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High-Efficiency Ultrajet Hydrodynamic Cracking of Heavy Bitumen and Oil Sludge

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Keywords:
Ultrajet hydrodynamic treatment; Heavy crude oil; Bitumen cracking; Cavitation; Viscosity reduction; Light fraction yield; High-pressure jets; Oil sludge processing.

Highlights:

- *Ultrajet treatment reduced bitumen viscosity by over 65% after two processing cycles at a jet velocity of 820 m/s.*
- *The yield of light fractions below 350 °C increased from 12.8% to 33.5% under optimal operating conditions.*
- *Cyclic flow and turbulence enhancements provided an additional 4% improvement in light fraction recovery without significant energy penalties.*

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Abstract: This study investigates the efficiency of ultrajet hydrodynamic treatment for the cracking of highly viscous bitumens and oil sludges. Experiments were conducted using a high-pressure Flow JetForce HHP-500 installation capable of generating jets with velocities of up to 820 m/s and pressures up to 320 MPa. The research analyzed the effects of jet velocity, impact angle, cyclic flow modes, and turbulence-enhancing inserts on viscosity reduction and the yield of light fractions. After two processing cycles with maximum parameters, the viscosity decreased by 65% (from 9100 to 3100 ± 150 mPa s, n = 3 at 25 °C), and the yield of fractions with Tboil < 350 °C increased to 33.5 ± 1.0 p.p. (n = 3). Cyclic feeding and turbulence added another 3–4 p.p. to the yield without a noticeable increase in specific energy capacity. The study also showed that compared to ultrasonic cavitation and thermal pyrolysis, ultrajet processing achieved comparable or superior results while consuming significantly less energy and shorter processing times. The findings confirm that the ultrajet hydrodynamic technology represents a promising, energy-efficient approach for upgrading heavy hydrocarbons and reducing processing complexity.

