THEORETICAL BASES OF CHEMICAL TECHNOLOGY

ТЕОРЕТИЧЕСКИЕ ОСНОВЫ ХИМИЧЕСКОЙ ТЕХНОЛОГИИ

ISSN 2686-7575 (Online)

https://doi.org/10.32362/2410-6593-2022-17-6-473-482

UDC 66-963;620.93

RESEARCH ARTICLE

Evaluation of the influence of hydrodynamic cavitation treatment of dark petroleum products on the yield of fractions with boiling points up to 400°C

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Abstract

Objectives. *The reduction of the anthropogenic burden on the environment is generally associated with the transition to alternative energy sources. However, some of these have only regional significance, while the effectiveness of others remains doubtful. On this point, innovative processes aimed at increasing the depth of oil refining may be equally important for reducing the carbon footprint. Wave-based technologies such as cavitation may also be included in these processes. Among the various methods for inducing such cavitation phenomena in oil refining, hydrodynamic approaches are especially promising. It has been shown that the treatment effectiveness increases with greater pressure or when augmenting the number of cavitation processing cycles. The aim of this work is to identify the factor (i.e., pressure gradient or number of treatment cycles) having the greatest influence on the change of the characteristics of the oil product.*
Methods. *Cavitation phenomena were created by pumping dark oil products through a diffuser. The pressure gradient ranged from 20 to 50 MPa, while the number of cavitation processing cycles varied from 1 to 10. The influence of cavitation conditions on the change of fractional composition of petroleum products was analyzed. Target fractions are those having a boiling point up to 400°C.*

Results. *It is shown that increased pressure generated in the diffuser leads to a linear increase in the yield of desired cuts. The dependence of the yield of these fractions on the number of processing cycles is described by the growth model with saturation. A proposed equation describes the influence of pressure and number of cycles on the yield of the fractions from initial boiling point temperature (T_{IBP}) to 400 °C following cavitation processing of dark oil products. Some of the coefficients of this equation have been associated with the physicochemical characteristics of the feedstock.*

Conclusions. *An equation for predicting the maximum possible yield of the T_{IBP}–400 °C fraction as a result of cavitation processing under different conditions of the process is proposed according to the physicochemical characteristics of the feedstock. The prediction error did not exceed 12%. The equation analysis and comparison of energy consumption between different process regimes shows that a higher yield of the target product is achieved by increasing pressure gradient rather than the number of processing cycles.*

Keywords: *cavitation, petroleum products, oil refining, depth of oil refining, energy efficiency*

For citation: Peshnev B.V., Burlyaeva E.V., Terenteva V.B., Nikishin D.V., Nikolaev A.I., Andronov K.S. Evaluation of the influence of hydrodynamic cavitation treatment of dark petroleum products on the yield of fractions with boiling points up to 400°C. *Tonk. Khim. Tekhnol. = Fine Chem. Technol.* 2022;17(6):473–482 (Russ., Eng.). https://doi.org/10.32362/2410-6593-2022-17-6-473-482

НАУЧНАЯ СТАТЬЯ

Оценка влияния гидродинамической кавитационной обработки темных нефтепродуктов на выход фракций, выкипающих до 400 °C

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Аннотация

Цели. *Снижение антропогенной нагрузки человечества на окружающую среду связывают с использованием альтернативных источников энергии. Однако часть из них имеет только региональное значение, а эффективность других дискуссионна. Для сокращения углеродного следа не меньший интерес представляют инновационные процессы, направленные на увеличение глубины переработки нефти. К числу таких процессов можно отнести и волновые технологии, частным случаем которых является кавитация. Кавитационные явления для нефтепереработки создают различными методами, наиболее перспективным из которых считаются гидродинамические. Установлено, что эффективность воздействия возрастает как при повышении давления при прокачке нефтепродукта, так и при увеличении количества актов воздействия. Цель данной работы – какой из двух факторов – градиент давлений или количество циклов воздействия – оказывает большее влияние на изменение характеристик нефтепродукта.*

Методы. *Явление кавитации создавали, прокачивая темные нефтепродукты через диффузор. Давление варьировалось от 20 до 50 МПа, а количество актов воздействия – от 1 до 10. Анализировалось влияние условий кавитации на изменение фракционного состава нефтепродуктов. В качестве целевых рассматривались фракции, выкипающие до 400 °С.*

