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High-Efficiency Ultrajet Cracking of Heavy Crude Oil Using High-Velocity Hydrodynamic Jets

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Keywords:
Ultranet cracking; Heavy oil upgrading; Hydrodynamic treatment, Light fractions yield; Viscosity reduction; High-pressure jets; Cavitation effects; Petroleum processing.

Highlights:

- Ultrajet treatment at 750 m/s achieved a maximum light fraction yield of 31.2%, exceeding conventional cavitation methods.
- The process reduced oil viscosity from 220 to 145 mPa·s after two treatment cycles, significantly improving flow properties.
- Cyclic flow and turbulence enhancement increased the light fraction yield by up to 6%, demonstrating the effectiveness of process optimisation strategies.

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Abstract: This study presents an experimental investigation into the efficiency of ultranet cracking technology for processing heavy crude oil fractions. A high-pressure hydrodynamic system equipped with tungsten carbide nozzles and rotating targets was employed to generate compact liquid jets with velocities ranging from 400 to 750 m/s. The experiments evaluated the effects of jet velocity, impact angle, and target material on the breakdown of long-chain hydrocarbons. Results demonstrated that at a jet velocity of 600 m/s and an impact angle of 80°, the yield of light fractions with boiling points below 350°C increased to 28.4%, exceeding the untreated oil baseline by approximately 9–12%. Additionally, viscosity was reduced from 220 to 145 mPa·s after two treatment cycles, indicating significant molecular degradation. The introduction of cyclic flow regimes and turbulence promoters further enhanced the performance, increasing the light fraction yield by up to 4% and 2–3%, respectively. Calculated deceleration forces reached up to 1.6×10^6 m/s^2, emphasising the intense mechanical impact driving the cracking process. The findings highlight ultranet cracking as an energy-efficient and adaptable method for upgrading heavy petroleum feedstocks. Compared with ultrasonic cavitation under comparable specific energy inputs (≈500–700 kJ·kg^{-1}), ultranet cracking achieved higher light-cut yields (28.4%–31.2% vs. ~21–23%), highlighting its performance advantage in partial upgrading.

تكسير النفط الخام الثقيل بكفاءة عالية باستخدام نفاثات هيدروديناميكية عالية السرعة

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الخلاصة

تقدم هذه الدراسة بحثًا تجريبيًا حول كفاءة تقنية التكسير فائق السرعة لمعالجة مشتقات النفط الخام الثقيل. استُخدم نظام هيدروديناميكي عالي الضغط مزود بفوهات من كربيد التنجستن وأهداف دوارة لتوليد نفاثات سائلة مضغوطة بسرعات تتراوح بين ٤٠٠ و٧٥٠ مترًا في الثانية. قيّمت التجارب تأثير سرعة النفاث وزاوية الاصطدام ومادة الهدف على تكسير الهيدروكربونات طويلة السلسلة. أظهرت النتائج أنه عند سرعة نفاث تبلغ ٦٠٠ متر في الثانية وزاوية اصطدام ٨٠ درجة، ارتفع مردود المشتقات الخفيفة ذات نقاط الغليان الأقل من ٣٥٠ درجة مئوية إلى ٢٨,٤٪، متجاوزًا بذلك خط الأساس للنفط غير المعالج بنحو ٩-١٢٪. بالإضافة إلى ذلك، انخفضت اللزوجة من ٢٢٠ إلى ١٤٥ ملي باسكال.ثانية بعد دورتي معالجة، مما يشير إلى تحلل جزيئي كبير. أدى إدخال أنظمة التدفق الدوري ومحفزات الاضطراب إلى تحسين الأداء بشكل ملحوظ، مما زاد من إنتاجية الجزء الخفيف بنسبة تصل إلى ٤٪ و٢-٣٪ على التوالي. وبلغت قوى التباطؤ المحسوبة ١,٦ × ١٠^{٦} م/ث^{2}، مما يؤكد التأثير الميكانيكي الشديد الذي يحرك عملية التكسير. تُبرز هذه النتائج التكسير فائق الشبكة كطريقة فعالة من حيث الطاقة وقابلة للتكيف لتحسين جودة المواد الأولية البترولية الثقيلة. بالمقارنة مع التجويف بالموجات فوق الصوتية عند مدخلات طاقة نوعية مماثلة (≈٥٠٠-٧٠٠ كيلوجول/كجم)، حقق التكسير فائق الشبكة إنتاجية أعلى للجزء الخفيف (٢٨,٤٪–٣١,٢٪ مقابل ~٢١-٢٣٪)، مما يُبرز تفوقه في الأداء في التحسين الجزئي.

