield, wt. %	35.47	34.53	37.03	44.92
VGO yield, wt. %	36.51	34.00	40.60	30.07
VTB yield, wt. %	15.82	18.02	10.61	8.70
H ₂ S yield, wt. %	1.93	2.88	2.15	3.10
Net conversion, wt. %	76.0	77.8	76.50	88.7
ATB, TSE, wt. %	0.19	0.22	0.10	0.07
PBFO, TSP, wt. %	0.09	0.07	0.09	0.03

Properties of the FCC gas oils and FCCPT diesel used as cutter stocks in this study are summarized in Table 4.

Table 4. Properties of the FCC gas oils, FCCPT diesel, and H-Oil diesel used as cutter stocks in this study.

	FCCPT Diesel	LCO	HCO	SLO
Density at 15 °C, kg/m ³	884.6	935.0	1036	1112.1
Sulphur, wt. %	0.0582	0.174	0.715	0.773
Simulated distillation, % mass		ASTM D-2887		
IBP	180	138	202	227
5	237	169	257	311
10	267	188	275	336
20	302	206	295	361
30	323	220	306	380
40	338	230	319	395
50	349	234	328	410
60	359	250	342	426
70	369	255	354	443
80	378	267	368	462
90	391	279	391	488
95	402	290	410	507
FBP	430	333	452	540
Kw	11.7	10.35	9.88	9.65
Kinematic viscosity at 80 °C, mm ² /s	2.97	1.42	4.42	33.35
MW, g/mole	267	162	224	294

Properties of the H-Oil hydrocracked vacuum residues (VTB) obtained at the H-Oil unit during processing the three different crude oil blends are presented in Table 5.

Table 5. Properties of the H-Oil hydrocracked vacuum residues (VTB) obtained at the H-Oil unit during processing the three different crude oil blends.

H-Oil VTB Properties	60% Urals/ 40% LSCO	72.5% Urals/ 14.1% LSCO/ 13.4% BH	63% Urals/ 31% LSCO/ 6% BH
Density at 15 °C, kg/m ³	1025.9	1046.9	1035.9
Sulfur, wt.%	0.897	1.522	1.153
Concarbon content, wt.%	20.7	26.9	23.5
Specific viscosity at 120 °C, °E	24.0	46.5	29.8
Kinematic viscosity at 120 °C, mm ² /s	178	345	221
Kinematic viscosity at 80 °C, °mm ² /s *	2172	5772	2989
Softening point, °C	34.9	45.7	38.9
C ₇ asphaltenes, wt.%	16.1	27.6	18
C ₅ asphaltenes, wt.%	22.6	32.2	25.7
MW, g/mole	668	663	664
HTSD, wt.% (ASTM D-7169)			
IBP 0.5	473	407	349
10	527	514	513
30	570	565	566
50	603	598	600
70	643	638	638
90	706	697	696
95	761	719	715
FBP 99.5	959	774	773
Recovery, %	94.9	91.2	97.3

* Note: The kinematic viscosity at 80 °C was estimated by the use of modified Walther equation as reported in our recent research [30] with reference kinematic viscosity at 120 °C and slope of -3.664 determined for H-Oil VTB.

2.2. Methods

2.2.1. Physical and Chemical Characterization of Studied Oils

Densities of the crude oils, FCC gas oils, and FCCPT diesel were measured in accordance with ASTM D4052 method using Anton Paar DMA 4100 digital analyzer consisting of a U-shaped, oscillating sample tube, electronic excitation system, and frequency counting. The density of the H-Oil VTBs was measured indirectly from the series of solutions of residue and toluene at different concentrations. Detailed information about the applied procedure for density measurement by dilution is given in [6]. Density measurement has repeatability 0.01 kg/m³ and reproducibility 0.05 kg/m³ according to technical specification of Anton Paar DMA 4100 digital analyzer.

Engler specific viscosity was measured in accordance with ASTM D1665 over a temperature range of 120 to 145 °C. Sulfur content of the investigated samples was determined by energy dispersive X-ray fluorescence spectrometry in accordance with ASTM D 4294 method. Softening point (ring and ball) of the H-Oil VTBs under study was measured as is described in ASTM D6493 standard method. High-temperature simulation distillation was applied to characterize the boiling properties of studied oil samples as follows: ASTM D2887 for gas oils and vacuum gas oil; ASTM D7169 for H-Oil VTBs. Concarbon content of the studied oils was measured as carbon residue, left after evaporation and pyrolysis of petroleum products under specified conditions as detailed in standard method ISO 10370. Asphaltene (C₇, and C₅) content was measured as heptane and pentane insolubles following the procedure described in standard method ASTM D 6560. Total sediment existent content (TSE) of the investigated samples was measured by hot filtration in accordance with method ISO 10307-1. Total sediment potential content was determined using standard thermal procedures for ageing of residual fuel oil as detailed in standard method ISO 10307-2. SARA composition of vacuum residue fractions was measured by patented

method SAR-AD and LNB in house method. More details about both SARA procedures are presented in [31,32].

The molecular weights of the studied H-Oil VTBs and the cutter stocks were estimated by the new empirical correlation reported in our recent research [33].

More detailed information about the methods employed to characterize the crude oils whose properties are given in Table 1 is given in our recent research [34]. The methods availed to characterize the vacuum residues whose properties are given in Tables 2 and 5 are detailed in the studies [35,36].

The specification of heavy fuel produced in the LNB refinery is close to that of RMK 700 heavy fuel oil reported in the standard ISO 8217:2017.

The net 540 °C+ vacuum residue conversion in the H-Oil hydrocracker was calculated using Equation (1)

$$\text{Conversion (wt.\%)} = \frac{\text{HOilFeed}_{540\text{ }^{\circ}\text{C}+} - \text{HOilProduct}_{540\text{ }^{\circ}\text{C}+}}{\text{HOilFeed}_{540\text{ }^{\circ}\text{C}+}} \quad (1)$$

where

HOilFeed_{540 °C+} = mass flow rate of the H-Oil feed fraction boiling above 540 °C determined by high-temperature simulated distillation method ASTM D 7169 of the feed and multiplied by the mass flow rate of the feed in t/h;

HOilProduct_{540 °C+} = mass flow rate of the H-Oil product fraction boiling above 540 °C determined by high-temperature simulated distillation method ASTM D 7169 of the liquid product multiplied by the flow rate of the liquid product in t/h.

The excess molar volume of investigated blends was estimated by the use of Equation (2) as reported in [37].

$$V^E = \left[\frac{x_1 M_1 + x_2 M_2}{\rho} \right] - \frac{x_1 M_1}{\rho_1} - \frac{x_2 M_2}{\rho_2} \quad (2)$$

where

M1 and M2 are the molar masses, *1 and *2 are the densities of components (1:H-Oil VTB) and (2:cutter stock), respectively, and ρ denotes the density of the mixture.

In addition to the excess molar volume, the relative changes in volume ΔV were also calculated by the use of Equation (3) as reported in [38].

$$\Delta V = \frac{V^E}{(x_1 V_1^{\circ} + x_2 V_2^{\circ})} = \frac{\frac{m_1 + m_2}{\rho_m} - \frac{m_1}{\rho_1} - \frac{m_2}{\rho_2}}{\frac{m_1}{\rho_1} + \frac{m_2}{\rho_2}} \quad (3)$$

where

x_j , M_i , and V_i° are mole fraction, molar mass, and molar volume of the individual component i , respectively.

