UDC: 665.6.032.5:532.135; https://doi.org/10.37878/2708-0080/2026-2.08
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HEAVY CRUDE OIL RHEOLOGY: SOLVENT AND THERMAL IMPACT

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The aim of this work is to establish the relationship between the chemical composition of heavy crude oil and its rheological response to organic solvents of different nature, as well as to quantitatively assess the degree of viscosity reduction. Comprehensive analytical methods (XRF, FTIR, SARA, gas chromatography) revealed that the studied crude oil is characterized by a paraffinic–resinous matrix enriched with heteroatoms and metals, which determines its extremely poor flowability. It was experimentally proven that the addition of 15 vol.% xylene at 25 °C reduces the oil viscosity by more than 150 times (from 3.3 × 10^5 to 2.19 × 10^3 cP), whereas the use of naphtha provides only a 30-fold viscosity reduction. The combined application of a chemical reagent (xylene) and thermal treatment (up to 60°C) was shown to achieve a viscosity of approximately 4.1 × 10^2 cP, which is sufficient for efficient transportation.

The obtained results confirm the key role of solvent type in modifying the rheological properties of heavy crude oils and demonstrate the potential of the developed chemical-thermal methods for improving their transportability.

KEYWORDS: *Heavy crude oil, viscosity reduction, organic solvents, xylene, solvent naphtha, rheological properties, SARA analysis, FTIR spectroscopy, gas chromatography.*

РЕОЛОГИЯ ТЯЖЕЛОЙ НЕФТИ: ВЛИЯНИЕ РАСТВОРИТЕЛЕЙ И ТЕМПЕРАТУРНОГО ФАКТОРА

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Целью работы является установление взаимосвязи между химическим составом тяжелой нефти и её реологическим откликом на воздействие органических растворителей различной природы, а также количественная оценка степени снижения вязкости. Комплексными аналитическими методами (XRF, FTIR, SARA, газовая хроматография) установлено, что исследуемая нефть характеризуется парафино-смолистой матрицей с повышенным содержанием гетероатомов и металлов, что определяет её крайне низ-

кую текучесть. Экспериментально доказано, что добавление 15 об.% ксилола при 25 °C снижает вязкость нефти более чем в 150 раз (с 3,3 × 10^5 до 2,19 × 10^3 сП), в то время как использование нафты обеспечивает лишь 30-кратное снижение вязкости. Показано, что комбинированное применение химического реагента (ксилол) и термического воздействия (до 60 °C) позволяет достичь вязкости ~4,1 × 10^2 сП, что является достаточным для эффективной транспортировки.

Полученные результаты подтверждают ключевую роль типа растворителя в модификации реологических свойств тяжелых нефтей и демонстрируют перспективность разработанных химико-термических методов для улучшения их транспортабельности.

КЛЮЧЕВЫЕ СЛОВА: *тяжёлая нефть, снижение вязкости, органические растворители, ксилол, нафта, реологические свойства, SARA-анализ, ИК-спектроскопия, газовая хроматография.*

АУЫР МҰНАЙДЫҢ РЕОЛОГИЯСЫ: ЕРІТКІШТЕР МЕН ТЕМПЕРАТУРАЛЫҚ ФАКТОРДЫҢ ӘСЕРІ

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Жұмыстың мақсаты – ауыр мұнайдың химиялық құрамы мен әртүрлі табиғаттағы органикалық еріткіштердің әсеріне берілетін реологиялық реакциясы арасындағы өзара байланысты анықтау, сондай-ақ тұтқырлықтың азаю дәрежесін сандық бағалау.