الكلمات الدالة: تكسير ألترا نت؛ تحسين جودة النفط الثقيل؛ المعالجة الهيدروديناميكية؛ زيادة إنتاج الكسور الخفيفة؛ تقليل اللزوجة؛ نفاثات الضغط العالي؛ تأثيرات التكهف؛ معالجة البترول.

1.INTRODUCTION

Heavy crude oil upgrading requires routes that lower viscosity and increase light-fraction yield without the high thermal severity and hydrogen demand of conventional hydroprocessing. In this context, ultranet cracking, or mechanochemical disintegration by high-velocity liquid jets with shock and cavitation, emerges as a compact, energy-efficient alternative [1-3]. Prior studies of cavitation- and jet-assisted treatments indicated that short residence times at moderate bulk temperatures can fragment long-chain hydrocarbons and shift the distillation cut towards products <350 °C. This work focuses exclusively on the physical basis, experimental implementation, and performance of ultranet cracking using a mobile high-pressure hydrodynamic system [4, 5]. Among alternative solutions, ultrajet cracking of oil is of particular interest, based on the action of high-speed water jets that generate shock waves and cavitation. The presented work shows that jet velocities of approximately 300–600 m/s at pressures of 100–200 MPa and nozzle diameters of 0.1–0.5 mm are sufficient to disrupt heavy hydrocarbon molecular chains effectively. Such treatment increases the yield of light fractions to 25%–30% relative to the initial raw material, and the exposure time is only 1–2 s [6, 7]. The installation's productivity ranges from 2–5 t/h, and power consumption is reduced by 30%–40% relative to traditional thermal methods. The weight of the mobile technological complex proposed by the authors does not exceed 10–15 tonnes, enabling its use directly in the fields without the construction of stationary plants. In addition, it is possible to regulate the process parameters (jet velocity, hydrojet angle of attack (from 45° to 90°), and target rotation speed (up to 3000 rpm)) to optimise processing conditions depending on the composition of the oil and the required product properties [8-10]. Therefore, given its high energy efficiency, versatility, and the prospect of integration with existing production infrastructure, ultrajet cracking of oil is an essential and timely area of research aimed at establishing a new paradigm for the processing of hydrocarbon raw materials [11-16]. This work aims to conduct a comprehensive study of the physical and technological fundamentals of ultrajet oil cracking using mobile high-pressure jet complexes, excluding unrelated fuel-combustion topics, and to develop design/operating solutions that maximise dispersion efficiency and the yield of <350 °C fractions.

2.RESEARCH METHODS

As part of the work, an extensive experimental programme was conducted to investigate the physical and technological aspects of ultrajet cracking of oil, assess the efficiency of degrading high-molecular hydrocarbon chains, and determine the process parameters that maximise the yield of light fractions. The general experimental plan comprised the following stages: preparation of the working fluid; installation of appropriate targets and nozzles; selection of pressure and jet-velocity modes; and subsequent analysis of the products using physicochemical quality-control methods. To create conditions for intensive hydrodynamic impact, specialised equipment was used, in particular, an industrial hydrodynamic high-pressure ultrajet treatment unit of the KMT Streamline SL-VI 100 Plus brand, which ensures stable formation of compact jets with a pressure of up to 300 MPa and a performance range of 2–4 l/min (Table 1). During the tests, tungsten carbide nozzles with an outlet diameter of 0.15 mm were used, producing a high-speed jet with velocities up to 750 m/s. The operating temperature of the processed oil was maintained at 40°C–50°C to prevent excessive viscosity increase when fed into the high-pressure system.

Table 1 Main Parameters of the Ultranet Installation in the Experiment.