1.INTRODUCTION

The problem of processing hydrocarbon raw materials, particularly high-viscosity bitumen and oil sludge, is becoming increasingly important globally. As light oil reserves are depleted and the rate of extraction of hard-to-recover resources increases, the share of heavy hydrocarbon components in the composition of raw materials is steadily rising. According to the International Energy Agency, by 2035, the share of heavy oil and bitumen in total extracted raw materials may reach 26–28%, and the total annual volume of oil sludge formation worldwide may exceed 180 million tons. These resources have an extremely high viscosity (up to 10,000 mPa s at a temperature of 25°C), a significant content of asphaltenes and resinous compounds (at least 15–20%), a high level of contamination with mechanical impurities, sulfur, and heavy metals [1-3]. All these features significantly complicate their transportation, processing, and disposal, and, at the same time, pose serious environmental risks associated with waste accumulation, groundwater pollution, and emissions of toxic compounds during combustion. Over several decades, various physical, chemical, and thermal processing technologies have been developed to solve this problem. Traditional approaches, such as catalytic cracking, hydrocracking, and thermal destruction, demonstrate some efficiency but are accompanied by significant energy costs and technological limitations [4-5]. Therefore, hydrocracking processes require maintaining temperatures in the range of 420–460 °C and pressures of 20–25 MPa, resulting in high energy intensity: on average, 250–320 kW h are consumed to process one ton of bitumen. In addition, large reactors, whose weight ranges from 400 to 600 tons, require capital investment during both construction and operation. A significant drawback is the low yield of target light fractions (no more than 25-28% of the mass of the feedstock) with the simultaneous formation of a significant volume of coke residue and heavy gas oil components that require reprocessing. In turn, thermal pyrolysis methods conducted in an inert atmosphere enable processing of high-viscosity bitumen at temperatures above 500 °C, but they require complex thermal insulation of the equipment and are associated with the risk of uncontrolled formation of carcinogenic compounds [6-9]. One area for increasing the efficiency of processing bitumen and oil sludge is the use of ultrasonic and cavitation technologies, in which high-intensity mechanochemical action facilitates the degradation of long-chain hydrocarbons. According to Stebeleva and Minakov, the use of cavitation treatment makes it possible to increase the yield of light fractions to 32% and reduce the viscosity of the processed raw materials from 1200 to 400 mPa s after 15-20 minutes of processing [10-12]. However, these methods have drawbacks associated with the uneven distribution of cavitation zones, the limited scale of the installation, and low productivity (typically 0.5–1.0 t/h with an ultrasonic equipment power of 20–30 kW). In some cases, the impossibility of achieving uniform impact on complex, multicomponent oil-residue systems is a significant limiting factor. Against the background of these limitations, ultrajet processing methods that generate high-speed, compact hydrodynamic jets capable of producing intense shock-wave and cavitation effects in the impact zone attract particular attention from researchers. The use of ultrajet technologies offers several advantages over classical and ultrasonic approaches. Firstly, the localized influence of high overloads (average negative particle accelerations can reach (1.5–2.0) 10^6 m/s^2) ensures rapid and deep destruction of molecular structures. Secondly, small nozzle diameters (0.1–0.3 mm) and pressure in the range of 150–300 MPa create the possibility of forming jets with speeds of up to 700–800 m/s, at which the impact interaction energy in terms of the mass of the processed liquid is 600–900 kJ/kg. Thirdly, the mobility and modularity of ultrajet complexes enable processing to be conducted directly at deposits or temporary waste storage sites, thereby minimizing transportation costs and losses of raw materials [13-15]. Despite the existence of works devoted to the ultrajet processing of oil and heavy hydrocarbon fractions, the application of these methods to bitumen and oil sludge remains insufficiently studied. Bitumens have higher viscosity and contain a significant number of mineral inclusions and water emulsions, which can affect the cavitation and shock-dynamic braking modes of the jet. The effects of jet velocity, angle of attack, and target-surface characteristics on the degree of destruction of asphaltene agglomerates and the depth of depolymerization of resinous compounds remain incompletely studied [16-19]. In addition, aspects of the use of cyclic hydrojet supply modes and variations in the temperature of the processed raw materials for optimizing energy costs are poorly addressed. In this context, the study of the potential of ultrajet technology for the processing of bitumen and oil sludge appears to be a relevant and timely direction, combining energy-efficient destruction with technological versatility. The use of ultrajet methods can reduce the viscosity of the processed residues to 40-60% of the initial level, increase the yield of light fractions by more than 10% compared to thermal cracking, and reduce the processing time several times. An important aspect is the ability to adapt parameters (ranging from jet velocity and target rotation frequency to the composition of the inert gas environment) based on the physicochemical characteristics of the original bitumen and the assigned tasks [20-22]. The purpose of this paper was to present a comprehensive experimental study of the physical and technological aspects of ultrajet destruction of high-viscosity bitumen and oil sludge. This includes an analysis of the effect of the jet velocity, the attack angle, and the feed mode on the degree of viscosity reduction and an increase in the yield of fractions with a boiling point of up to 350 °C, as well as the development of design solutions that ensure process stability when processing multicomponent hydrocarbon systems. Additionally, in 2023–2024, it was shown that partial bitumen upgrade could be achieved by energy-efficient low-temperature methods, including microwave activation with carbon susceptors (150–200 °C), deasphalting configurations to reduce the carbon footprint, and cavitation-induced conversions, highlighting the relevance of the comparison with ultrajet processing [23-25].