Кешенді аналитикалық әдістерді (XRF, FTIR, SARA, газдық хроматография) қолдану арқылы зерттелетін мұнай парафин-смолалық матрицаға ие екені, гетероатомдар мен металдардың жоғары мөлшерімен сипатталатыны анықталды, бұл оның өте төмен ағымдылығын анықтайды. Эксперименталды түрде 25 °C-та 15 көлемді % ксилол қосу мұнайдың тұтқырлығын 150 еседен астам төмендететіндігі (3,3 × 10^5-тен 2,19 × 10^3 сП-ге дейін) дәлелденді, ал нафта қолдану тек 30 есе төмендетуді қамтамасыз етеді. Ксилолды химиялық реагент ретінде және термиялық әсерді (60 °C дейін) біріктіріп қолдану тұтқырлықты ~4,1 × 10^2 сП-ге дейін азайтуға мүмкіндік беретіні көрсетілді, бұл тиімді тасымалдауға жеткілікті.

Алынған нәтижелер ауыр мұнайдың реологиялық қасиеттерін модификациялауда еріткіш түрінің негізгі рөлін растайды және олардың тасымалдауға жарамдылығын жақсарту үшін әзірленген химиялық-термиялық әдістердің перспективалы екенін көрсетеді.

ТҮЙІН СӨЗДЕР: *ауыр мұнай, тұтқырлықты төмендету, органикалық еріткіштер, ксилол, нафта, реологиялық қасиеттер, SARA-талдау, ИҚ-спектроскопия, газдық хроматография.*

Introduction. The development of heavy crude oil resources is a key focus for countries with large high-viscosity hydrocarbon reserves, including Kazakhstan, where a significant share of oil consists of heavy, highly viscous crudes. These oils are characterized by low API gravity and high contents of resins, asphaltenes, and paraffins, leading to complex rheology and limited natural mobility [1,2]. Aggregation of these components forms structured systems that resist flow at low shear rates, reducing production and transport efficiency [2,3].

Studies on high-viscosity oils from western Kazakhstan confirm pronounced non-Newtonian behavior and strong dependence on external influences [3,4]. While thermal methods can reduce viscosity, they are energy-intensive and operationally complex, often impractical for surface transport and pipelines [6,7].

Chemical approaches offer an alternative by weakening intermolecular interactions and disrupting asphaltene–resin structures, thereby improving flowability [4,5]. However, systematic studies on chemical enhancement for Kazakhstan's heavy crudes remain limited [1,8].

The scientific novelty of this work consists in establishing the relationship between the physicochemical characteristics of a heavy crude oil and its rheological response to organic solvents. Using comprehensive compositional analysis (XRF, FTIR, SARA, GC), it is shown that the high viscosity is governed by a paraffinic-resinous matrix with high resin content rather than asphaltene aggregation. Based on this finding, it is quantitatively demonstrated that the disruption of these associative structures is achieved most effectively with an aromatic solvent (xylene), which provides a 150-fold viscosity reduction at 25 °C, whereas a paraffinic solvent (naphtha) yields only a 30-fold reduction. This work thus identifies the key compositional factors dictating solvent efficiency for heavy crude oils representative of Kazakhstan.

Materials and methods

Heavy crude oils typically behave as structured non-Newtonian fluids, so their flowability cannot be described by a single viscosity value. In wax-forming systems, rheological behavior depends on composition, thermal history, and shear history. Previous studies show that waxy oils can exhibit shear-dependent viscosity and yield-like behavior, with rheology changing significantly upon wax crystallization [9,10].

This behavior is often attributed to internal structures formed by high-molecular-weight components such as resins, asphaltenes, and long-chain hydrocarbons, which create spatial networks that resist deformation [11]. In rheological analysis, such effects are commonly described using parameters like apparent yield stress and shear-dependent viscosity. In modern terms, many complex fluids are classified as "yield-stress fluids," displaying characteristics between ideal solids and liquids [12,13].

Accordingly, in this study, viscosity values were determined under strictly controlled temperature and mixing conditions using a repeatable protocol designed to minimize the influence of uncontrolled thermal and shear histories.