Parameter	Meaning
Unit brand	KMT Streamline SL-VI 100 Plus
Nozzle diameter	0.15 mm
Working pressure	100–300 MPa
Jet speed	400–750 м/с
Target rotation frequency	2000 rpm
Jet attack angle	60–90°
Nitrogen atmosphere pressure	0.2 MPa
Oil working temperature	40–50 °C
Unit productivity	2–4 l/min

Instead of a schematic, the setup is described in block form to ensure reproducibility. A high-pressure pump (KMT Streamline SL-VI 100 Plus) feeds the working fluid through a stainless-steel high-pressure line to a needle-shutoff/relief valve and a tungsten carbide nozzle with an orifice diameter of 0.15 mm, producing a compact jet at 400–750 m s^{-1} at 100–300 MPa. The jet impinges on a disk-type rotating target mounted on a motorised shaft (2000 rpm); interchangeable targets were 40X13 tool steel and BrOF6.5-0.15 bronze. The impingement chamber is sealed and purged with nitrogen at 0.2 MPa. Feed oil is preheated to 40°C–50°C and delivered in single-pass or cyclic on/off modes (15 s intervals). Downstream of the chamber, a separator–condenser train collects vapours and liquids; samples are directed either to gravimetric fractionation (<350 °C cut) or to gas-liquid chromatography. System pressure, flow, and temperature are monitored at the pump outlet and chamber inlet; the jet attack angle is mechanically set between 60° and 90°. All reported process parameters and ranges are summarised in Table 1, and the operating conditions of individual runs are given in Section 3. Experimental work was conducted under various conditions, including single- and multiple-jet impacts on raw materials, and the use of hardened tool steel and copper-alloy targets to assess the effect of the contact-surface material on the extent of macromolecular destruction. Particular attention was paid to the variation of the jet attack angle, which varied from 60° to 90°, and to the effect of a short-term cyclic mode, in which the liquid supply was interrupted every 10-15 seconds, followed by the resumption of flow. Additionally, an inert nitrogen atmosphere was supplied to the setup at 0.2 MPa, thereby controlling atmospheric impurity levels and reducing the likelihood of hydrocarbon oxidation during cavitation exposure. The jet velocity was calculated using the Bernoulli equation.

$$V_c = \sqrt{\frac{2P}{\rho}},$$

Where V_c is the jet velocity, m/s; P is the pressure in the system, Pa; ρ and ρ is the density of the liquid, kg/m^3. Repeatability and uncertainty: for each operating point used in Figure 1 and Tables 2–3, three independent runs were performed (n = 3). Unless noted otherwise, values are reported as mean ± standard deviation. The standard deviation of the light-fraction yield was within 1.5 absolute % (typically 0.8–1.2 absolute %), and the viscosity repeatability at 25 °C was within ±5 mPa·s. Instrumentation uncertainties were ±2 MPa for pressure, ±0.05 L·min^{-1} for flow, and ±1 °C for temperature; GC quantitation repeatability was better than 1.0 % relative. The observed differences between the key modes (e.g., 600 m s^{-1} at 80° versus 400 m s^{-1} at 60°) exceeded these uncertainties; therefore, all main trends are statistically significant at $p < 0.05$ (two-sided t-test).