Результаты. *Показано, что выход целевых фракций линейно увеличивается при повышении давления, возникающего в диффузоре. Зависимость выхода этих фракций от количества циклов обработки описывается моделью роста с насыщением. Предложено уравнение, описывающее влияние давления и количества циклов на выход фракции от температуры начала кипения ($T_{НК}$) до 400 °С после кавитационной обработки темных нефтепродуктов. Установлена связь некоторых из коэффициентов этого уравнения с физико-химическими характеристиками исходного сырья.*

Выводы. *Предложено уравнение, позволяющее по физико-химическим характеристикам исходного сырья предсказать максимально возможный выход фракции $T_{НК}$–400 °С в результате кавитационной обработки при различных условиях ведения процесса. Ошибка прогнозирования не превышает 12%. Анализ полученного уравнения и сопоставление энергозатрат при различных режимах ведения процесса показывают, что больший выход целевого продукта достигается в результате увеличения давления, а не числа циклов обработки.*

Ключевые слова: *кавитация, нефтепродукты, переработка нефти, глубина переработки, энергетическая эффективность*

Для цитирования: Пешнев Б.В., Бурляева Е.В., Терентьева В.Б., Никишин Д.В., Николаев А.И., Андронов К.С. Оценка влияния гидродинамической кавитационной обработки темных нефтепродуктов на выход фракций, выкипающих до 400 °С. *Тонкие химические технологии*. 2022;17(6):473–482. https://doi.org/10.32362/2410-6593-2022-17-6-473-482

INTRODUCTION

Recently, there has been a pronounced tendency in the global energy sector to minimize emissions of carbon oxides (hydrocarbon combustion products) into the atmosphere. To achieve this, various alternatives are offered: wind power, hydrogen-based energy forms, solar energy, storage, etc. Each of the methods under consideration has advantages (which are typically considered in detail) and disadvantages (which advocates generally keep silent about). For example, wind and geothermal energy are only of regional importance. The use of solar energy is also complicated by the seasonal factor. Renewable sources of raw energy materials (biofuels) involve the use of significant areas of agricultural land. When using hydrogen as an energy vector, net zero carbon is achieved only when the gas is obtained by electrolyzing water using renewable energy sources. In other cases, the carbon footprint may be even greater than that of traditional energy carriers.

In this regard, in order to reduce the anthropogenic load of mankind on the environment, it may be more effective to develop technologies aimed at increasing the depth of oil refining.

Oil refining depth is understood as the ratio of the volume of products obtained from oil (minus the cost of refining it) to that of the feedstock oil [1, 2]. As a rule, only refined products are taken into account. The overall oil refining depth in Russia is estimated at 84.4%, varying from 74.5% (enterprises of *Rosneft*) to 94.6% (*Omskii NPZ*, *Gazprom Neft*). For comparison, the oil refining depth at the enterprises of the European Union is estimated at 85%, while in the United States of America, the comparable figure reaches 96%.[1]

An increase in oil refining depth is usually associated with the use of visbreaking, hydrocracking, and coking processes. In recent years, new plasma- and wave-based technologies for increasing the yield of light fractions in oil refining processes have been

[1] The territory of discoveries. PJSC Rosneft. Annual report. 2020. URL: https://www.rosneft.ru/upload/site1/document_file/a_report_2020.pdf (accessed September 21, 2021).

proposed [3–5]. The latter should be recognized as more promising, since they do not imply complete destruction of raw materials, but can be successfully combined with traditional processes [6, 7]. Such wave-based technologies include those relying on the phenomenon of cavitation.

Cavitation consists in the nucleation at the interface of phases (liquid–liquid, liquid–solid) of a gas bubble nucleus, including its growth and subsequent collapse. It is noted that at the stage of compression of a gas bubble, temperatures can reach 5000 K, while, following collapse, they can increase to 10000 K [8–10]. If this phenomenon occurs in a hydrocarbon environment, it can lead to cracking reactions. The validity of this assumption is confirmed by reports of a decrease in the boiling point of petroleum products, the distillation temperatures of 50% of fractions, as well as a decrease in viscosity [11–13]. A number of researchers recorded the appearance of unsaturated hydrocarbons and hydrocarbons of lower molecular weight following exposure to cavitation [14, 15].

Although a large number of publications have been devoted to the study of the effect of cavitation on the physicochemical characteristics of petroleum products, the overwhelming majority of them are descriptive. The authors mainly record the changes that are taking place, and there have been practically no attempts to generalize them, to propose a mathematical model that would allow predicting changes based on the characteristics of the raw materials. One more important point was left aside. The researchers noted that when processing raw materials in a hydrodynamic flow, the changes depend not only on the pressure arising in the diffuser, but also on the number of exposure cycles, but which of these factors affects the result more significantly was not considered.