2.2.2. Application of Intercriteria Analysis to the Data Generated in This Study

The intercriteria analysis (ICrA) was created in the Institute for Biophysics and Biomedical Engineering, Bulgarian Academy of Sciences (BAS), as a tool to support decision-making in multiobject multicriteria problems [39–41]. It found successful applications in medicine, biology, economics, physics, etc., and it can be considered as a component of the artificial intelligence toolkit [42]. It was also successfully applied in several studies in the field of chemistry and technology of petroleum [43–45]. As input data, the ICrA method requires an $m \times n$ table with the measurements or evaluations of m objects against n criteria. As a result, it returns an $n \times n$ table with intuitionistic fuzzy pairs, defining the degrees of relation between each pair of criteria, hence the name “intercriteria”, and allows making informed decisions which render account of the inherent uncertainty that complex real-life

problems exhibit. For the sake of terminological precision, in ICrA, the term “correlation” between the criteria is avoided but the terms “positive consonance”, “negative consonance”, and “dissonance” are being used instead. For industrial objects which are characterized by a relatively strong “noise” caused by different disturbances of the process, the meaning of $\mu = 0.70 \div 1.00$; $\nu = 0 \div 0.30$ denotes a statistically meaningful significant positive relation, where the strong positive consonance exhibits values of $\mu = 0.90 \div 1.00$; $\nu = 0 \div 0.1$, and the weak positive consonance exhibits values of $\mu = 0.70 \div 0.80$; $\nu = 0.20 \div 0.30$. Respectively, the values of negative consonance with $\mu = 0 \div 0.30$; $\nu = 0.70 \div 1.00$ mean a statistically meaningful negative relation, where the strong negative consonance exhibits values of $\mu = 0 \div 0.1$; $\nu = 0.90 \div 1.00$, and the weak negative consonance exhibits values of $\mu = 0.20 \div 0.30$; $\nu = 0.70 \div 0.80$. All other cases are considered as dissonance. For more detailed explanation of the essence of ICrA, the reader can refer to our previous study [46].

3. Results

3.1. Variation of Density of H-Oil VTB and Total Sediment Potential of Its Blends with FCC HCO as Partially Blended Fuel Oil (PBFO)

The LNB H-Oil VTB is used for both heavy fuel oil and road pavement bitumen production. The maximum specified limit for density at 15 °C of the heavy fuel oil is 1025 kg/m³. Figure 1 shows how the density of the H-Oil VTB varies with conversion level alteration. It is evident from the data in Figure 1 that the H-Oil density increases with conversion enhancement. It is also apparent from the data in Figure 1 that when blends of Urals and Siberian Light crude oil are processed in the LNB refinery, the density of the obtained H-Oil VTB is lower than that of the H-Oil VTBs produced during processing of crude oil blends containing Middle East crudes. The most challenging characteristic of the fuel oil produced from blends of H-Oil VTB and cutter stocks is the sediment content after thermal ageing (total sediment potential = TSP) [6]. Figure 2 indicates the values of the TSP of the partially blending fuel oil (PBFO) of the cases discussed in the data of Figure 1. The data in Figure 2 indeed exhibit that the attainment of TSP lower than the maximum specified limit for the fuel oil limit of 0.1 wt.% is very difficult to achieve. The very high level of 0.9 wt.% TSP in the PBFO was registered during processing 100% Urals at LHSV of 0.25 h⁻¹ and reaction temperature of 418 °C [21]. The reduction of LHSV below 0.19 h⁻¹ with reaction temperature augmentation up to 430 °C and the replacement of the cascade to parallel mode of fresh catalyst addition allowed achievement of conversion level between 76.0 (at LHSV of 0.18 h⁻¹) and 91.7 wt.% (at LHSV of 0.12 h⁻¹), while the sediment content after thermal ageing of the partially blended fuel was ≤0.1 wt.% during processing Urals and its blends with Siberian Light crude oil [47]. All these data point out that the meeting of maximum VTB density and the sediment content specifications for the fuel oils produced from H-Oil VTB and cutter stocks is a challenging task.

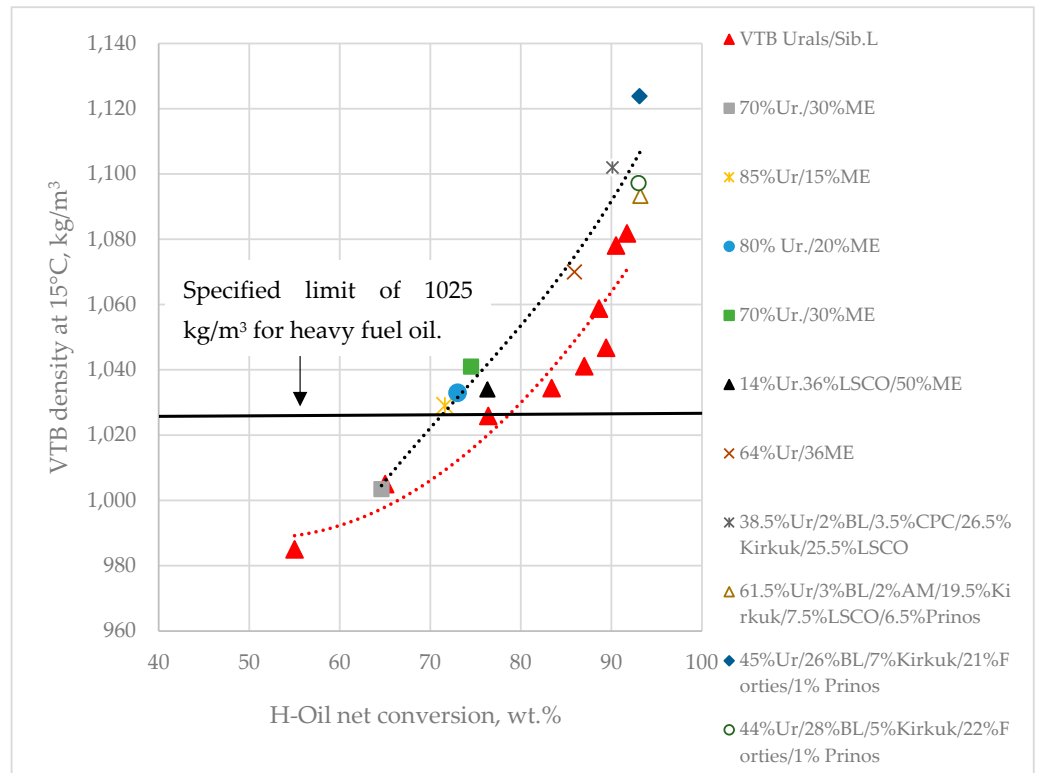


Figure 1. Dependence of H-Oil VTB density on conversion level. (The black dashed line is a regression line related to processing vacuum residue blends of Urals crude oils with Middle East (ME), Prinos (Greece), and Forties (UK) crude oils in the H-Oil hydrocracker. The meaning of abbreviations is as follows: Ur. = Urals crude oil; BL = Basrah Light crude oil; AM = Arab Medium crude oil. The red dashed line is a regression line related to processing only vacuum residue obtained from Urals and Siberian Light crude oils).

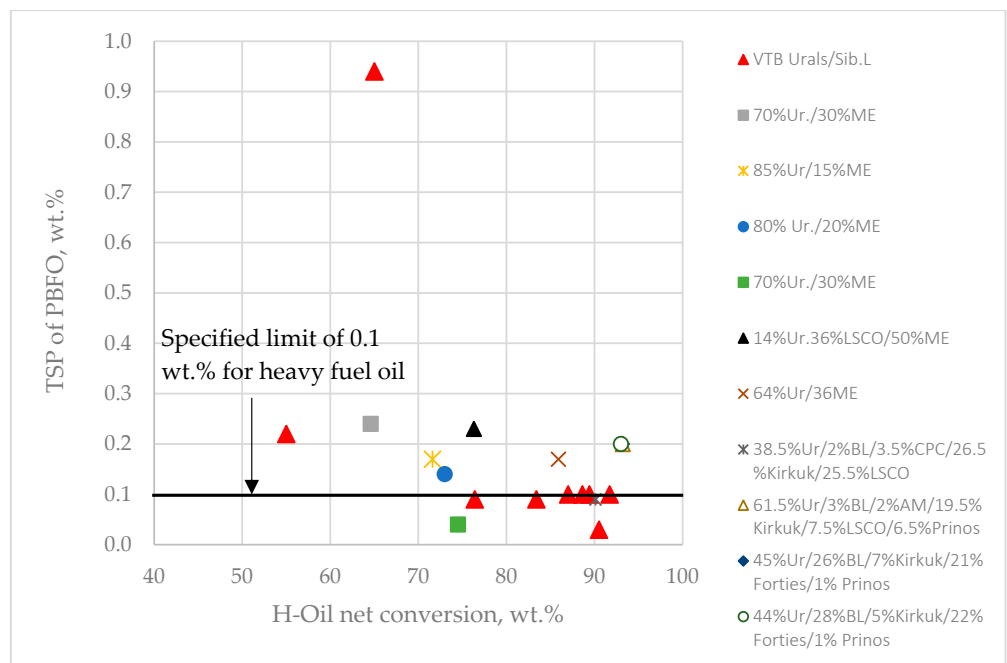


Figure 2. Total sediment potential of the partially blended fuel oil produced from H-Oil VTB and FCC HCO (typical blend 70% VTB/30% HCO) for the cases shown in Figure 1.