Samples and chemicals:

To evaluate the influence of chemical treatment on oil rheology, organic solvents were introduced individually in separate experimental series to avoid additive interactions. Two solvents commonly used in petroleum practice for viscosity reduction were selected: xylene and solvent naphtha. The main physicochemical properties of xylene are presented in *Table 1*.

Table 1 - **Comparative physicochemical properties of xylene and solvent naphtha (D40 grade)**

Property	Xylene (mixed isomers)	Solvent naphtha (D40 grade)	Unit
Chemical name	Xylene (mixed isomers)	Solvent naphtha	-
CAS number	1330-20-7	64742-94-5	-
Molecular formula	C_8H_{10}	Mixture of hydrocarbons	-
Molecular weight	106.17	140-160	$g \cdot mol^{-1}$
Density (25 °C)	0.86	0.86-0.91	$g \cdot mL^{-1}$
Kinematic viscosity (40 °C)	< 0.74	< 1.2	$mm^2 \cdot s^{-1}$
Aromatic content	High (aromatic solvent)	< 0.1	%

Xylene is an aromatic hydrocarbon solvent composed mainly of ortho-, meta-, and para-xylene isomers. Its aromatic nature gives it strong affinity for asphaltene–resin structures, effectively disrupting intermolecular associations and reducing heavy crude oil viscosity [14].

Solvent naphtha is a petroleum-derived hydrocarbon solvent with a narrow boiling range and low viscosity, commonly used to dilute heavy crude oils and remove organic deposits [14].

While both solvents reduce viscosity, xylene provides stronger molecular-level disruption of associative structures, whereas solvent naphtha acts primarily through dilution but offers greater operational safety due to its higher flash point. All reagents were used without additional purification, and oil–solvent mixtures were prepared immediately before rheological measurements to ensure reproducibility.

Physicochemical characterization methods:

The original heavy crude oil from Permian reservoirs in East Kazakhstan was characterized to identify compositional factors affecting its flow properties. The analytical approach included elemental, molecular, and group-component analyses.

Elemental composition was determined using energy-dispersive X-ray fluorescence (XRF) spectrometry, providing data on sulfur content and trace elements typical of heavy crude oils. The method is non-destructive, suitable for viscous petroleum systems, and requires minimal sample preparation.

Molecular-structural characteristics were investigated using attenuated total reflectance Fourier-transform infrared spectroscopy (ATR-FTIR) to identify dominant functional groups and bonding environments, with attention to aliphatic chains, aromatic structures, and resin–asphaltene groups influencing heavy oil behavior [15,16]. Gas chromatography (GC) was also used to evaluate hydrocarbon distribution by volatility and distinguish lighter from heavier fractions [4].

Finally, SARA analysis determined the relative contents of saturates, aromatics, resins, and asphaltenes, providing a compositional basis for interpreting crude oil structure and flowability [5].

Mixing of reagents with crude oil:

Mixing of crude oil with chemical reagents was performed using an overhead LABSOL OS20-S laboratory stirrer with two flat stainless-steel impellers. The stirrer

operates at 50–2200 rpm with a nominal motor power of 60 W. To ensure homogeneity, the stirring speed was set to 200 rpm for 10 minutes.

Reagent concentrations were calculated on a volumetric basis relative to the crude oil at 5%, 10%, and 15%. All mixtures were prepared at a constant total volume, with the reagent proportion adjusted according to the selected dosage. This concentration range was chosen to identify conditions where viscosity reduction becomes pronounced without causing significant mixture instability under laboratory conditions. Mixing was conducted in sealed 250 mL cylindrical vessels to prevent solvent evaporation and maintain constant sample composition.

Thermostating:

After mixing, samples were thermostated at predetermined temperatures and held for 30 minutes to reach thermal equilibrium before viscosity measurements.

Viscosity was measured at 25, 30, 35, 40, 45, 50, 55, and 60 °C—a range covering typical heavy oil handling and transportation conditions, from ambient temperature to moderate heating used to improve flowability.