The present work is dedicated to identifying the factors that have the greatest impact on the change in the characteristics of petroleum products.

EXPERIMENTAL

Dark oil products of primary and secondary oil refining were selected as objects of research: fuel oil, catalytic gas oil (CGO), vacuum gas oil (VGO) and fuel oil provided by *Gazpromneft – MNPZ* (FOM), Russia, as well as fuel oil (FOK) provided by *Kirishinefteorgsintez*, Russia. The characteristics of the research objects are given in Table 1.

The studies were conducted in accordance with the methodology described in [6, 16]. Petroleum products were pumped through a diffuser, on which pressure was applied to actuate the phenomenon of cavitation. The pressure varied from 20 to 50 MPa, while the number of exposure cycles ranged from 1 to 10. The total yield of fractions boiling off in the temperature range from the initial boiling point (T_{IBP}) to 400°C was taken as the target indicator.

RESULTS AND DISCUSSION

The effect of the processing conditions of the FOM sample on the yield of the fraction T_{IBP}–400°C is shown in Fig. 1.

Table 1. Characteristic of research subjects

Indicator	Sample			
	CGO	VGO	FOM	FOK
Density, g/cm^3	1.1002	0.8998	0.9684	0.9478
Yield of T_{IBP}–350°C fraction, wt %	5.2	8.4	5.0	13.2
Yield of 350–400°C fraction, wt %	25.8	34.5	9.0	15.8
Yield of 400–480°C fraction, wt %	69.0	40.9	28.0	47.0
Yield of 480+°C fraction, wt %		16.2	58.0	24.0

Note: CGO – catalytic gas oil; VGO – vacuum gas oil; FOM – fuel oil provided by *Gazpromneft – MNPZ*; FOK – fuel oil provided by *Kirishinefteorgsintez*.

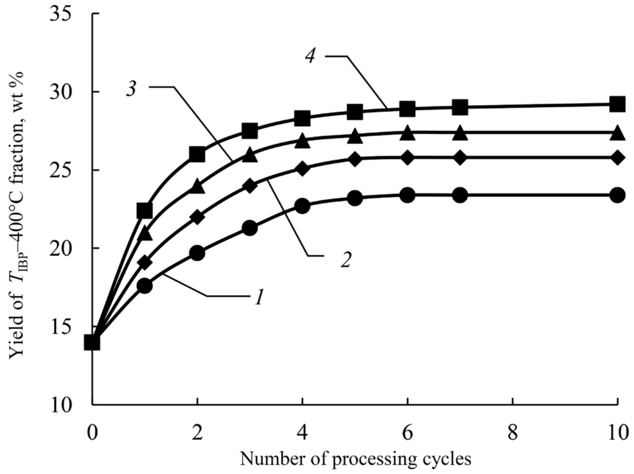

Fig. 1. Influence of the processing conditions on the yield of fractions T_{IBP}–400°C of a fuel oil (*Gazpromneft – NMPZ*) sample: *1* – treatment pressure 20 MPa; *2* – treatment pressure 30 MPa; *3* – treatment pressure 40 MPa; *4* – treatment pressure 50 MPa.

The presented results are consistent with those obtained earlier: an increase in pressure and the number of exposure cycles led to an increase in the yield of the fraction boiling up to 400°C. At the same time, the greatest increase in the yield of target fractions occurred during the first processing cycles. After 5 cycles of exposure, no significant increase in the yield of fractions was recorded, with the curve of their yield dependence on the number of treatment cycles reaching the saturation line. Similar results were obtained for other samples.

Such dependencies are well described by growth models with saturation. These models based on exponential dependence are often called linear growth functions, since the growth rate of the studied quantity is a decreasing linear function [17]. One such model proposed by L. Bertalanffy has been widely used to solve problems in chemistry and biology [18].

According to this model, the dependence of the yield of fractions R on the number of cycles t can be described by equation (1):

$$R(t) = A(1 - Be^{-kT}), \qquad (1)$$

where A is the limit value of R (saturation value); B is the coefficient characterizing the difference between the initial and limit values of R ($R(0) = A(1-B)$); k is the growth rate coefficient. The greater the k, the faster saturation is achieved.

For all samples, the dependence of the yield of the target fractions on pressure, regardless of the number of processing cycles, is linear (Fig. 2), while the values of the correlation coefficient between the yield of the fraction T_{IBP}–400°C and pressure exceed 0.98.