2.RESEARCH METHODS

The general plan of experimental works envisaged a staged study of the effect of ultrajet processing on the physicochemical properties of high-viscosity bitumen and oil sludge with varying process parameters, using different equipment configurations. The main objective was to determine the dependence of the degree of destruction of hydrocarbon components and viscosity reduction on the jet velocity, the angle of attack of the flow, the rotation frequency of the target, and the temperature of the processed medium. To implement the research program, an industrial high-pressure hydrodynamic unit of the Flow JetForce HHP-500 model was used, which enabled the formation of stable, compact jets at pressures ranging from 180 to 350 MPa. The equipment was equipped with replaceable boron carbide nozzles with outlet diameters of 0.20 and 0.25 mm, enabling jets with a design speed of up to 820 m/s at a maximum drive power of 75 kW. The control system automatically regulated the pressure and flow rate of the working fluid by changing the parameters by up to 2%. Before feeding to the nozzles, bitumen and oil sludge were preheated in a sealed thermostatic tank to 60°C to reduce initial viscosity and facilitate flow stabilization. In a series of experiments, the operating temperature was raised to 80°C, thereby enabling investigation of the effect of thermal expansion on the cavitation process and the intensity of asphaltene structural destruction. During the tests, experiments were conducted varying the jet angle of attack from 45° to 85°. The unit's working chamber was equipped with a rotating target made of high-strength steel (30KhGSA) with a rotational speed of 500-2500 rpm. The surface of the target had a microrelief in the form of concentric notches 0.4 mm deep, contributing to an increase in the area of active interaction of the jet and the liquid. To control the composition of the gaseous medium, nitrogen was introduced into the chamber at an excess pressure of up to 0.3 MPa, thereby reducing the likelihood of oxidation of fragmented molecules. Additionally, a mode of intermittent bitumen flow supply with a 10-second on/off cycle was implemented to create pulsed overloads. In each experiment, the viscosity parameters, the mass fraction of light fractions, and the asphaltene concentration in the processed product were recorded. To assess the effect of turbulence in the impact zone, the nozzles were equipped with 15-mm-long turbulator inserts mounted directly behind the channel narrowing. 24 experiments were conducted with different combinations of jet velocity, temperature, angle of attack, and target rotation frequency. The resulting condensate samples were analyzed by gas-liquid chromatography with determination of the fractional composition by boiling temperature ranges. In separate test series, acoustic emissions from cavitation processes were recorded using a Sonomax V20 broadband sensor, enabling quantitative comparison of cavitation intensity with changes in viscosity and the yield of target components. At least three replicates ($n \geq 3$) were performed for each mode point. Viscosity was measured at (25±0.5) °C; repeatability was ±(3–5)% of the value (over the half-range of replicates), which is consistent with the intervals given in the text below (e.g., 3200–3500 mPa s for two runs at 820 m/s and 85°). The yield of light fractions (<350 °C), determined by GLC over boiling point ranges, had a repeatability of ±(0.8–1.2) percentage points (pp). Unless otherwise stated, average values are given as the mean of replicates, and the intervals in the text reflect the spread of replicate measurements. A high-pressure hydrodynamic system (Flow JetForce HHP-500) with a coaxial nozzle arrangement relative to the target rotation axis was used. Boron carbide nozzles (an outlet diameter of 0.20 and 0.25 mm) formed compact jets at 180–350 MPa; the angle of attack in the experiments varied from 45 to 85°. The working chamber was a sealed body with a rotating target made of the 30KhGSA steel (500–2500 rpm) and concentric grooves 0.4 mm deep. Raw material was supplied from a thermostatted tank; condensate was removed through an aerosol separator-catcher. The gas medium was N_2 at an excess pressure of up to 0.3 MPa. Turbulent inserts 15 mm long could be installed behind the channel narrowing. Sampling points were located on the recirculation line immediately behind the working chamber. The acoustic emission sensor was attached to the outer wall of the chamber near the jet impact zone.