3.2. Density of the Blends of H-Oil VTB Produced from the Three Studied Crude Mixtures with the Cutter Stocks FCC LCO, HCO, SLO, and FCCPT Diesel

Table 6 presents data of densities (ρ) of the mixtures from the three studied H-Oil VTBs with the cutter stocks FCC LCO, HCO, SLO, and FCCPT diesel.

The data of $\Delta\rho$, which is a difference between measured blend density and estimated blend density assuming no excess volume of mixing [48], showed both negative and positive deviations much bigger than the repeatability of the used apparatus: Anton Paar DMA 4100 ± 0.01 kg/m³. This finding implies that the assumption of no excess volume of mixing is not valid for the study in this work on heavy oil blends.

The data in Table 6 show that the specified maximum limit of density of 1025 kg/m³ can be met if the cutter stocks are FCC LCO and FCCPT diesel. The use of FCC HCO and SLO as cutter stocks leads to production of fuel oil with higher than 1025 kg/m³ density.

Table 6. Densities ρ , Molar Excess Volumes V^E , Relative Changes in Volume ΔV , for the studied blends of H-Oil VTBs and the cutter stocks FCC LCO, HCO, SLO, and FCCPT diesel.

Mass %	χ_1	ϕ_1	ρ kg/m ³	$\Delta\rho$ kg/m ³	V^E cm ³ /mol	ΔV	χ_1	ϕ_1	ρ kg/m ³	$\Delta\rho$ kg/m ³	V^E cm ³ /mol	ΔV
LCO (1) + VTB (60% Urals/40% LSCO) (2)						HCO (1) + VTB (60% Urals/40% LSCO) (2)						
30	0.637	0.320	994.0	−2.9	1.027	0.0029	0.560	0.300	1.0278	−1.1	0.435	0.0079
40	0.732	0.422	0.9892	1.7	−0.478	−0.0017	0.664	0.400	1.028.9	−1.1	0.353	0.0069
50	0.804	0.523	0.9800	1.6	−0.414	−0.0016	0.748	0.500	1.030.2	−0.8	0.225	0.0056
SLO (1) + VTB (60% Urals/40% LSCO) (2)						FCCPT Diesel (1) + VTB (60% Urals/40% LSCO) (2)						
30	0.492	0.283	1.047.3	−3.0	1.284	0.0022	0.516	0.332	974.9	−4.0	2.065	0.0033
40	0.601	0.381	1.055.1	−4.0	1.390	0.0024	0.624	0.436	967.3	3.0	−1.255	−0.0023
50	0.693	0.480	1.058.7	−9.0	3.051	0.0054	0.713	0.537	954.8	5.0	−1.922	−0.0034
LCO (1) + VTB (63% Urals/31% LSCO/6% BH) (2)						HCO (1) + VTB (63% Urals/31% LSCO/6% BH) (2)						
20	0.506	0.217	1.017	3.0	−4.256	−0.0029	0.426	0.200	1.034.2	−2.0	−2.841	0.0017
30	0.637	0.322	1.008.5	5.0	−3.971	−0.0050	0.560	0.300	1.034.6	−1.0	−2.248	0.0013
40	0.732	0.425	1.000.3	7.0	−3.816	−0.0072	0.664	0.400	1.035.1	−1.0	−1.820	0.0009
50	0.804	0.526	991.8	9.0	−3.586	−0.0090	0.748	0.500	1.035.5	0.0	−1.445	0.0005
SLO (1) + VTB (63% Urals/31% LSCO/6% BH) (2)						FCCPT Diesel (1) + VTB (63% Urals/31% LSCO/6% BH) (2)						
20	0.361	0.189	1.047.8	−2.0	−2.844	0.0020	0.383	0.226	999.5	−2.0	−2.697	0.0018
30	0.492	0.285	1.053.4	−4.0	−1.392	0.0031	0.516	0.334	987.8	2.0	−4.112	−0.0020
40	0.601	0.383	1.060.1	−5.0	−0.591	0.0034	0.624	0.438	975.3	6.0	−4.799	−0.0043
50	0.693	0.482	1.067.2	−5.0	−0.024	0.0034	0.713	0.539	962.9	9.0	−5.287	−0.0062
LCO (1) + VTB (72.5% Urals/14.1% LSCO/13.4% BH) (2)						HCO (1) + VTB (72.5% Urals/14.1% LSCO/13.4% BH) (2)						
30	0.637	0.324	1.015.4	5.0	−6.300	−0.0047	0.560	0.302	1.043.8	0.0	−5.822	−0.0002
40	0.732	0.427	1.006.6	7.0	−5.678	−0.0074	0.664	0.402	1.043.4	1.0	−4.688	−0.0008
50	0.804	0.528	995.7	8.0	−4.618	−0.0079	0.748	0.503	1.042.7	1.0	−3.685	−0.0012
SLO (1) + VTB (72.5% Urals/14.1% LSCO/13.4% BH) (2)						FCCPT Diesel (1) + VTB (72.5% Urals/14.1% LSCO/13.4% BH) (2)						
30	0.492	0.287	1.064.8	−1.0	−6.312	0.0006	0.516	0.337	981.8	−10.0	−1.259	0.0084
40	0.601	0.386	1.070.3	−2.0	−4.576	0.0012	0.624	0.441	968.7	−7.0	−1.880	0.0050
50	0.693	0.485	1.075.6	−3.0	−3.015	0.0018	0.713	0.542	962.4	3.0	−5.081	−0.0025

Note: χ_1 = molar fraction of the cutter stock; ϕ_1 = volume fraction of the cutter stock; ρ = measured density of the mixture H-Oil VTB/cutter stock; $\Delta\rho = \rho_{\text{measured}} - \rho_{\text{regular}}$;

$$\rho_{\text{regular}} = \frac{100}{\frac{\text{wt.\%}_{\text{VTB}}}{\rho_{\text{VTB}}} + \frac{\text{wt.\%}_{\text{dil}}}{\rho_{\text{dil}}}}$$

3.3. Sediment Content in the Blends of H-Oil VTB Produced from the Three Studied Crude Mixtures with the Cutter Stocks FCC LCO, HCO, SLO, and FCCPT Diesel

Figure 3 shows diagrams of the effect of addition of the cutter stocks FCC HCO, LCO, SLO, and FCCPT diesel to the three studied H-Oil VTB samples on their sediment content. These data indicate that the three studied H-Oil VTBs exhibit different behavior concerning sediment formation in their blends with the investigated cutter stocks. The H-Oil VTB obtained from the crude blend 60% Urals/40% LSCO demonstrates a very low sediment formation when it is blended with the FCC HCO. However, the FCC LCO and SLO added to this H-Oil VTB sample do not allow attainment of the specification maximum limit of 0.1 wt.% TSE. In contrast, the H-Oil VTB obtained from the crude blend 72.5% Urals/14.1% LSCO/13.4% BH exhibits the highest sediment formation with the FCC HCO among the other H-Oil VTBs. The FCC LCO seems to be the best diluent for this particular H-Oil VTB. The H-Oil VTB obtained from the crude blend 63% Urals/31% LSCO/6% BH displays the lowest sediment formation with the FCC HCO, followed by the FCC SLO. The most depressing effect of LCO on sediment formation in the H-Oil VTB obtained from the crude blend 72.5% Urals/14.1% LSCO/13.4% BH is in line with the report of Tirado and Ancheyta [19], whereas the most depressing effect of HCO on sediment formation in the H-Oil VTBs obtained from the crude blends 60% Urals/40% LSCO and 63% Urals/31% LSCO/6% BH is in line with the report of Marafi et al. [18]. These results indicate that the sediment formation is a very delicate matter and even the ratio of the same crudes is changed which may have a substantial effect on the rate of sediment formation. For example, the processing of Basrah Heavy crude oil in the amount of 6% in the crude oil blend that contains Urals and Siberian Light crude oils appears to have an improvement effect on the H-Oil VTB sediment solvation in the FCC SLO that is not observed with the other two studied H-Oil VTB samples. The FCCPT diesel as observed from Figure 3d seems to play the role of anti-solvent that increases sedimentation in all studied H-Oil VTBs.