Viscosity measurement:

Kinematic viscosity was measured using a BGD 155/2S digital rotational viscometer (Biuged Precise Instruments, PRC). The instrument features a touchscreen display, interchangeable spindles No. 1–4, and measures viscosity from 12 to 6,000,000 cP at rotational speeds of 0.1–100 rpm. Dynamic viscosity is calculated based on the measured torque resistance. Instrument accuracy is ±1%, with repeatability of ±0.5%.

The viscometer was verified using calibration fluids prior to measurements to ensure reliability. Each measurement was performed in triplicate, and the average value was calculated. Sample volume was 100 mL. Measurements were conducted at the same temperatures used during thermostating, enabling direct assessment of the temperature dependence of viscosity and reagent effectiveness under consistent conditions.

Results and discussion

Compositional controls of high crude oil viscosity:

The compositional characteristics of the initial crude oil were analyzed using XRF, FTIR, SARA, and gas chromatography to identify factors governing its high viscosity and flow behavior. Single measurements were interpreted within the instrumental precision specified by the manufacturer. Given the qualitative and comparative nature of the analysis, the results are considered reliable within the stated accuracy limits.

To further elucidate the compositional factors responsible for the elevated viscosity, particular attention was given to elemental composition. Quantitative XRF analysis was performed to determine sulfur, heteroatoms, and trace metals associated with complex organic structures. The obtained elemental concentrations are presented in *Table 2*.

Table 2 - **Elemental composition of the crude oil sample**

Element	S	Cl	P	Ni	Fe	Ca	Sn	Hg	Zn	Cu	Mo	Co	As	Se
Concentration (ppm)	4728	521	414	134	103	79	19	18	15	9	8	8	4	3

XRF analysis revealed high sulfur content (4728 ppm, ~0.47 wt%) along with notable Ni (134 ppm) and Fe (103 ppm) concentrations, indicating enrichment in heteroatoms and metal-containing organic complexes (*Table 2*). Such composition promotes strong intermolecular interactions and limits the effectiveness of purely thermal viscosity reduction. The presence of chlorine and trace metals further reflects the crude oil's chemical complexity.

To identify the functional composition and structural features of the hydrocarbon matrix, FTIR spectroscopy was performed. This method identifies dominant chemical bonds and functional groups, and assesses the relative contributions of aliphatic and aromatic structures-key factors governing rheological behavior. The resulting FTIR spectrum is shown in *Figure 1*.

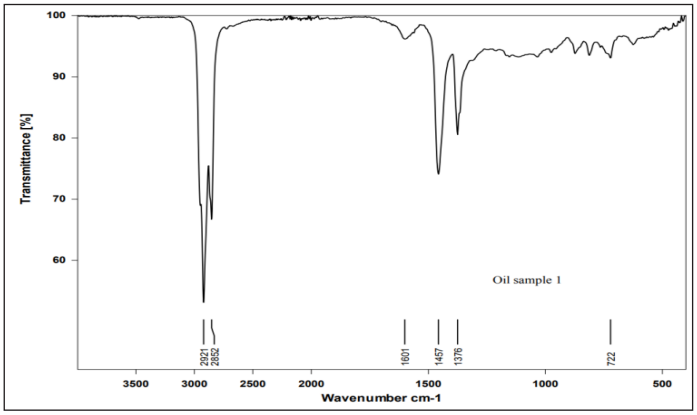

Figure 1 - **FTIR spectrum of the heavy crude oil sample**

For detailed spectral interpretation, characteristic absorption bands corresponding to the principal vibrational modes of hydrocarbon chains and substituent groups were identified and analyzed. The wavenumber positions, along with their intensity and bandwidth parameters, are summarized in *Table 3*, enabling qualitative spectral features to be correlated with quantitative indicators of functional group distribution.