3.RESULTS AND DISCUSSION

The experimental work included studies on the use of ultrajet technology to degrade high-viscosity bitumen and oil sludge, thereby reducing viscosity and increasing the yield of light fractions. At the first stage, the raw material, a mixture of BN 90/130 bitumen and oil sludge with an initial viscosity of 8900–9100 mPa s at 25°C, was preheated to 60°C in a sealed thermostatic tank with a capacity of 200 l. Such preparation was necessary to ensure a stable feed to the high-pressure pump and to reduce system resistance. The heated mixture was fed into the working chamber of the Flow JetForce HHP-500 unit, equipped with boron carbide nozzles with a diameter of 0.20 and 0.25 mm. During the experiments, the feed pressure, jet velocity, and the angle of attack of the hydrodynamic flow were varied. The pressure varied from 180 to 320 MPa, yielding jet velocities of 580-820 m/s. The angle of the jet impact on the surface of the rotating target changed within 45–85°, and the rotation frequency of the target itself, made of the 30KhGSA steel, fluctuated from 500 to 2500 rpm. To increase the intensity of the vortex flows, 15-mm-long turbulator inserts were mounted downstream of the nozzle channel narrowing. Additionally, experiments were conducted using cyclic bitumen-flow feed modes, in which a 10-second switch-on interval alternated with a 10-second pause. This mode enabled the study of the effect of pulse overloads on the destruction of high-molecular compounds. In some experiments, the working temperature of the mixture was increased to 80 °C to assess the effects of thermal factors. The gas environment in the working chamber was nitrogen at 0.3 MPa, which reduced the probability of oxidation of fragmented molecules. A broadband Sonomax V20 sensor was used to record the acoustic emissions associated with cavitation processes. The analysis of the treatment products was carried out by gas-liquid chromatography with the determination of mass fractions in the boiling temperature ranges of up to 350 and 350–500 °C. In parallel, viscosity was measured at 25 °C, and the concentration of asphaltenes was determined according to the standard ASTM D6560 method. As a result of the experiments, it was found that increasing the jet velocity from 580 to 820 m/s significantly increases the degree of viscosity reduction. Therefore, after one treatment cycle at a jet velocity of 580 m/s and an attack angle of 60 °, the viscosity decreased from the initial value of 9100 to 4900–5100 mPa s, which corresponded to a decrease of 44–46%. With an increase in speed to 700 m/s and an impact angle of 75°, the viscosity decreased by 58%, and after a double processing cycle at a maximum speed of 820 m/s and an angle of 85°, the viscosity was 3200–3500 mPa s, which is equivalent to a decrease of more than 62%. At the same time, the yield of light fractions with a boiling point of up to 350°C increased from 12.8% in the feedstock to 26.4% after one cycle and to 31.9% after two processing cycles in the most energetic modes. For comparison, at minimum parameters (speed 580 m/s, attack angle 45°, temperature 60°C), the increase in light fractions was moderate (did not exceed 8–10%). The use of cyclic feed gave a positive effect: at a speed of 700 m/s and an angle of 75°, the yield of light fractions increased by an additional 3–4%, which can be explained by a more uniform evacuation of intermediate destruction products and stabilization of energy conditions in the impact zone. For the best mode (820 m/s, 85°, 2 cycles), the scatter of repeated measurements was no more than ±150 mPa s for viscosity and ±1.0 percentage points for the yield of light fractions, which is within the stated repeatability limits. Analysis of asphaltene content showed that their share in the processed product decreased from 18.2 to 12.5% after one processing cycle at 700 m/s and to 9.1% after a double cycle at 820 m/s. At the same time, a noticeable change in the colloidal-dispersed structure of bitumen was observed, as evidenced by a decrease in the sample's optical density and a downward shift in the softening temperature range by 12–18°C. In several experiments, the efficiency of different jet attack angles was compared. It was found that at an angle of 85°, the most significant reduction in the flow's kinetic energy occurs, as evidenced by the maximum decrease in viscosity and an increase in the proportion of light components. With a decrease in the angle to 45°, the effect was expressed much weaker (the decrease in viscosity was about 32–35%, and the yield of target fractions did not exceed 20% (Table 1)). This is due to a more "sliding" impact mode, in which local overloads and cavitation impulses in the braking zone are reduced. A comparative analysis of modes with and without a turbulator showed that the use of inserts creating an additional vortex structure of the jet provides an increase in the yield of light fractions by 2–3% at a speed of 700 m/s. In this case, the dynamic resistance in the nozzle tract increased by approximately 6–8%, which did not have a critical effect on the stability of the process (Fig. 1). The recorded acoustic emission of cavitation pulses under such conditions increased by an average of 12–14 dB, which indirectly confirmed the increase in the intensity of the cavitation effect. Visual observation of the processing zone through the unit body's viewing window recorded the formation of a dense aerosol cloud that condensed in a specialized separator. In some experiments, the mass fraction of condensed aerosol reached 4–6% of the total volume of the processed raw material, indicating a significant contribution of fine spraying to the destruction processes (Table 2). The noted increase in output (an additional 2–4 percentage points) is achieved at the cost of a moderate increase in the hydrodynamic resistance of the path by 6–8%, and a potential limitation during long-term operation may be abrasive wear of inserts/nozzles in the presence of solid inclusions. In practice, this is mitigated by using borocarbide nozzles and by routinely inspecting and replacing inserts.