It is worth noting that the sediment content in the blends H-Oil VTB/cutter stock does not exhibit the typical trend of reduction with aromatic cutter stock content enhancement observed in our earlier study [21]. This implies that the increased high aromatic FCC gas oil content does not contribute to sediment dissolution in the studied H-Oil VTBs and is an illustration of how complicated the matter of sediment formation in the hydrocracked residual oils is. The increase of the low aromatic FCCPT diesel content also shows no augmenting effect on the sediment content in the studied H-Oil VTB-FCCPT diesel blends.

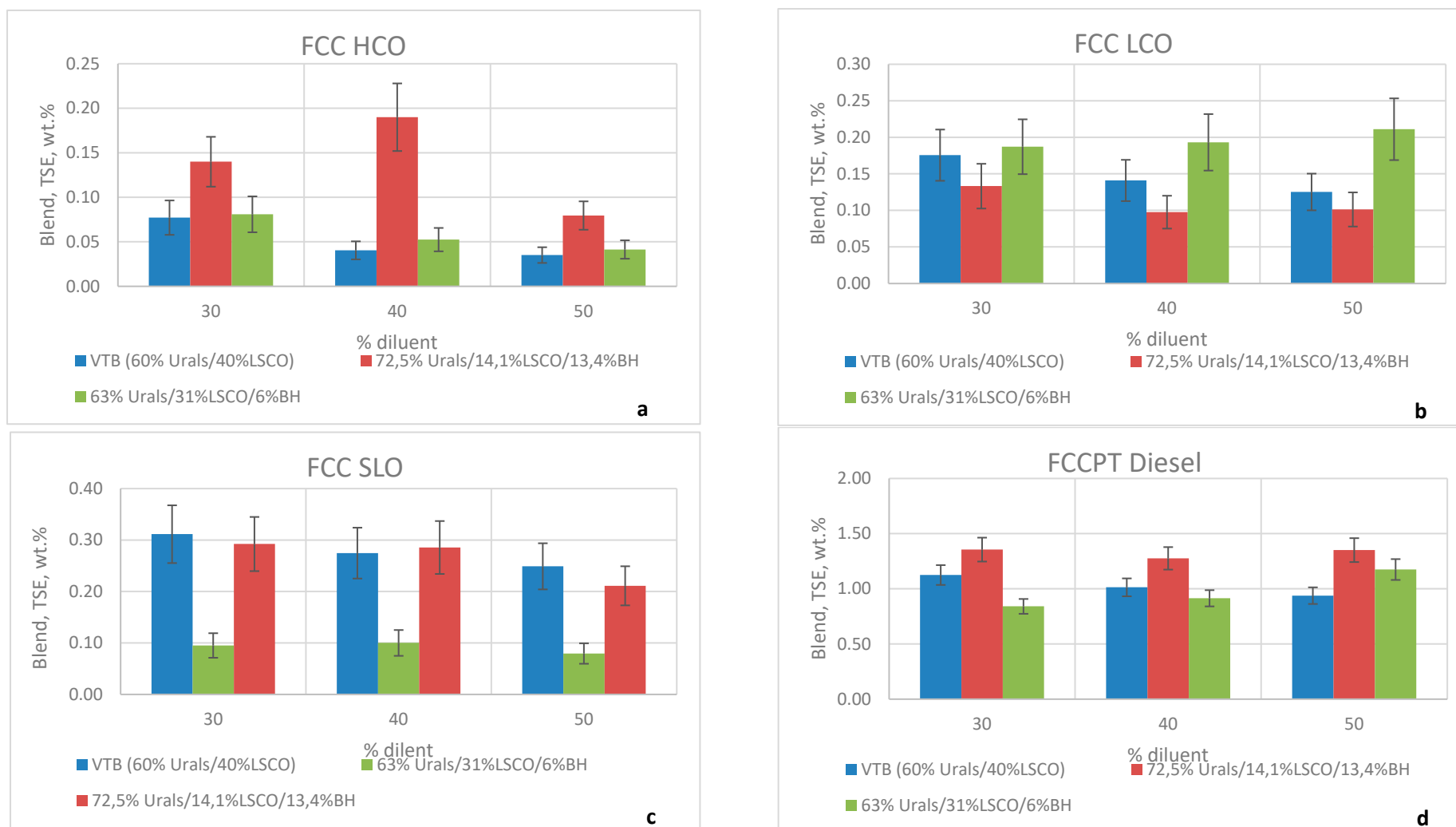


Figure 3. Effect of adding of FCC HCO (a); FCC LCO (b); FCC SLO (c); and FCCPT Diesel (d) to the three studied H-Oil VTBs on their total sediment existent (TSE) content.

3.4. Viscosity Variation in the Blends of H-Oil VTB Produced from the Three Studied Crude Mixtures with Alteration of the Content of the Cutter Stocks FCC LCO, HCO, SLO, and FCCPT Diesel in the Mixtures

Figure 4 shows graphs of dependence of viscosity of the blends H-Oil VTB/cutter stocks for the three studied H-Oil VTBs, and four investigated cutter stocks. These data show that the blend viscosity dependence can be described as an exponential function of cutter stock content. Expectedly, the highest viscosity H-Oil VTB sample (72.5% Urals/14.1% LSCO/13.4% BH) demonstrated the highest viscosity of the blends H-Oil VTB/cutter stocks. The amount of different cutter stocks needed to add to the three studied H-Oil VTBs to achieve the maximum viscosity limit specified for heavy fuel oil of 110 mm²/s is summarized in Table 7. The data in Table 7 logically indicate that the highest viscosity H-Oil VTB sample (72.5% Urals/14.1% LSCO/13.4% BH) needs the highest amount of cutter stock to meet the required for heavy fuel oil specification of 110 mm²/s. These data also show that the highest viscosity cutter stock FCC SLO demands the highest amount of addition to the H-Oil VTBs to attain the heavy fuel oil specification of 110 mm²/s.

Another case of H-Oil VTB obtained in the H-Oil hydrocracker during processing vacuum residue blend derived from the crude oil blend 78% Urals/2.5% LSCO/19.5% Kirkuk blend was also investigated in this research. The dependence of viscosity of this particular H-Oil VTB on temperature and on the content of FCC HCO, whose viscosity at 40, 60, and 80 °C was 8.82, 4.83, and 2.71 respectively, is presented in Figure 5. It is evident from the data in Figure 5 that the H-Oil VTB viscosity depends exponentially on both temperature and the content of diluent.

Properties of the Kirkuk crude oil and the obtained thereof vacuum residue were additionally included in the data of Tables 1 and 2. The data in Tables 1 and 2 were used to estimate the amount of the vacuum residues coming from each individual crude in the vacuum residue blend processed in the H-Oil hydrocracker, and also to calculate the viscosity of the vacuum residue blend using Equations (4)–(6) discussed in our earlier research [34].

$$\text{VR Blend Viscosity} = 10^{10 \left(\frac{41.10743 - \text{VBI blend}}{49.08258} \right)} - 0.8 \quad (4)$$

$$\text{VBI blend} = \sum_i^n x_i \text{VBI}_i \quad (5)$$

where

VR Blend Viscosity—kinematic viscosity of the VR blend at 80 °C, mm²/s;

VBI blend viscosity blending index of the VR blend;

x_i —volume part of individual VR in the blend;

n —number of individual VRs in the blend (in our case $n = 4$)

VBI_i —viscosity blending index of individual VR. It is calculated by the expression:

$$\text{VBI}_i = 41.10743 - 49.08258 \times \log \log(\text{CST}_i + 0.8) \quad (6)$$

where

CST_i = kinematic viscosity of individual oil at 800 °C, mm²/s.