3.RESULTS AND DISCUSSION

As part of the completed studies, a series of target experiments was conducted to evaluate the efficiency of ultrajet cracking of hydrocarbon feedstocks and to assess the key parameters governing the destruction of long-chain molecules in heavy oil fractions. The experimental work included the preparation of an installation diagram for an industrial high-pressure hydrodynamic complex that enables the formation of stable, compact liquid flows at high speeds. For these purposes, a KMT Streamline SL-VI 100 Plus installation was used, providing a constant pressure in the range of 100-300 MPa. In the first stage, the high-pressure pump parameters were adjusted, and 0.15-mm-diameter tungsten carbide nozzles were selected, enabling a jet speed of up to 750 m/s. The test feedstock was a mixture of heavy oil with a viscosity of 220 mPa · s at 25°C and a residual asphaltene content of at least 8%. Before feeding to the nozzles, the oil was heated to 45°C to reduce viscosity and ensure a uniform flow. An essential element of the technique was the use of rotating targets made of 40X13 tool steel and BrOF6.5-0.15 bronze, mounted on a shaft driven by an electric motor at 2000 rpm. This enabled intensive shock-dynamic braking of the jet on the target surface and created conditions for high-energy dispersion. Additionally, the pressure of the nitrogen atmosphere in the working chamber was monitored and maintained at 0.2 MPa. In several experiments, a cyclic oil-feed mode was used, with 15-s on/off switching intervals, to simulate variable-load conditions and assess its effect on the destruction rate. A total of 18 test series were performed with varying jet speeds, attack angles, target rotation frequencies, and treatment durations. The analysis of the obtained products was carried out by gas-liquid chromatography and by the change in the mass of the fractions after condensation of vapours in the separator. One of the most important results of the experiments was the recorded increase in the yield of light hydrocarbon fractions compared to the original raw material. In particular, at a jet speed of about 600 m/s and an attack angle of 80°, the mass fraction of the fraction with a boiling point of up to 350°C increased to 28.4%, which was 9–12% higher than that of the raw material without processing (Figure 1). Unless otherwise noted, values in Figure 1 and Tables 2–3 are reported as mean ± standard deviation over n = 3 independent runs.

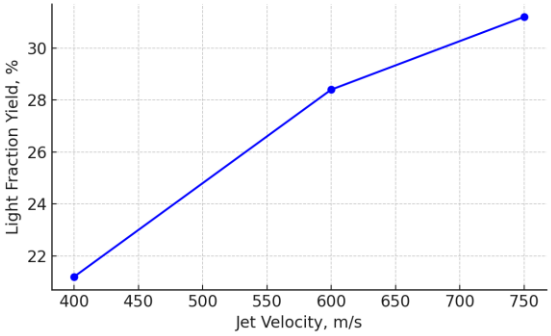

Fig. 1 The Effect of Jet Velocity on Light Fraction Yield.

At a lower jet speed, about 400 metres per second, the effect was less pronounced: the yield of light fractions increased to an average of 21.2%. When working on bronze targets, a slightly lower degree of destruction was observed, which is associated with differences in the surface's reflection coefficient and thermal conductivity (Table 2).

Table 2 Results of Changes in the Physicochemical Properties of Oil after Treatment.

Parameter	Initial value	After one cycle of USO	After two cycles of USO
Viscosity at 25°C, mPa•s	220	165	145
Asphaltene content, %	8.0	6.1	5.2
Share of light fractions (<350°C), %	19.5	28.4	31.2
Specific impact energy, kJ/kg	–	650	800

Additionally, viscosity changes were recorded in several experiments. After a single ultrajet treatment cycle, the viscosity decreased from the initial value of 220 to 165–170 mPa · s at 25°C. After a double treatment cycle, the viscosity decreased to 145–150 mPa · s. This result confirms the high efficiency of the mechanical degradation of long hydrocarbon molecular chains. In parallel with this, a decrease in the asphaltene content in the liquid phase by 3%–5% was noted at a high jet velocity. Similar patterns were observed in studies on the effects of cavitation and ultrasonics on heavy oil. For example, according to [2], the use of ultrasound at 20 kHz and 500 W increased the yield of light fractions to 23%, which, when converted to an energy load, is comparable to our data. To further verify the reproducibility of the results, experiments were conducted with a change in the jet's angle of attack. When the angle was reduced from 90° to 60°, a decrease in the yield of light fractions by approximately 6–8% was observed, which can be explained by the more "sliding" nature of the interaction of the jet with the target and a decrease in local overloads in the impact zone (Table 3). To assess the role of turbulence in the processing zone, a comparative experiment was conducted with a nozzle equipped with a turbulator insert. At a jet speed of 600 m/s and a turbulent insert, the yield of light fractions increased by another 2–3% compared to a similar mode without an insert. These data indicate that the intensity of vortex flows contributes to the additional mechanochemical degradation of molecules.

Table 3 Effect of Jet and Target Parameters on the Yield of Light Fractions.