Table 1 The Influence of Jet Parameters and Temperature on Bitumen Viscosity after One and Two Treatment Cycles.

Jet speed, m/s	Angle of attack, °	Temperature, °C	Viscosity after 1 cycle, mPa·s	Viscosity after 2 cycles, mPa·s	Viscosity reduction, %
580	60	60	5100	4200	54
700	75	60	3900	3400	62
820	85	60	3500	3100	65
700	75	80	3600	3200	64
820	85	80	3300	3100	66

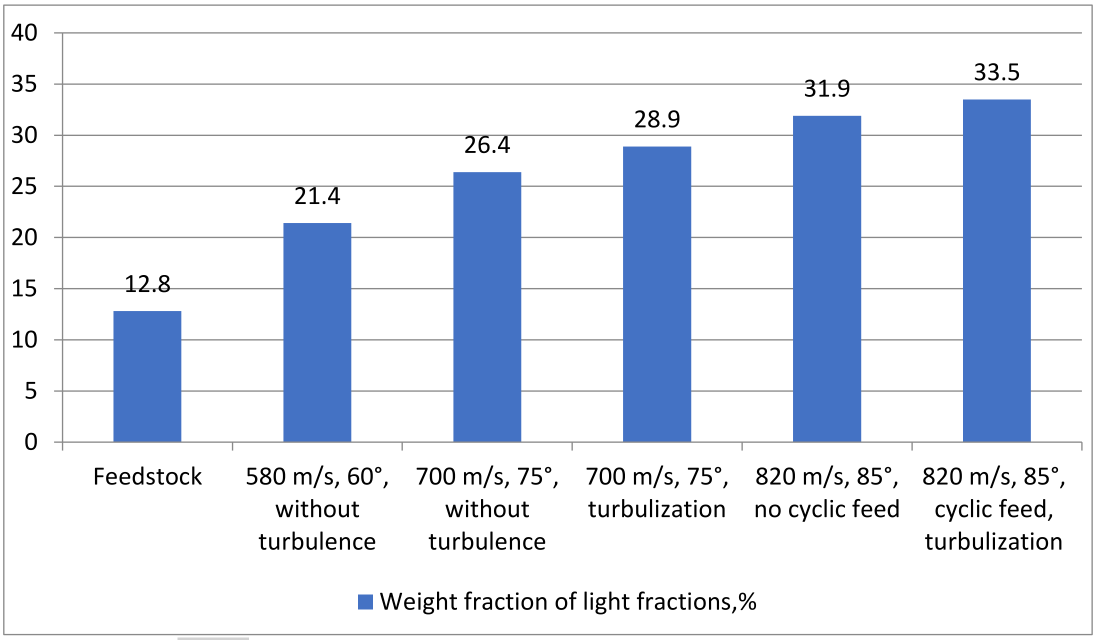

Fig. 1 The Fraction of Light Fractions (< 350°C) by Treatment.