Figure 6 depicts a graph of dependence of the H-Oil VTB specific viscosity on the viscosity of the vacuum residue blend estimated by the use of Equations (4)–(6) that feeds the H-Oil VR hydrocracker. It is clear from these data that the H-Oil VTB viscosity is linearly dependent on the viscosity of the vacuum residue processed in the H-Oil hydrocracker.

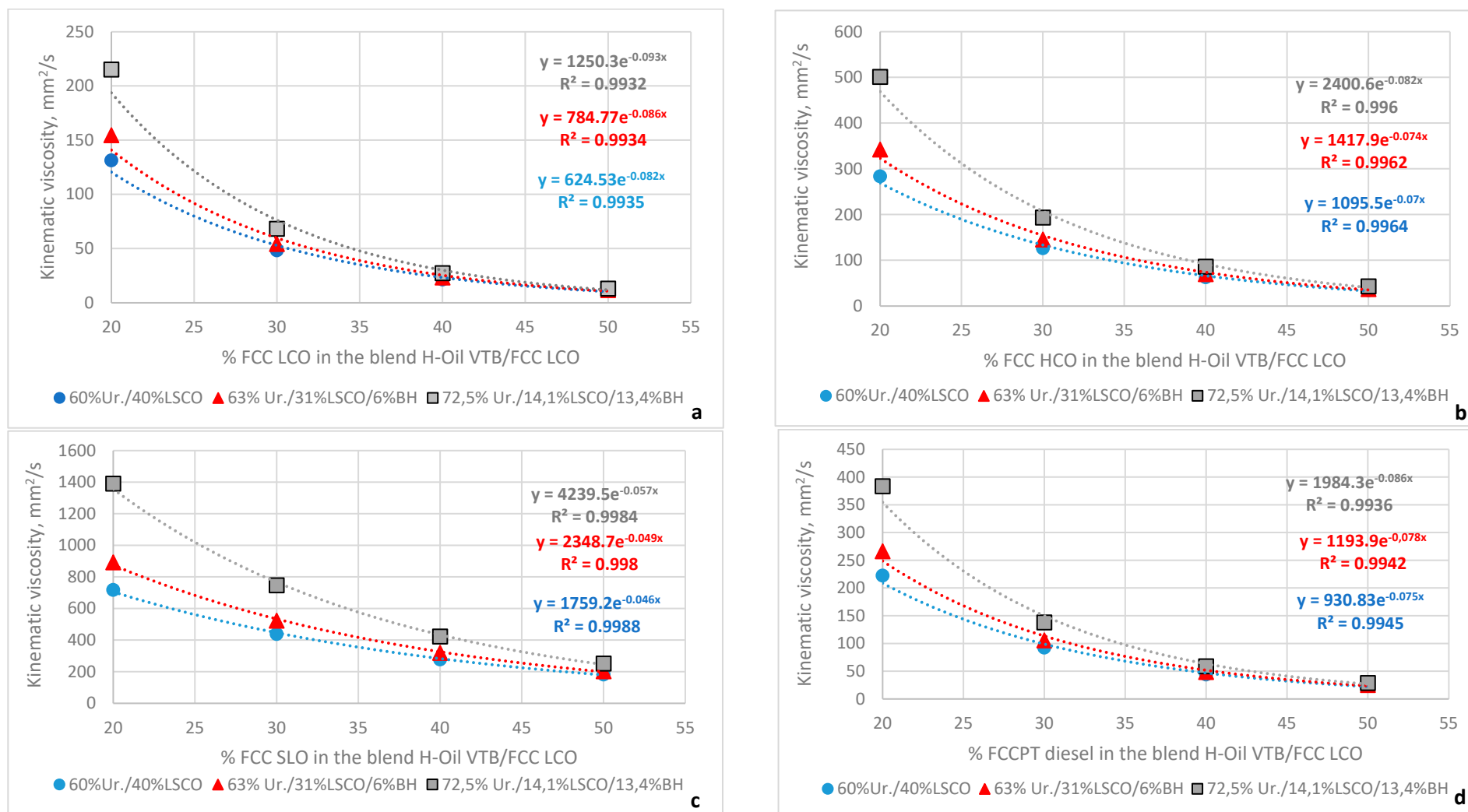


Figure 4. Effect of adding of FCC LCO (a); FCC HCO (b); FCC SLO (c); and FCCPT Diesel (d) to the three studied H-Oil VTBs on their viscosities.

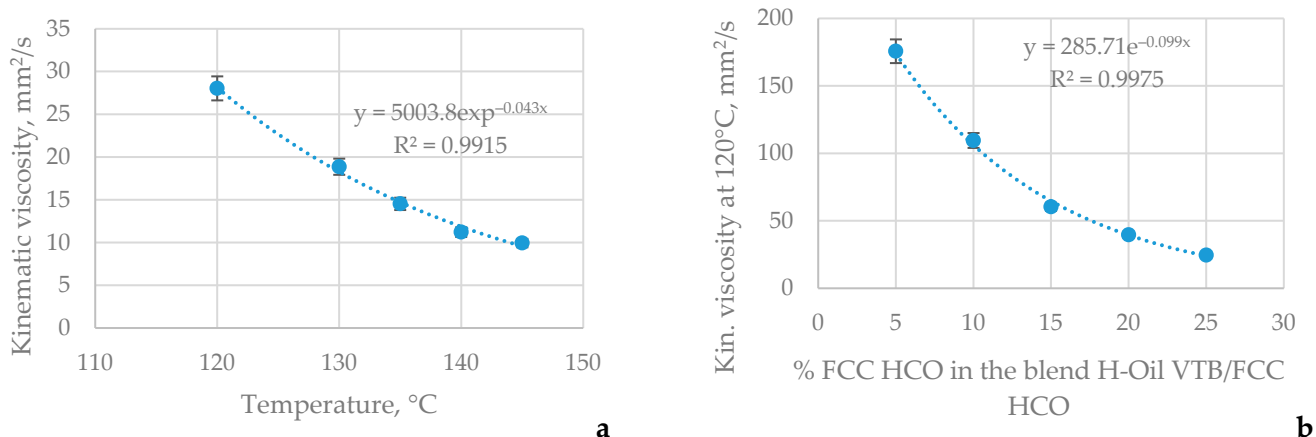


Figure 5. Dependence of H-Oil VTB (78% Urals/2.5% LSCO/19.5% Kirkuk) on temperature (a), and on the content of FCC HCO in the blend H-Oil VTB/FCC HCO (b).

Table 7. Required content of cutter stocks to reach the specified maximum viscosity of 110 mm²/s according to the fuel oil specification in the blends of the three studied H-Oil VTBs with the cutter stocks FCC LCO, HCO, SLO, and FCCPT diesel.

Amount of Cutter Stocks in Percent of the Blend H-Oil VTB/Cutter Stock Needed to Achieve Blend Viscosity of 110 mm ² s			
Cutter Stock	H-Oil VTB 60% Urals/40% LSCO	H-Oil VTB 63% Urals/31% LSCO/6% BH	H-Oil VTB 72.5% Urals/14.1% LSCO/13.4% BH
LCO	21.2	22.8	26.1
HCO	32.8	34.5	37.6
FCCPT	28.5	30.6	33.6
SLO	60.3	62.5	64.1

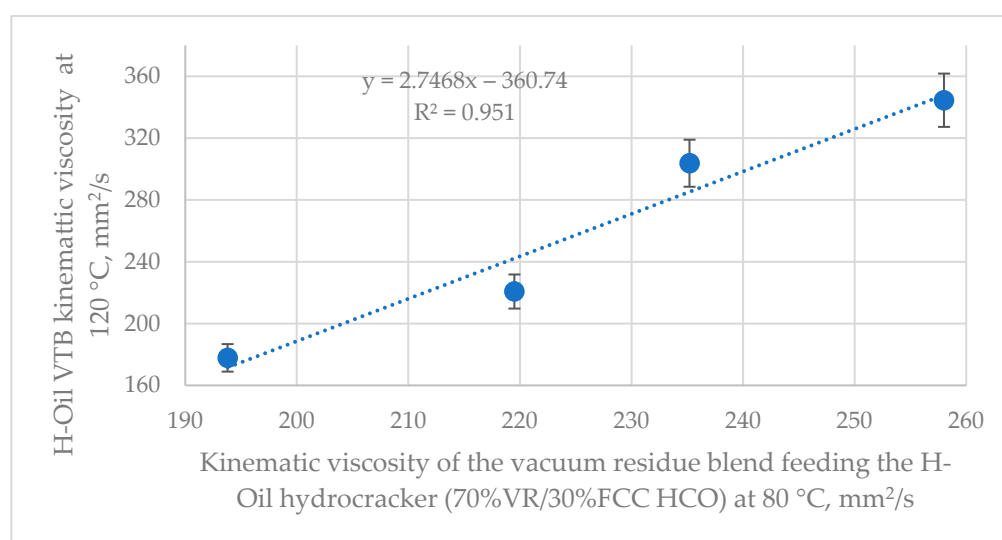


Figure 6. Relationship between kinematic viscosity of the LNB H-Oil VR feedstock (70% VR blended with 30% FCC HCO) and the H-Oil VTB specific viscosity.

