УДК 665.63:665.642.4; https://doi.org/10.37878/2708-0080/2026-2.20
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STUDY OF THE CATALYTIC HYDROVISBREAKING PROCESS OF VACUUM RESIDUE FOR THE PRODUCTION OF LIGHT FRACTIONS

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This study investigates the effect of preliminary physical activation of vacuum residue using ultrasonic cavitation and its combination with a magnetic field on the efficiency of catalytic hydrovisbreaking. The process was carried out at 450 °C and a hydrogen pressure of 5.0 MPa using an HR-538/Zeocar-600 catalyst system. Feedstock activation included ultrasonic treatment and combined ultrasonic–magnetic field exposure.

The results show that physical activation enhances the conversion of heavy hydrocarbons and improves product distribution. The yield of light distillates increases from 56.3% to 63.1%, while gas formation decreases from 9.5% to 5.8% and the fraction above 360°C decreases from 28.7% to 25.7%, without an increase in coke formation. The combined treatment exhibits a synergistic effect, providing greater improvements than ultrasonic treatment alone. In addition, fuel quality improves, with sulfur content decreasing in both gasoline and diesel fractions and aromatic hydrocarbons being reduced, alongside an increase in saturated components. Key performance indicators such as octane and cetane numbers remain essentially unchanged.

Overall, the combined application of ultrasonic cavitation and magnetic field treatment represents an effective approach for intensifying hydrovisbreaking, enabling deeper and more selective conversion of heavy feedstock without increasing process severity.

KEYWORDS: *visbreaking, vacuum residue, magnetic field, ultrasonic cavitation.*

ИССЛЕДОВАНИЕ ПРОЦЕССА КАТАЛИТИЧЕСКОГО ГИДРОВИСБРЕКИНГА ГУДРОНА С ЦЕЛЬЮ ПОЛУЧЕНИЯ ЛЕГКИХ ФРАКЦИЙ

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В данной работе исследовано влияние предварительной физической активации гудрона с использованием ультразвуковой кавитации, а также её сочетания с магнитным полем, на эффективность каталитического гидровисбрекинга. Процесс проводился при температуре 450 °C и давлении водорода 5,0 МПа с использованием каталитической системы HR-538/Цеокар-600. Активация сырья включала ультразвуковую обработку и комбинированное воздействие ультразвука и магнитного поля.

Показано, что физическая активация повышает степень превращения тяжёлых углеводородов и улучшает распределение продуктов. Выход светлых дистиллятов увеличивается с 56,3 % до 63,1 %, при этом образование газа снижается с 9,5 % до 5,8 %, а доля фракции с температурой кипения выше 360 °C уменьшается с 28,7 % до 25,7 % без увеличения коксообразования. Комбинированная обработка проявляет синергетический эффект, обеспечивая более выраженные улучшения по сравнению с воздействием одного ультразвука. Дополнительно улучшается качество топлив: снижается содержание серы и ароматических углеводородов, увеличивается доля насыщенных соединений, при этом октановое и цетановое числа практически не изменяются.

В целом комбинированное применение ультразвуковой кавитации и магнитного поля является эффективным методом интенсификации гидровисбрекинга, обеспечивающим более глубокую и селективную переработку тяжёлого сырья без ужесточения технологических условий.

КЛЮЧЕВЫЕ СЛОВА: *висбрекинг, гудрон, магнитное поле, ультразвуковая кавитация.*

ЖЕҢІЛ ФРАКЦИЯЛАР АЛУ МАҚСАТЫНДА ГУДРОННЫҢ КАТАЛИТИКАЛЫҚ ГИДРОВИСБРЕКИНГІН ЗЕРТТЕУ

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Бұл жұмыста гудронды алдын ала физикалық белсендірудің (ультрадыбыстық кавитация және оның магнит өрісімен үйлескен әсері) каталитикалық гидровисбрекинг

процесінің тиімділігіне әсері зерттелді. Процесс 450 °С температурада және 5,0 МПа сутек қысымында HR-538/Zeocar-600 каталитикалық жүйесін қолдану арқылы жүргізілді. Шикізатты белсендіру ультрадыбыстық өңдеуді және ультрадыбыс пен магнит өрісінің үйлескен әсерін қамтыды.