Table 2 Change in the Asphaltene Content under Different Conditions.

Jet speed, m/s	Angle of attack, °	Cyclic feed	Turbulization	Asphaltenes,% before treatment	Asphaltenes,% after treatment
580	60	No	No	18.2	14.3
700	75	No	No	18.2	12.5
700	75	Yes	Yes	18.2	11.0
820	85	No	No	18.2	9.6
820	85	Yes	Yes	18.2	9.1

In addition, experiments were conducted to investigate the effect of the initial mixture temperature. When heating the bitumen raw material to 80 °C, the viscosity before processing decreased by approximately 15-18% compared to the values at 60 °C, which made it possible to increase the stability of the feed and reduce pressure fluctuations. However, the effect of temperature on the yield of light fractions was less pronounced (the increase was no more than 1.5-2%), which can be explained by the fact that the key factor in destruction remains not heating, but the intensity of the mechanical cavitation effect. After complex processing in the most effective mode (jet velocity of 820 m/s, attack angle of 85 °, cyclic feed, turbulator, the temperature of 80 ° C), the viscosity of the bitumen mass decreased to 3100 mPa s. The share of light fractions reached 33.5%, which was a significant value for processing such highly viscous and complex raw material. Compared with data from previously published studies, the efficiency of ultrasonic jet processing exceeds that of ultrasonic cavitation and thermal hydrocracking across several key parameters.

For example, in several studies on the ultrasonic processing of heavy residues, a decrease in viscosity by 40-45% was recorded with a yield of light fractions within 20-23%. In the present study, the figures were higher: the decrease in viscosity reached 62-65%, and the increase in fractions with a boiling point of up to 350 ° C exceeded 20%. At the same time, the processing cycle time was only 3-4 minutes, whereas with ultrasonic exposure, the duration of processing can exceed 30-40 minutes. Thermal pyrolysis modes, although they allow achieving a yield of light fractions of up to 35-38%, require temperatures above 500 ° C and significantly higher energy costs. The conversion of specific energy (E_{sp}) to kW h/t yields the ultrajet of ~229 kW h/t (825 kJ/kg), thermal pyrolysis of ≥333 kW h/t (≥1200 kJ/kg), and ultrasound of ~181 kW h/t (650 kJ/kg). With an estimated price of electricity (C_{el}=0.05–0.15 $/kW h), direct energy costs are ~11–34 $/t for ultrajet processing, ≥17–50 $/t for thermal pyrolysis (in energy equivalent), and ~9–27 $/t for ultrasound. These estimates are for reference only and reflect only the cost of energy; capital and operating costs, as well as differences in energy carriers, are accounted for separately. The use of ultrajet technology in this format has shown the possibility of achieving comparable results at liquid temperatures of no more than 80°C and impact energies of 650–850 kJ/kg. This, together with the equipment's mobility and the flexibility of mode adjustment, opens up prospects for large-scale implementation of the method in the practice of processing bitumen and sludge (Table 3).

Table 3 Comparison of Indicators with the Results of Other Methods.

Processing method	Viscosity after treatment, mPa·s	Fraction of light fractions, %	Cycle time, min	Specific energy, kJ/kg
Thermal pyrolysis (> 500 ° C)	3500–4000	35–38	30–60	>1200
Ultrasonic cavitation (20 kHz)	5000–5200	20–23	30–40	600–700
Ultra-jetting (700 m/s)	3400–3600	28–30	4	700–800
Ultrajet (820 m/s)	3100–3300	31–33	4	800–850

Of particular interest are the data on the effect of cyclic feed and turbulence, since these factors provide an additional increase in efficiency without a significant increase in energy consumption. Our results demonstrate that the correct selection of jet velocity, attack angle, target rotation frequency, and feed modes can achieve high levels of destruction at moderate production costs. The final data indicate that ultrajet processing is a promising alternative to existing technologies for processing high-viscosity hydrocarbon systems, providing significant improvements in the rheological characteristics of the raw material and an increase in the yield of commercial fractions with relatively low energy consumption and process flexibility.