4. Discussion

4.1. Variation of the Molar Excess Volume of the Blends of H-Oil VTBs with the Cutter Stocks

The data in Table 6 indicate that the mixing of the three H-Oil VTBs with the cutter stocks is associated with deviation from regular solution behavior. The excess molar volume of the blends of H-Oil VTB with the cutter stocks indicates specific interactions between the mixing oils. These interactions can be stronger or weaker than those existing between the molecules of the pure individual H-Oil VTB and cutter stocks thus leading to deviations in the regular solution behavior. The sign on the value of the excess molar volume, therefore, shows the magnitude of deviation from ideality and the strength of the interaction between the H-Oil VTB and cutter stocks relative to the interactions of the molecules of the individual oils before mixing. The positive excess molar volume indicates volume expansion on mixing and thus repulsive interaction of mixing H-Oil VTB and cutter stocks, or weaker interactions than the interactions of the pure individual oils. On the other hand, negative excess molar volume shows stronger interactions of mixed molecules than individual molecules before mixing. Figure 7 shows how the molar excess volume varies with the mole % alteration of the cutter stocks in the blends. It is evident from these data that the H-Oil VTB (60% Urals/40% LSCO) with the cutter stocks FCC LCO and HCO exhibits molar excess volume very close to zero suggesting that the molecules of this particular H-Oil VTB and those of the cutter stocks FCC LCO and HCO have interactions very close to each other. On the other hand, the H-Oil VTBs (63% Urals/31% LSCO/6% BH) and (72.5% Urals/14.1% LSCO/13.4% BH) demonstrate a higher magnitude of negative molar excess volume. This suggests that the interactions between the H-Oil VTB molecules with the molecules of the FCC LCO and HCO are featured by stronger attractive forces than between the H-Oil VTB molecules themselves. This can explain the reduction of the molar excess volume for the blends of the H-Oil VTBs from the crude blends containing the crude oil Basrah Heavy with the high aromatic FCC gas oils. The increase of the content of the Basrah Heavy in the crude blend obviously leads to enhancement of the intermolecular forces of attraction between the molecules of H-Oil VTB with those of the FCC gas oils. With the FCC SLO, the H-Oil VTB (60% Urals/40% LSCO) demonstrates positive values of the molar excess volume suggesting the presence of repulsive interaction between the molecules of this particular H-Oil VTB with the molecules of the FCC SLO. It is interesting to note here that with the blends of H-Oil VTBs with the lower aromatic FCCPT diesel, the attractive forces become stronger with the increase of mole% content of the FCCPT diesel in the blend, a phenomenon not observed with the H-Oil VTB blends with the high aromatic FCC gas oils. From repulsive forces between the molecules of the H-Oil VTB (60% Urals/40% LSCO) with the molecules of FCCPT diesel at 50 mole% of FCCPT diesel in the blend, they become attractive at 60 mole% and higher, which indicates how complicated the molecular interactions between the H-Oil VTBs and the cutter stocks are.

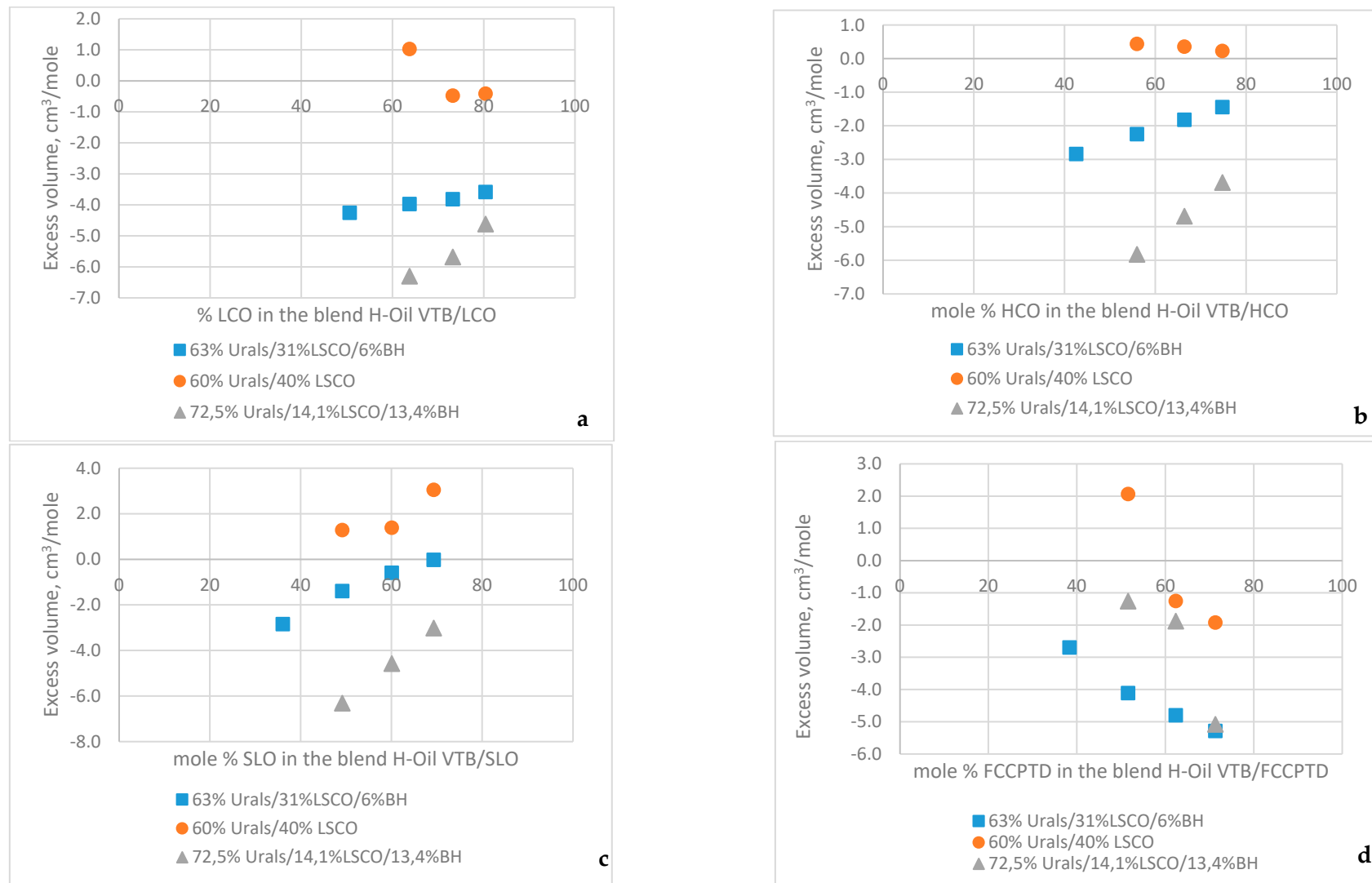


Figure 7. Molar excess volume for the mixtures H-Oil VTB/LCO (a), H-Oil VTB/HCO (b), H-Oil VTB/SLO (c), and H-Oil VTB/FCCPTD (d).