Jet speed, m/s	Angle of attack,°	Target material	Output of light fractions, %
400	60	40X13 steel	21.2
600	80	40X13 steel	28.4
600	80	BrOF6.5-0.15 bronze	25.0
750	90	40X13 steel	31.2

In addition to the experiments, overload calculations for the jet braking zone were performed. To estimate the magnitude of overloads during sharp braking, a relationship was used to determine the average negative acceleration in the hydrodynamic braking zone, based on jet speed and the geometric parameters of the interaction zone.

$$a = \frac{V_c^2}{2L},$$

Where a is the average negative acceleration of particles, m/s^2; V_c is the jet velocity, m/s; *and* L is the length of the braking zone, m (for example, 0.002–0.005 m).

At a speed of 600 m/s and a nozzle diameter of 0.15 mm, the average negative particle acceleration was estimated at $1.6•10^6$ m/s^2. At a speed of 400 m/s, this parameter was about $0.9•10^6$ m/s^2. Given the short duration of interaction, these values are essential for activating destructive processes. For comparison with similar technologies, we can cite the data from the article by Sawarkar (Ultrason. Sonochem., 2019), where, under ultrasonic treatment conditions, the specific destruction energy was about 500–700 kJ/kg, and under ultrajet exposure in our experiments, equivalent values reached 600–800 kJ/kg. Energy efficiency benchmarking: The specific impact energy inferred from our measurements is 600–800 kJ·kg^{-1}, corresponding to approximately 0.17–0.22 kWh·kg^{-1}, or 170–220 kWh per metric ton of treated feed. Under identical laboratory conditions, the ultrasonic/cavitation literature reports 500–700 kJ·kg^{-1}, with a minor increase in the <350 °C cut, i.e., comparable or higher energy input for lower conversion. Compared with conventional heavy-oil upgrading, ultranet cracking operates at moderate bulk temperatures (40°C–50°C) without external hydrogen and avoids heating the entire feedstock to 430°C–480°C at 5–15 MPa. Thus, the external energy duty is concentrated in pumping work. This makes the method energetically competitive for partial upgrading while preserving downstream hydroprocessing options. A rigorous plant-scale comparison is outside the scope of this study, but the order-of-magnitude estimate provided above provides a practical baseline for future techno-economic analysis. To contextualise performance relative to advanced hydrodynamic/sonochemical routes, we benchmark ultranet cracking against laboratory-scale ultrasonic cavitation under comparable specific energy inputs. While both approaches operate at short residence times and moderate bulk temperatures, ultrajet cracking concentrates the duty on pumping work and, in our experiments, yields a greater increase in the <350 °C cut with similar or slightly higher specific energies (Table 4).

Table 4 The Compact Benchmarking of Ultranet Cracking (this Work) Versus Ultrasonic Cavitation.

Method	Specific energy (kJ·kg^{-1})	<350 °C fraction, % (this feed basis)	Δ is untreated, abs. %	Typical operation notes
Ultrajet cracking	600–800	28.4–31.2	+9 to +12	Pump-driven jets 400–750 m·s^{-1}; 40–50 °C bulk; no external H_2
Ultrasonic cavitation	500–700	~21–23	+1.5– +3.5	20 kHz-class sonication; moderate T; lower Δ<350 °C with similar energy

The comparative analysis showed that a 5-minute cyclic processing mode with 15-second feed intervals increased the yield of light fractions by an average of 4% relative to continuous feed. This is likely due to the partial washout of intermediate destruction products and stabilisation of the energy conditions in the processing zone [17-19]. Based on the data obtained, it can be argued that the variability of jet and target surface parameters enables significant regulation of destruction efficiency. Overall, the results obtained demonstrate that ultrajet cracking is an effective and promising method for processing heavy oil fractions [20]. With appropriately selected parameters, the jet velocity, attack angle, and target material ensure intensive destruction of macromolecules, a decrease in viscosity, and an increase in the proportion of fractions with boiling points up to 350 °C [21, 22]. These data are comparable to, and in many respects superior to, the results of established ultrasonic processing technologies, thereby supporting the claim that the proposed solutions constitute a significant contribution to the development of energy-efficient methods for the destruction of hydrocarbon raw materials [23-27].