Table 3 - **Characteristic absorption bands of the crude oil FTIR spectrum**

Wavenumber (cm^{-1})	Absolute intensity	Relative intensity	Band width	Threshold	Shoulder
2920.90	0.530	0.470	122.200	100.17	0
2852.28	0.667	0.091	25.042	18.73	0
1456.97	0.741	0.259	40.396	55.27	0
1375.52	0.805	0.133	25.336	28.08	0
721.65	0.931	0.047	8335.154	7.18	0
1601.03	0.962	0.026	63.051	89.13	0

FTIR spectroscopy confirmed the dominance of aliphatic structures, with intense C–H stretching bands at 2921 and 2852 cm^{-1} and deformation bands at 1457 and 1376 cm^{-1} (*Table 3, Figure 1*). A characteristic rocking band near 721 cm^{-1} indicates long linear alkyl chains, while weak aromatic signals and the absence of pronounced C=O

and O–H bands suggest low aromaticity and limited oxygenated functionality. This structural profile is typical of paraffinic–resinous oils with strong associative behavior.

To further clarify how the identified group composition influences rheological behavior, additional quantitative characteristics were evaluated. The corresponding parameters, reflecting the structural contribution of individual fractions to viscosity control, are presented in *Table 4*.

Table 4 - **Group composition of the crude oil sample**

Component	Content (%)	Component	Content (%)
Paraffinic–naphthenic hydrocarbons	39.6	Resins (Type 1)	19.0
Light aromatic hydrocarbons	2.4	Resins (Type 2)	24.4
Medium aromatic hydrocarbons	2.5	Asphaltenes	1.4
Heavy aromatic hydrocarbons	10.7		

SARA analysis revealed high contents of saturates (39.6%) and resins (43.4%), with low aromatics (15.6%) and minimal asphaltenes (1.4%), indicating a relatively stable colloidal system (*Table 4*). Despite the low asphaltene content, the combination of resins and long-chain paraffins increases viscosity through the formation of spatial networks that restrict molecular mobility.

To further characterize hydrocarbon distribution and complement compositional analyses, gas chromatography was performed. This technique provides insight into carbon number distribution and the relative contribution of light, medium, and heavy fractions. The resulting gas chromatogram is presented in *Figure 2*.

Gas chromatographic analysis (NetChrom v2.1) revealed a broad hydrocarbon distribution from C_5 to C_{34}, with intensity maxima in the C_{13}–C_{18} range and a pronounced heavy tail toward higher carbon numbers. The limited content of light fractions and dominance of mid-to-heavy paraffins explain the low volatility and poor flowability of the crude oil (*Figure 2*).

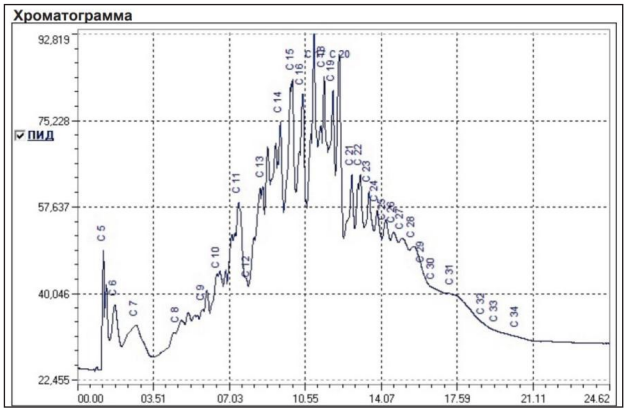

Figure 2 - **Gas chromatogram of the crude oil sample**

The integrated compositional data indicate that the high viscosity of the studied crude oil is governed by a paraffinic–resinous matrix enriched with heteroatoms and metals rather than by asphaltene aggregation. This compositional profile justifies the

application of solvent-based and composite chemical reagents to disrupt associative interactions and improve crude oil mobility.