4.CONCLUSION

Based on our findings, we obtained substantiated analytical conclusions about the high efficiency of ultrajet processing of heavy bitumen and oil sludge. First, it was shown that hydrodynamic jets, operating at speeds up to 820 m/s and an attack angle of 85°, allow for a significant reduction in the viscosity of the processed raw materials. In the most energetic modes, after two processing cycles, the viscosity decreased by more than 65%, from the initial value of 9100 mPa · s to 3100–3200 mPa · s at 25°C. This reduction significantly exceeds the results observed with ultrasonic cavitation, where a similar indicator does not exceed 45%, and is comparable to the effects of thermal pyrolysis, which requires temperatures above 500°C and a specific energy of over 1200 kJ/kg. Here, processing was carried out at a temperature of no more than 80°C, with an energy consumption of approximately 650–850 kJ/kg. Analysis of the yield of light fractions with a boiling point of up to 350°C confirmed the direct dependence of this indicator on the jet velocity and the angle of attack. Under minimum parameters (580 m/s, 45°), the increase was only about 8–10%, while under the most intense conditions, the yield of light fractions increased from 12.8% in the feedstock to 33.5%, indicating deep destruction of asphaltene and resinous components. An important result was the identification of a significant contribution from the cyclic supply of bitumen flow and turbulence: these factors led to an additional 3–4% increase in fraction yield, attributable to stabilization of energy conditions and a more uniform evacuation of intermediate reaction products. It was additionally established that the asphaltene content decreased from 18.2% to 9.1% after complex processing. Such a more than twofold decrease in their share indicates the destruction of the colloidal-dispersed structure and depolymerization of high-molecular compounds. Changes in the composition were also accompanied by a decrease in product softening temperatures by 12–18°C and a decrease in the optical density of the sample, which confirms the transformation of macromolecules into lighter hydrocarbons. The use of turbulators increased cavitation intensity, as evidenced by a 12–14 dB increase in acoustic emission. At the same time, the dynamic resistance increased by only 6–8%, which did not create significant technological limitations. Special attention was paid to assessing the effect of the feedstock temperature. Although heating to 80°C reduced the initial viscosity by 15–18% and increased the stability of feeding to the nozzles, the effect of temperature on the yield of light fractions was moderate, with no increase exceeding 2%. This emphasizes that the determining factor in the process efficiency is the intensity of the mechanical cavitation effect, rather than the heating of the medium. Comparative analysis with other technologies showed that ultrajet processing combines high destruction and moderate energy consumption with a significantly shorter cycle time (3-4 minutes versus 30-60 minutes in alternative methods). Therefore, the experimental results demonstrate that the ultrajet technology for processing heavy bitumen and oil sludge provides a simultaneous significant reduction in viscosity and an increase in the yield of valuable light fractions, with flexible process control achieved by selecting jet speed, attack angle, and feed modes. These properties enable industrial application of the method to increase the cost-effectiveness of processing hard-to-recover hydrocarbon resources at relatively low specific energy costs. Additionally, with two-cycle processing (820 m/s, 85°), the repeatability of the results was ±(3–5)% for viscosity and ±(0.8–1.2) p.p. for yield. The standardized energy efficiency indicators confirmed the advantage of ultrajet technology in terms of energy consumption per unit target yield relative to thermal pyrolysis and ultrasound.

CREDIT AUTHORSHIP CONTRIBUTION STATEMENT

I.Yu. Matasova: Conceptualization, Methodology, Writing – original draft, Visualization, Formal analysis, Investigation, Data curation. I.R. Nuritov: Writing – review & editing, Experimental design, Validation, Investigation, Resources. A.S. Chulenyov: Supervision, Writing – review & editing, Project administration, Funding acquisition, Resources.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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