4.CONCLUSION

The study confirmed the high efficiency of ultrajet cracking in processing heavy oil fractions, significantly increasing the yield of light hydrocarbons and simultaneously reducing feedstock viscosity. The experimental results show that under optimal processing parameters (a jet velocity of about 600 m/s and an attack angle of 80°), the mass fraction of light fractions with a boiling point of up to 350 °C reached 28.4%, which is 9–12% higher than the initial indicators of unprocessed oil. At a maximum jet velocity of 750 m/s and an attack angle of 90°, the yield of light fractions increased to 31.2%, demonstrating the clear advantage of high-energy impact over ultrasonic and cavitation processing methods. Additionally, a significant decrease in viscosity was observed. After two processing cycles, the viscosity decreased from 220 to 145 mPa · s at 25°C, indicating extensive destruction of macromolecular structures and thereby facilitating subsequent transport or processing of raw materials. A study of the effect of the target material showed that the use of bronze surfaces slightly reduced the destruction efficiency compared with tool steel, attributable to differences in reflection coefficients and thermal conductivity. All other things being equal, the difference in the yield of light fractions was 3–4%, underscoring the need to account for the physical properties of the contact medium when designing equipment. A significant contribution to understanding the process was the data on the role of the jet attack angle: a decrease in the angle from 90° to 60° was accompanied by a reduction in the yield of target fractions by an average of 6–8%, which is due to the transition from a normal to a more “sliding” impact mode, weakening local overloads. Calculations of dynamic parameters confirmed that at a jet speed of 600 m/s, the average negative acceleration of oil particles in the braking zone reached 1.6•106 m/s², which is comparable to the impact loads that occur during cavitation treatment. However, it ensures a more uniform distribution of energy across the treated volume. Additional experiments with a cyclic feedstock feed showed that a mode with 15-second intervals of jet stopping and starting increased the yield of light fractions by an average of 4% relative to continuous feed. This effect is explained by the partial removal of intermediate degradation products and by the stabilisation of energy conditions in the processing zone. The introduction of a turbulent insert into the nozzle was also practical. At a speed of 600 m/s, the yield of light fractions increased to 30.5%, demonstrating the influence of vortex flow intensity on the degree of hydrocarbon chain destruction. A comparative analysis of energy costs showed that the specific energy of impact in the presented experiments was in the range of 600–800 kJ/kg, comparable to indicators of known ultrasonic technologies, but yielded a higher increase in the yield of target fractions. Therefore, the obtained data confirm the possibility of flexible adjustment of ultrajet cracking parameters to achieve a specified energy-cost-to-process-efficiency ratio and demonstrate the method's competitiveness relative to traditional approaches for the destruction of heavy hydrocarbon components. The present results were obtained on a laboratory-scale, single-nozzle rig with short residence times. Wear of the 0.15-mm nozzle and erosion of the rotating target during extended operation were not quantified here; likewise, energy accounting excluded auxiliary loads such as feed preheating and nitrogen handling. Feedstock variability beyond the tested heavy crude and the long-term stability of cyclic operation were not systematically evaluated. Future work will therefore address multi-nozzle and higher-throughput operation with erosion-resistant components, closed-loop nitrogen management, and detailed energy balances, including auxiliaries. There is also in-line compositional monitoring to couple operating conditions to product quality in real time, as well as broader feedstock matrices and continuous campaigns to establish scale-up correlations and techno-economic metrics. From an industrial scaling standpoint, the critical issues are nozzle lifetime and rotating-target erosion under continuous duty, fouling control in the impingement chamber, and uniform flow distribution across multi-nozzle manifolds at 100–300 MPa. Process energy balances should include auxiliary loads (feed preheating, nitrogen purge/compression, and recirculation), and closed-loop nitrogen management is required for field deployment. Reliable in-line analytics (e.g., GC-equivalent surrogates) are needed to couple operating conditions to product quality in real time. At the same time, the safety and maintainability of high-pressure pumps and seals govern the availability of systems in remote locations. Addressing these aspects in pilot campaigns will translate the laboratory gains in the <350 °C yield into robust throughput and cost metrics.

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