Effect of chemical reagents on heavy crude oil flowability:

As an initial step in assessing the efficiency of chemical viscosity-reduction methods, the rheological behavior of the untreated crude oil was investigated as a function of temperature. This analysis provides a reference framework for distinguishing between purely thermal effects and chemically induced viscosity reduction. The temperature-dependent viscosity data of the crude oil sample are presented in *Table 5*.

Table 5 - **Temperature-dependent viscosity of the crude oil sample**

№	Temperature, °C	Viscosity, cP	№	Temperature, °C	Viscosity, cP
1	25	331,800	5	45	22,080
2	30	135,000	6	50	17,400
3	35	82,800	7	55	12,900
4	40	29,880	8	60	7,650

The crude oil viscosity reaches approximately 3.3×10^5 cP at 25 °C (*Table 5*), indicating extremely poor flowability. Even at 40–45 °C, viscosity remains at $(2–3) \times 10^4$ cP, showing that thermal treatment alone is insufficient to achieve acceptable rheological properties. A substantial decrease occurs only above 60 °C, where viscosity drops to several thousand cP; however, such temperatures are often impractical for field and transportation operations. Therefore, chemical treatment was considered as a complementary approach.

Given the paraffinic–resinous composition of the crude oil, two organic solvents—xylene and solvent naphtha—were selected as flow-modifying reagents. These solvents reduce viscosity by dissolving paraffinic and resinous components and weakening intermolecular associations within the oil structure.

Effect of organic solvents on the viscosity of crude oil:

To evaluate the effect of organic solvents on crude oil viscosity, systematic viscometric measurements were performed at different temperatures and solvent concentrations. The resulting data, showing viscosity changes upon addition of xylene and solvent naphtha, are presented in *Table 6*.

Table 6 - **Influence of xylene and solvent naphtha on the viscosity of crude oil as a function of temperature**

№	Temperature, °C	Xylene 5%	Xylene 10%	Xylene 15%	Solvent naphtha 5%	Solvent naphtha 10%	Solvent naphtha 15%
1	25	41760	7560	2190	92400	27050	10000
2	30	22680	6240	2040	42360	14850	6650
3	35	14880	4770	1452	23400	10961	4420
4	40	9540	3360	1158	19170	7260	2940
5	45	6630	2790	888	12390	5102	1950
6	50	4830	1830	804	7690	3270	1300
7	55	4272	1374	678	5340	2375	860
8	60	3624	1092	408	4020	1740	570

Viscosity measurements in *Table 6* show a pronounced reduction in crude oil viscosity after adding xylene and naphtha across the 25–60 °C range. The dilution effect intensifies with higher solvent concentration and temperature, reflecting the combined influence of chemical and thermal factors.

All viscosity values in *Tables 5* and *6* are averages of repeated measurements. Experimental uncertainty did not exceed ±2%, consistent with the viscometer's accuracy and repeatability. This uncertainty does not affect the observed trends or comparative assessment of solvent efficiency.

To illustrate the effect of xylene concentration on rheological behavior, viscosity–temperature relationships were analyzed. The corresponding viscosity profiles for crude oil treated with different xylene concentrations are presented in *Figure 3*.