4.2. Sediment Content in the Blends of H-Oil VTBs with the Cutter Stocks

The sediment content measured by the hot filtration test is considered to represent the amount of precipitate formed mainly by the asphaltenes contained in the H-Oil VTB [13,17,20,49,50]. The size of the openings of the filter in the hot filtration test is 1.6 μm (1600 nm) which means that only the particles bigger than 1600 nm will remain on the filter. The smaller particles will go through the filter. Gray et al. [51] and Vargas et al. [52,53] report that asphaltene precipitation begins with instantaneous formation of particles of dimensions from 200 nm to 2 μm . Keeping in mind that the content of inorganic material in the H-Oil VTB/cutter stock blends measured by the ash content was lower than 0.03 wt.%, we could safely assume that the sediment content in the studied H-Oil VTB/cutter stock blends should be ascribed to the asphaltene precipitation phenomenon. The processing of blends of vacuum residual oils derived from different crude oils in the H-Oil hydrocracker has shown in our recent research that it has an impact on both the extent of hydrodemetalization and hydrodeasphaltization [47]. In this study, we have seen that the VTBs obtained from different VR blends demonstrate a different response to sediment formation when blending with the different cutter stocks (Figure 3). In order to search for any relation between the composition of the crude oil blend processed, the excess molar volume and the sediment content in the H-Oil VTB/cutter stock blends intercriteria analysis (ICrA) evaluation was performed. Tables 8 and 9 indicate μ , and ν values of ICrA evaluation of relations between the crude oil blend composition, sediment content, and the excess molar volume of the H-Oil VTB/cutter stock blends. Concerning the sediment content only, the LSCO has a strong negative statistically meaningful relation $\mu = 0.00$ only with the low aromatic FCCPT diesel cutter stock. This implies that the processing of VR from LSCO in the H-Oil hydrocracker makes the obtained H-Oil VTB form less sediments when blending with low aromatic cutter stocks. However, as observed from the data in Figure 3, the FCCPT diesel has made the highest sediment content in the blends H-Oil VTB/cutter stocks among all studied cutter stocks. This puts a great doubt on the possibility to attain sediment content of less than 0.1 wt.% even when VR from 100% LSCO is processed, and the obtained H-Oil VTB is mixed with the low aromatic FCCPT diesel. It is interesting to note here that the H-Oil VTB/FCC LCO blend sediment content has strong negative statistically meaningful relations $\mu = 0.00$ with the sediment content of the blends H-Oil VTB/FCC HCO, SLO, and FCCPT diesel. This finding may suggest that the components forming the sediments which are soluble in LCO seem to be not or less soluble in FCC HCO, SLO, and FCCPT diesel. From the available data, it is difficult to deduce which crude oil may contribute to the appearance of this phenomenon.

Regarding the effect of the crude oil blend composition on the molar excess volume, as a measure of the molecular interactions, one can see from the data in Tables 8 and 9 that Urals and Basrah Heavy crude oil have strong negative statistically meaningful relations $\mu = 0.00$ with the molar excess volume of the mixtures H-Oil VTB/FCC, LCO, HCO, and SLO, while the LSCO has strong positive statistically meaningful relations $\mu = 1.00$ with the same cutter stocks. It could be concluded from here that both Urals and Basrah Heavy increase the negative value of the molar excess volume of the H-Oil VTB mixtures with FCC LCO, HCO, and SLO, which is enhancing the attractive forces between the molecules of H-Oil VTBs and those of the FCC gas oils.

Table 8. μ values of ICRA evaluation of relations between the crude oil blend composition, sediment content, and the excess molar volume of the H-Oil VTB/cutter stock blends.

Nu	Urals, %	LSCO, %	BH, %	LCO (TSE)	HCO (TSE)	SLO (TSE)	FCCPTD (TSE)	LCO (VE)	HCO (VE)	SLO (VE)	FCCPTD (VE)
Urals, %	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
LSCO, %	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
BH, %	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
LCO (TSE)	0.33	0.67	0.33	1.00	0.00	0.00	0.00	0.67	0.67	0.67	0.33
HCO (TSE)	0.67	0.33	0.67	0.00	1.00	0.67	0.67	0.33	0.33	0.33	0.67
SLO (TSE)	0.33	0.33	0.33	0.00	0.67	1.00	0.33	0.33	0.33	0.33	0.67
FCCPTD (TSE)	0.67	0.00	0.67	0.00	0.67	0.33	1.00	0.00	0.00	0.00	0.33
LCO (VE)	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
HCO (VE)	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
SLO (VE)	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
FCCPTD (VE)	0.33	0.67	0.33	0.33	0.67	0.67	0.33	0.67	0.67	0.67	1.00

Note: green color means statistically meaningful positive relation; red color implies statistically meaningful negative relation. The intensity of the color designates the strength of the relation. The higher the color intensity, the higher the strength of the relation. Yellow color denotes dissonance.

Table 9. ν values of ICRA evaluation of relations between the crude oil blend composition, sediment content, and the excess molar volume of the H-Oil VTB/cutter stock blends.

Nu	Urals, %	LSCO, %	BH, %	LCO (TSE)	HCO (TSE)	SLO (TSE)	FCCPTD (TSE)	LCO (VE)	HCO (VE)	SLO (VE)	FCCPTD (VE)
Urals, %	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
LSCO, %	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
BH, %	0.00	1.00	0.00	0.67	0.33	0.33	0.00	1.00	1.00	1.00	0.67
LCO (TSE)	0.67	0.33	0.67	1.00	0.00	0.67	0.67	0.33	0.33	0.33	0.67
HCO (TSE)	0.33	0.67	0.33	0.00	1.00	0.00	0.00	0.67	0.67	0.67	0.33
SLO (TSE)	0.33	0.33	0.33	0.67	0.00	0.00	0.00	0.33	0.33	0.33	0.00
FCCPTD (TSE)	0.00	0.67	0.00	0.67	0.00	0.00	0.00	0.67	0.67	0.67	0.33
LCO (VE)	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
HCO (VE)	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
SLO (VE)	1.00	0.00	1.00	0.33	0.67	0.33	0.67	0.00	0.00	0.00	0.33
FCCPTD (VE)	0.67	0.33	0.67	0.67	0.33	0.00	0.33	0.33	0.33	0.33	0.00

Note: green color means statistically meaningful positive relation; red color implies statistically meaningful negative relation. The intensity of the color designates the strength of the relation. The higher the color intensity, the higher the strength of the relation. Yellow color denotes dissonance.

Whereas the LSCO augments the positive value of the molar excess volume of the H-Oil VTB mixtures with FCC LCO, HCO, and SLO, this suggests an increase of the repulsive forces between the molecules of H-Oil VTBs and those of the FCC gas oils. The three studied crude oils exhibit lack of meaningful relations with the molar excess volume of the blends H-Oil VTBs/FCCPT diesel. Therefore, it is difficult to determine which crude oil contributes to attractive or repulsive forces between the molecules of the H-Oil VTBs and the molecules of FCCPT diesel.

The data in Tables 8 and 9 show the presence of strong negative statistically meaningful relations $\mu = 0.00$ between the molar excess volume of the blends H-Oil VTB/FCC gas oils and the sediment content of the mixtures H-Oil VTBs/FCCPT diesel. This finding suggests that the stronger the molecular attractive interactions between H-Oil VTBs and the aromatic FCC gas oils, the higher the tendency these H-Oil VTBs to make more sediments when mixing with FCCPT diesel.