Нәтижелер көрсеткендей, физикалық белсендіру ауыр көмірсутектердің айналу дәрежесін арттырып, өнімдердің таралуын жақсартады. Жеңіл дистилляттардың шығымы 56,3 %-дан 63,1 %-ға дейін артады, газ түзілуі 9,5 %-дан 5,8 %-ға дейін төмендейді, ал қайнау температурасы 360 °С-тан жоғары фракциялар үлесі 28,7 %-дан 25,7 %-ға дейін азаяды, бұл ретте кокстың түзілуі артпайды. Біріктірілген өңдеу ультрадыбыспен ғана әсер етумен салыстырғанда анағұрлым жоғары нәтижелер беретін синергетикалық әсер көрсетеді. Сонымен қатар, жанармай сапасы жақсарады: күкірт пен ароматты көмірсутектердің мөлшері төмендейді, қаныққан қосылыстардың үлесі артады, ал октан және цетан сандары іс жүзінде өзгермейді.

Жалпы алғанда, ультрадыбыстық кавитация мен магнит өрісін бірге қолдану гидровисбрекинг процесін қарқындатудың тиімді әдісі болып табылады және технологиялық жағдайларды күшейтпей-ақ гудронды терең әрі селективті өңдеуді қамтамасыз етеді.

ТҮЙІН СӨЗДЕР: *висбрекинг, гудрон, магнит өрісі, ультрадыбыстық кавитация.*

Introduction. In the global structure of hydrocarbon resources, the share of heavy and highly viscous crude oils is steadily increasing, while reserves of conventional light hydrocarbons are declining. This trend makes the development of efficient technologies for the processing of heavy oils and natural bitumen an urgent task [1].

Upgrading of heavy petroleum feedstock is aimed at converting high-molecular-weight components into lighter fractions with improved physicochemical properties. The main industrial approaches include thermal cracking, catalytic cracking, and hydrocracking. Thermal cracking is characterized by high severity and significant coke formation, along with limited control over product distribution. Catalytic cracking improves selectivity and reduces coke yield but is often limited by catalyst deactivation. Hydrocracking and hydrovisbreaking combine catalytic and hydrogenation functions, enabling deeper conversion of heavy hydrocarbons with simultaneous removal of heteroatoms such as sulfur and nitrogen [2–5].

Hydrovisbreaking involves hydrogen-assisted cleavage of C–C bonds and hydrogenation of aromatic structures, leading to the formation of lighter petroleum products [6]. The process is typically conducted at temperatures of 300–450 °C in the presence of bifunctional catalysts such as metal/zeolite systems (e.g., NiMo/Y-zeolite, Pt/ZSM-5), which provide both hydrogenation and acidic cracking functions [7–9]. Compared with purely thermal processes, hydroprocessing technologies offer improved selectivity and lower coke formation due to stabilization of reactive intermediates by hydrogen [10–11].

Despite these advantages, hydroprocessing remains associated with high hydrogen consumption and significant operational costs. Therefore, current research is focused on process intensification methods that enhance conversion efficiency without increasing reaction severity [12].

One promising approach is the preliminary physical activation of feedstock. Ultrasonic treatment has been widely studied as a method for improving the properties of heavy oils. According to previous studies [13–14], ultrasonic cavitation promotes the disruption of asphaltene–resin structures, enhances mass transfer, and generates localized high-temperature and high-pressure microzones. These effects facilitate bond cleavage in heavy hydrocarbons

and improve their reactivity during subsequent catalytic processing. The selection of a short ultrasonic treatment time (on the order of minutes) is typically sufficient to induce cavitation effects while avoiding excessive heating or secondary recombination processes.