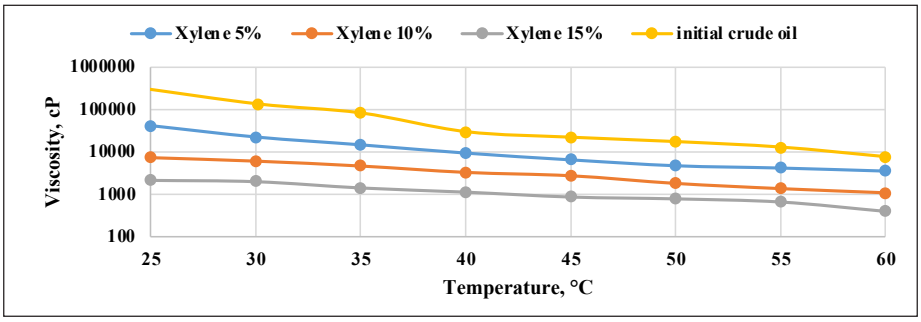

Figure 3 - **Viscosity–temperature behaviour of crude oil treated with xylene**

Xylene addition significantly reduces viscosity even at the lowest concentration of 5% (Figure 3). At 25 °C, viscosity drops from approximately 3.3×10^5 cP for untreated crude oil to 4.18×10^4 cP, and further decreases to 2.19×10^3 cP at 15% concentration. The effect intensifies with temperature: at 60 °C with 15% xylene, viscosity falls to approximately 4.1×10^2 cP.

The influence of solvent naphtha was investigated under the same temperature conditions. Viscosity–temperature profiles at different solvent concentrations enabled direct comparison with untreated oil and demonstrated the dilution effect. The results are presented in *Figure 4*.

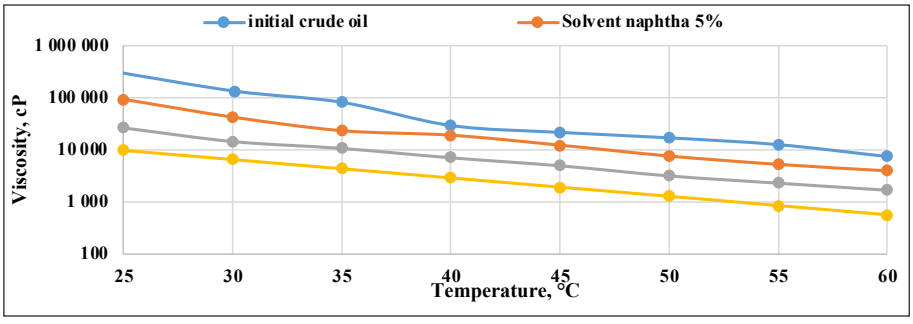

Figure 4 - **Viscosity–temperature behaviour of crude oil treated with solvent naphtha**

A similar trend is observed for solvent naphtha (Figure 4), though viscosity values remain higher than with xylene. At 25 °C, viscosity drops to 9.24×10^5 cP at 5% and to 1.0×10^4 cP at 15%. At 60 °C with 15% solvent naphtha, viscosity reaches approximately 5.7×10^2 cP, indicating lower efficiency than the aromatic solvent.

For direct comparison, the viscosity–temperature behavior of crude oil treated with 15 vol.% xylene and 15 vol.% solvent naphtha was analyzed. The comparative profiles are presented in *Figure 5*.

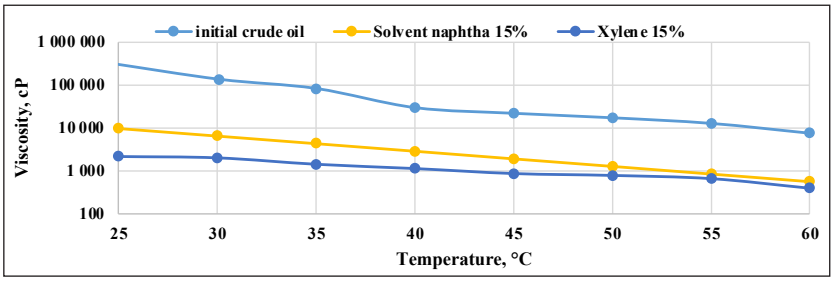

Figure 5 - **Comparative viscosity reduction by xylene and naphtha (15 vol.%)**

Comparative results (*Figure 5*) show that both xylene and solvent naphtha effectively reduce crude oil viscosity across the investigated temperature range. At 15 vol.%, xylene provides greater reduction, especially at low and moderate temperatures, while the difference narrows at higher temperatures due to thermal thinning. These results confirm that temperature and solvent type are key factors governing the rheological behavior of heavy crude oils.