4.3. Viscosity Dependence of H-Oil VTB on the Viscosity of the Processed Vacuum Residue Blend in the H-Oil Hydrocracker and Prediction of Viscosity of the Blends H-Oil VTB/Cutter Stocks

Similar to the vacuum residue visbreaking where the visbreaker residue was found to linearly depend on the viscosity of the vacuum residue blend reported in our earlier research [34], the vacuum residue ebullated bed H-Oil hydrocracking demonstrated the same linear relationship (Figure 6). The data in Figure 6 suggest that the higher the viscosity of the VR hydrocracker feed, the higher the viscosity of the hydrocracked unconverted vacuum residue. It is worth noting here that the four points in Figure 6 lie on the same line, although the difference in conversion level between the four cases shown in Table 3 is 12 wt.%. This implies that a difference in conversion level of 12 wt.% has no impact on viscosity of the H-Oil VTB. Equations (4)–(6) used to estimate the viscosity of the mixed H-Oil VR feed were also employed to predict the viscosity of blends of the additionally studied H-Oil VTB obtained from the crude oil blend (78% Urals/2.5% LSCO/19.5% Kirkuk) with the FCC HCO. Figure 8 shows a graph of agreement between estimated by Equations (4)–(6) and measured viscosity of the blends H-Oil VTB (78% Urals/2.5% LSCO/19.5% Kirkuk)/FCC HCO. These data indubitably show the good prediction ability of Equations (4)–(6) with an average absolute % deviation (%AAD) of 8.8%.

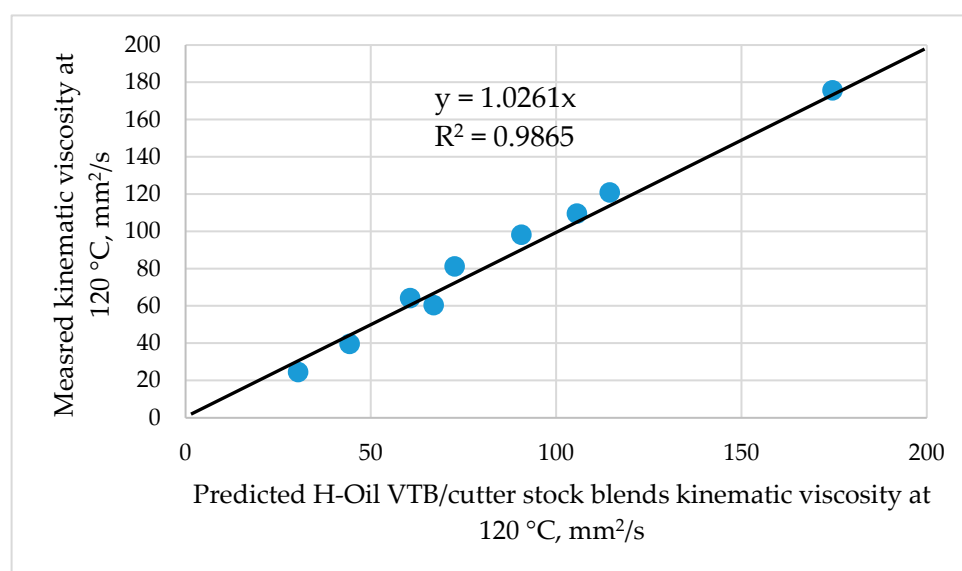


Figure 8. Agreement between estimated by Equations (3)–(5) and measured viscosity of the blends H-Oil VTB (78% Urals/2.5% LSCO/19.5% Kirkuk)/FCC HCO.

This research confirmed our earlier results reported in [43,54] showing the good prediction ability of Equations (4)–(6) to estimate viscosity of oil blends which have different

properties. By the use of these equations, one can predict viscosity of the VR ebullated bed hydrocracking feed, and consequently the H-Oil VTB viscosity by the equation embedded in Figure 6, and the required amount of cutter stocks to meet the heavy fuel oil specification for viscosity.

5. Conclusions

Crude oil blends of Urals, Siberian Light (LSCO), and Basrah Heavy (BH) were processed in LNB refinery and derived thereof vacuum residue mixtures were hydrocracked in the H-Oil ebullated bed hydrocracker. The obtained H-Oil hydrocracked unconverted vacuum residues (VTBs) were blended with the high aromatic FCC gas oils LCO, HCO, and SLO, and with the low aromatic FCCPT diesel. The densities of the blends H-Oil VTB/cutter stocks were found to deviate from the regular solution behavior demonstrating both attractive and repulsive intermolecular forces between the molecules of the H-Oil VTBs and the ones from the cutter stocks. The application of intercriteria analysis revealed that both Urals and Basrah Heavy crude oils enhance the attractive forces between the molecules of H-Oil VTBs and those of the FCC gas oils, while the LSCO increases the repulsive forces between the molecules of H-Oil VTBs and those of the FCC gas oils. The three studied crude oils were difficult to define which one contributes to attractive or repulsive forces between the molecules of the H-Oil VTBs and the molecules of FCCPT diesel. The sediment content in the blends H-Oil VTB/cutter stock did not exhibit the typical trend of reduction with aromatic cutter stock content enhancement observed in the other studies illustrating how complicated the matter of sediment formation in the hydrocracked residual oils is. The increase of the low aromatic FCCPT diesel content also showed no augmenting effect on the sediment content in the studied H-Oil VTB-FCCPT diesel blends. The application of ICRA evaluation did not disclose any statistically meaningful relation between the crude blend composition and the sediments in the blends H-Oil VTB/FCC gas oils. Solely the LSCO showed depressing effect on sediment content of the blends H-Oil VTBs/FCCPT diesel. However, the FCCPT diesel has made the highest sediment content in the blends H-Oil VTB/cutter stocks among all studied cutter stocks suggesting that even at processing VR from 100% LSCO, the blends of H-Oil VTB with the FCCPT diesel would report much higher than the required specification of maximum 0.1 wt.% sediments.

It was found that the viscosity of the H-Oil VTB obtained during hydrocracking of straight run vacuum residue blend linearly depended on the viscosity of the H-Oil VR feed blend. The applied equations to predict viscosity of blends containing straight run and hydrocracked vacuum residues and cutter stocks proved their good prediction ability.

The performed study has indicated that viscosity of the H-Oil VTB obtained from hydrocracking of vacuum residues derived from different crudes and their mixtures with cutter stocks can be predicted from information about viscosity of the straight run vacuum residues and those of the cutter stocks. However, the sediment formation rate in the blends H-Oil VTB cutter stocks did not show any possibility for prediction. Indeed, the high aromatic FCC gas oils demonstrated much lower sediments than the low aromatic FCCPT diesel. Nevertheless, the question regarding why the different FCC gas oils exhibited different sediment depressing effect for the H-Oil VTBs obtained from the different crude oil blends remains unclear. Given that residual oils are extremely complex mixtures of components, a significant number of additional experimental tests are needed to shed more light on this issue.

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Nomenclature

Aro	Content of aromatic compounds, wt.%
Asp	Content of asphaltenes, wt.%
ATB	Atmospheric tower bottom product
BH	Basrah heavy crude oil
C ₅ -asp	Content of n-pentane asphaltenes, wt.%
C ₇ -asp	Content of n-heptane asphaltenes, wt.%
EBVRHC	Ebullated vacuum residue hydrocracking
FBP	Final boiling point, °C
FCC	Fluid catalytic cracking
FCCPT	Fluid catalytic cracking pretreater
HAGO	Heavy atmospheric gas oil
HCO	Heavy cycle oil
HTSD	High-temperature simulated distillation
HVGO	Heavy vacuum gas oil
IBP	Initial boiling point, °C
Kw	Watson characterization factor
LCO	Light cycle oil
LSCO	Light Siberian crude oil
LHSV	Liquid hourly space velocity, h ⁻¹
LNB	LUKOIL Neftohim Burgas
LVGO	Light vacuum gas oil
MW	Molar weight, g/mol
PBFO	Partially blended fuel oil
Res	Content of resins, wt.%
SAR-AD	Patented method for separation of SAR (saturates, aromatics, and resins) combined with Asphaltene Determinator (AD)
SARA	Saturates, aromatics, and resins
SLO	Slurry oil
TBP	True boiling point, °C
TSE	Total sediment existent content, wt.%
TSP	Total sediment potential content, wt.%
V ^E	Excess molar volume, m ³
VGO	Vacuum gas oil
VTB	Vacuum tower bottom product
VR	Vacuum residue
WABT	Weight average bed temperature, °C
ΔV	Relative changes in volume
χ ⁱ	Mole fraction of the individual component i, mol/mol
M _i	Molar mass of the individual component i, g/mol
V ^o _i	Molar volume of the individual component i, m ³ /mol
ρ _i	Density of the individual component i, g/m ³
m _i	Mass fraction of the individual component i
φ ₁	Volume fraction of the cutter stock.

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