Magnetic field treatment is another physical method that has been investigated for modifying the properties of crude oils. Previous studies have shown that magnetic fields in the range of tens of millitesla can reduce viscosity and influence the structural organization of complex hydrocarbon systems [15]. These effects are generally attributed to changes in intermolecular interactions and possible influences on the behavior of paramagnetic species present in crude oil. However, the mechanisms of magnetic field action remain a subject of discussion, and its influence is often interpreted as indirect, affecting aggregation states and transport properties rather than causing direct chemical transformations.

In the present work, the selected magnetic field intensity (20–55 mT) corresponds to the range reported in the literature as effective for modifying the rheological and structural properties of heavy hydrocarbons, while maintaining low energy consumption. The duration of magnetic treatment (several hours) is chosen to ensure sufficient interaction time for structural reorganization within the dispersed system.

Although ultrasonic and magnetic treatments have been studied separately, their combined application in catalytic hydrovisbreaking processes remains insufficiently explored. The potential for a synergistic effect may arise from the simultaneous enhancement of dispersion, mass transfer, and stabilization of reactive intermediates, leading to improved conversion and selectivity.

The aim of this study is to investigate the effect of ultrasonic cavitation and magnetic field treatment, both individually and in combination, on the efficiency and selectivity of catalytic hydrovisbreaking of vacuum residue, with particular emphasis on identifying a synergistic effect between these physical activation methods.

Materials and methods

The aim of this study is to investigate the effect of physical factors, such as a magnetic field and ultrasonic cavitation, on the catalytic hydrovisbreaking process of vacuum residue. In this work, the hydrovisbreaking process of vacuum residue obtained from a blend of Baku crude oils was studied at a temperature of 450 °C and a hydrogen pressure of 5 MPa. The process was carried out with the separation of both gasoline and diesel fractions.

The quality characteristics of the vacuum residue used are presented in *Table 1*.

The experiments were carried out in an autoclave of type 8218/8c, made of forged chromium–nickel steel and equipped with a heating jacket and a rotating stirrer operating at a speed of 50–86 rpm.

Experimental procedure

The feedstock was kept in a magnetic field with an intensity of 20–55 mT for 3–5 hours, then activated by ultrasound for 3 minutes and placed into the autoclave for the hydrocracking process.

An amount of 200–300 mL of feedstock was loaded into a 1 L autoclave.

During the thermocatalytic conversion of the feedstock, a calculated amount of catalyst was added simultaneously.

The autoclave was hermetically sealed, and the required pressure was created using the appropriate gases.

Table 1 – **Physicochemical properties of vacuum residue**

Parameter	Value
Density at 20 °C, kg/m^3	959.0
Kinematic viscosity at 20 °C, mm^2/s	61.68
Flash point, °C	201
Fractional composition, wt.%	
up to 450 °C	5
up to 475 °C	19.5
up to 500 °C	30
Hydrocarbon composition, wt.%	
Paraffin–naphthenic hydrocarbons	29.7
Light aromatic hydrocarbons	9.5
Medium aromatic hydrocarbons	4.8
Heavy aromatic hydrocarbons	18.0
Resins:	
I	8.0
II	9.5
Asphaltenes	3.4
Sulfur, mg/kg	0.8

The reactor was then held for 20–30 minutes at room temperature without motion to check for tightness.

After confirming tightness, the heating elements were switched on. When the temperature reached approximately 50 °C below the target value, the motor was activated to rotate the autoclave and hydrogen was supplied to establish the required pressure.

After completion of the process, heating was switched off and the autoclave temperature was reduced as quickly as possible.

On the following day, the residual pressure was recorded; part of the generated gases was collected in a gas holder for analysis, while the remaining gases were released. The autoclave was then opened, and the obtained catalysate was sent for further analysis.

HR-538/Zeokar-600 is a mixture of HR-538 (a hydrogenation catalyst supplied by the French company Acssens) with 10 wt.% of the industrial cracking catalyst Zeokar-600.