Comparison of the obtained results with literature data:

The observed solvent-assisted viscosity reduction is consistent with trends reported for paraffinic–resinous heavy crude oils. Organic solvents improve flowability by weakening interactions among resins, asphaltenes, and long-chain hydrocarbons, especially at moderate temperatures where heating alone is insufficient [2,3,14].

Aromatic solvents like xylene are highly effective viscosity reducers due to their affinity for resin–asphaltene structures [2,14]. Hasan et al. [2] reported reductions of one to two orders of magnitude in heavy crude oils treated with aromatic solvents, while Norouzpour et al. [14] confirmed xylene's high efficiency in dissolving wax and asphaltene deposits. In line with these studies, adding 15 vol.% xylene in the present work reduced viscosity by over two orders of magnitude at 25–40 °C.

Solvent naphtha provided a more moderate but steady viscosity reduction, mainly through dilution effects, consistent with previous reports on petroleum-derived solvents [3,5]. Although less effective than xylene at disrupting resin–asphaltene structures, it offers advantages in operational safety and practical application [5,6]. A comparison with literature data is presented in *Table 7*.

Table 7 - **Comparison of viscosity reduction by organic solvents for heavy crude oils**

Study	Oil / solvent	Conc. (vol.%)	Temp (°C)	Effect
Hasan et al. [2]	Heavy oil / aromatic solvents	5–15	25–60	1–2 orders viscosity reduction
Ghannam et al. [3]	Heavy/light blends / petroleum solvents	≤20	25–70	Strong dilution, improved flowability
Norouzpour et al. [14]	Carbonate heavy oil / xylene	10–20	25–50	Efficient wax/asphaltene dissolution
He et al. [5]	Conventional heavy oil / solvent systems	5–15	30–80	Stable viscosity reduction
This study	Paraffinic–resinous oil / xylene	5–15	25–60	>2 orders reduction
This study	Paraffinic–resinous oil / solvent naphtha	5–15	25–60	Moderate dilution effect

The observed viscosity reduction and relative solvent performance show good agreement with previously reported trends, confirming that solvent type and dosage play a key role in controlling the rheological behavior of heavy crude oils.

Conclusions

This study has identified the key factors responsible for the anomalously high viscosity of the investigated heavy oil and experimentally substantiated effective methods for its reduction. A comprehensive physicochemical analysis (XRF, FTIR, SARA, and gas chromatography) revealed that the primary barrier to low-temperature transportation is the paraffin–resin matrix with a high content of heteroatoms and metals, which forms stable associative structures even with a minor asphaltene fraction. It was experimentally proven that using an aromatic solvent (xylene) in an amount of 15 vol.% reduces the oil viscosity by more than 150 times (from 3.3×10^5 to 2.19×10^3 cP) at 25°C, enabling cold transportation without preheating. Meanwhile, the use of naphtha provides a 30-fold viscosity reduction and can be considered an alternative in cases where the use of xylene is restricted by safety requirements. It was shown that the combined application of a chemical reagent (xylene, 15 vol.%) and moderate thermal treatment (up to 60°C) achieves a viscosity of ~4.1×10^2 cP, which meets the requirements for trunk pipeline transport and allows for a significant reduction in energy consumption required to maintain a high oil temperature throughout the transport system. The systematic data obtained on the rheological properties of the oil in the presence of solvents over a temperature range of 25–60 °C and a concentration range of 5–15 vol.% can be directly applied to pipeline hydraulic calculations, the selection of pumping equipment, and the adaptation of transport modes to account for seasonal temperature variations and infrastructure remoteness.

Thus, the results of this work not only elucidate the mechanisms underlying the rheological behavior of heavy paraffinic–resinous oil but also provide specific technological solutions aimed at improving the efficiency and energy efficiency of its production and transportation. These findings have high potential for implementation at oilfields in Kazakhstan, where the share of hard-to-recover high-viscosity oils is steadily increasing.

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