Table 2 – **Quality characteristics of the HR-538 catalyst**

Parameter	Value
NiO	3.5 wt.%
MoO_3	17.0 wt.%
Surface area	210 m^2/g
Total pore volume	0.47 cm^3/g
Pellet sizes	1.2 mm / 1.6 mm / 2.5 mm
Bulk density	0.67 kg/L (for 1.2 mm) / ≈0.70 kg/L (for 1.6–2.5 mm)
Compressive strength	~1.49 MPa

Table 3 – **Quality characteristics of the Zeokar-600 catalyst**

Parameter	Standard value
Bulk density under test conditions, kg/m^3	680–780
Mass fraction of target fraction 3.0–6.0 mm, %, not less than	92
Mass fraction of intact and mechanically strong beads of fraction 2.5–5.0 mm, %, not less than	86
Stable gasoline yield activity, %, not less than	52
Selectivity, %, not less than	75
Moisture content removed at 800 °C, %, not more than	2.5
Mass fraction of rare earth elements (as oxides), %, not less than	1.8
Mass fraction of components, %, not more than:	
– sodium oxide	0.55
– iron oxide	0.30
Platinum content characteristic – volumetric ratio of carbon dioxide to carbon monoxide (CO_2/CO), not less than	1.5
Catalyst strength under impact–abrasion conditions for 300 s, %, not less than	50

Results and discussion

The material balance of vacuum residue hydrovisbreaking under different feedstock pretreatment conditions is presented in *Table 4*. Three regimes were studied: standard conditions, ultrasonic cavitation, and combined ultrasonic cavitation with a magnetic field (0.25 T). The results demonstrate a systematic redistribution of products toward lighter fractions with simultaneous suppression of gas formation.

Under standard conditions, liquid products account for 56.3 wt.% with 9.5 wt.% gases and 4.0 wt.% coke. Ultrasonic cavitation increases light fractions to 58.9 wt.% and reduces gas formation to 8.7 wt.%, indicating more selective cracking of heavy components. The combined ultrasonic–magnetic treatment further enhances conversion, raising middle distillates to 37.4 wt.% and total liquids to 63.1 wt.%, while reducing gas yield to 5.8 wt.%

Table 4 – **Material balance of the vacuum residue hydrocracking process at 450 °C and a hydrogen pressure of 5.0 MPa**

Product	Standard conditions	Ultrasonic cavitation	Ultrasonic cavitation + 0.25 T magnetic field
Gases up to C_4	9.5	8.7	5.8
IBP–180 °C	27.6	27.8	25.7
180–360 °C	28.7	31.1	37.4
Σ gasoline + diesel	56.3	58.9	63.1
Fraction ≥360 °C	28.7	27.0	25.7
Coke	4.0	3.8	3.7
Losses	1.5	1.6	1.7

with nearly unchanged coke (3.7 wt.%). This suggests suppressed radical recombination and improved selectivity toward liquid products.

Overall, physical activation increases conversion depth and liquid yield while limiting gas formation and maintaining low coke production.

Gasoline fraction analysis

The properties of gasoline fractions obtained under different activation modes are summarized in *Table 5*. Feedstock pretreatment modifies both fractional composition and hydrocarbon distribution, although the boiling range remains characteristic of hydrocracked gasoline.

Table 5 – **Quality characteristics of gasoline fractions obtained by hydrocracking at 450 °C and a hydrogen pressure of 5.0 MPa using the HR-538/Zeokar-600**

Parameter	–	+	++
Distillation range, °C			
Initial boiling point	40	35	42
10 % distilled	48	45	47
50 % distilled	87	83	90
90 % distilled	160.0	154	156
Final boiling point	190.0	185	187
Density at 20 °C, kg/m^3	0.6953	0.6873	0.6908
Iodine number, g I_2/100 g	10	10.5	10.5
Hydrocarbon composition, wt.%			
Paraffins	70.4	68.8	69.9
Olefins	4.5	5.2	5.0
Naphthenes	11.1	12.8	12.4
Aromatics	14.0	13.2	12.7
Sulfur, wt.%	0.0534	0.0481	0.0438
Octane number (RON)	83	83	83

(–) standard conditions, (+) ultrasonic activation, (++) combined ultrasonic and magnetic field activation

Ultrasonic treatment shifts distillation to lower temperatures, indicating mild cracking of heavy precursors, while the combined ultrasonic–magnetic mode stabilizes the boiling profile. Density decreases under ultrasound (0.6953 → 0.6873 kg/m³) due to higher paraffin content, with a slight increase under combined conditions reflecting structural reorganization. Aromatics decrease while naphthenes and olefins increase, especially under combined activation, suggesting intensified hydrogen transfer and partial aromatic saturation. Sulfur content progressively decreases, confirming improved catalytic accessibility. Despite these changes, RON remains constant (83), indicating a balance between paraffinic increase and aromatic/olefinic variations.

Diesel fraction analysis

The properties of diesel fractions are given in *Table 6*. Feedstock pretreatment affects low-temperature behavior, sulfur content, and hydrocarbon composition, while maintaining a stable distillation range typical of hydrocracked diesel.

Ultrasonic activation slightly lowers early boiling temperatures, indicating mild cracking of heavy molecules, while the combined ultrasonic–magnetic treatment stabilizes this effect and limits over-fragmentation. Density decreases under ultrasound (0.8290 → 0.8237 kg/m³), reflecting reduced aromatics, with a slight rise under combined treatment due to structural rebalancing toward paraffin–naphthenes. Sulfur content drops from 0.132 to 0.100 wt.% in

Table 6 – **Quality characteristics of diesel fractions obtained by hydrocracking of vacuum residue at 450 °C and a hydrogen pressure of 5.0 MPa using the HR-538/Zeokar-600**

Parameter	–	+	++
Distillation range, °C			
Initial boiling point	182	180	183
10 % distilled	190	187	189
50 % distilled	285	283	281
90 % distilled	338	335	335
Final boiling point	340	338	338
Density at 20 °C, kg/m^3	0.8290	0.8237	0.8259
Iodine number, g I_2/100 g	9.4	10.0	10.4
Acid number, mg KOH/g	0	0	0
Pour point, °C	–30	–32	–32
Total sulfur, wt.%	0.132	0.100	0.100
Hydrocarbon composition, wt.%			
Paraffin–naphthenes	75.2	75.4	76.5
Olefins	6.4	7.0	6.7
Aromatics	18.4	17.6	16.8
Cetane number	48	48	48.5

(–) standard conditions, (+) ultrasonic activation, (++) combined ultrasonic and magnetic field activation

both modes, showing that ultrasound is the main driver of desulfurization, while the magnetic field has a secondary effect. Hydrocarbons shift toward more paraffinic–naphthenic and fewer aromatic structures, improving fuel quality. The cetane number remains stable (48–48.5), and the pour point decreases to –32 °C, indicating better low-temperature performance.

Conclusions

The results obtained demonstrate that preliminary physical activation of feedstock has a pronounced influence on the efficiency and selectivity of catalytic hydrocracking of heavy petroleum residues. In general, ultrasonic treatment enhances the conversion of high-molecular-weight hydrocarbons, promoting their transformation into lighter fractions and improving overall process efficiency.

The combined application of ultrasonic cavitation and magnetic field treatment exhibits the most significant effect, indicating the presence of a synergistic interaction between the two physical factors. This synergy manifests itself in a more selective conversion pathway characterized by enhanced formation of liquid products and suppression of undesirable gas-phase reactions and secondary degradation processes.

From a compositional perspective, physical activation contributes to a more favorable redistribution of hydrocarbon groups in both gasoline and diesel fractions. This is reflected in a general decrease in sulfur- and aromatic-containing structures and a relative increase in more saturated hydrocarbon types, which are associated with improved fuel quality and environmental performance. Importantly, these changes occur without deterioration of key performance indicators such as octane and cetane numbers, indicating the preservation of combustion characteristics.

Overall, the findings confirm that the integration of physical field-assisted pretreatment with catalytic hydroprocessing represents a promising strategy for intensifying heavy feedstock upgrading. The approach enables deeper and more selective conversion under

relatively mild operating conditions, highlighting its potential for further development in energy-efficient refinery technologies.

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