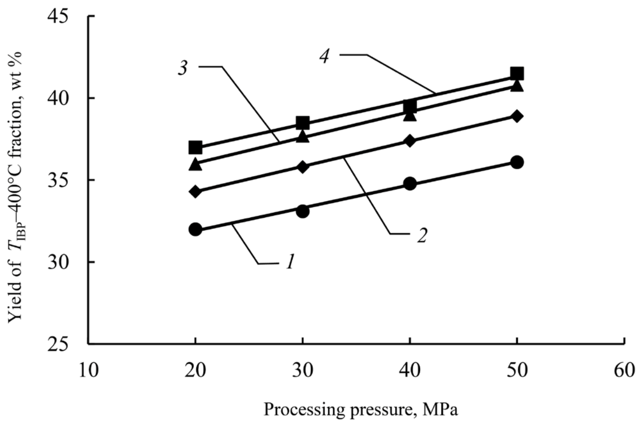

Fig. 2. Influence of the processing conditions on the yield of fractions T_{IBP}–400°C of a fuel oil (FOK) (*Kirishinefteorgsintez*) sample: *1* – 1 processing cycle; *2* – 3 processing cycles; *3* – 5 processing cycles; *4* – 10 processing cycles.

As a result, the relationship between the yield of the fraction T_{IBP}–400°C, pressure and the number of sample processing cycles can be described by the following mathematical model (2):

$$R = (A_0 + A_1 \cdot p)(1 - (B_0 + B_1 \cdot p)e^{-(k_0 + k_1 \cdot p)t}) \qquad (2)$$

For each sample, all coefficients of the model were calculated using the least squares method. The error of the calculated values of the fraction yield for each sample did not exceed 3% (Table 2). Thus, the proposed model describes the experimental data well.

Further analysis showed that there is a linear relationship between the yield of the fraction T_{IBP}–400°C of the initial sample (before its processing, R_0) and the values of the coefficients A_0 and B_0, which is described by equations (3) and (4):

$$A_0 = 0.72 \cdot R_0 + 12.3 \qquad (3)$$

$$B_0 = -0.012 \cdot R_0 + 0.53 \qquad (4)$$

Table 2. Growth model coefficients and calculation error values

Sample	Coefficients						Error, %	Error at average values of k, %
	A_0	A_1	B_0	B_1	k_0	k_1		
CGO	33.4	0.45	0.16	0.005	0.38	0.005	1.7	2.0
VGO	42.8	0.21	0.025	0.003	0.4	0.002	2.7	4.0
FOM	21.8	0.14	0.37	0.003	0.01	0.015	1.3	2.9
FOK	34.4	0.13	0.16	0.002	0.15	0.011	2.7	2.9

The value of the correlation coefficient between A_0 and R_0 is 0.98, while the corresponding value between B_0 and R_0 is 0.99.

Since the use of average values of growth coefficients $k_0 = 0.26$ and $k_1 = 0.009$ for all samples leads to only an insignificant increase in error, no greater than 4%, these coefficients can be taken as constants. The error values for the selected values k_0 and k_1 are also given in Table 2.

The coefficients A_1 and B_1 characterize the relationship between the output of the target fraction, the pressure, and the number of cycles. However, it was not possible to establish the relationship between the values of these coefficients and the characteristics of the initial sample on the basis of the available data. It is possible that the values of these coefficients are influenced by the group composition of the raw material or its gas content. The paper [19] presents the results indicating the influence of gas content on the yield and characteristics of fractions of petroleum products during their cavitation treatment. These results also suggest the influence of group composition.

The analysis of the obtained results allowed us to assume that the value of the yield of the fraction T_{IBP}–400°C after 7 processing cycles (after the curve reaches saturation) at different pressure values can be predicted using only data on the initial sample (before processing). The coefficients of linear dependence (5) were determined using the least squares method:

$$R = 0.25 \cdot p + 0.85 \cdot R_0 + 7.4 \quad (5)$$

The constructed model is adequate according to the Fisher criterion. The value of the determination coefficient R^2 for this model is 0.85, while the error is 12%.

Thus, before cavitation takes place, it is possible to estimate to what maximum value the yield of the target fraction will increase as a result of treatment at different pressures.

The presented results indicate that it is possible to predict the effectiveness of the impact (pressure created in the diffuser and the number of exposure cycles) on the yield of fractions boiling up to 400°C.

Analysis of equation (2) suggests that pressure has a greater effect on increasing the yield of the target fraction. For confirmation, the energy consumption levels for the creation of cavitation phenomena at different pressures and processing cycles, as well as target product output, were compared. To do this, equation (6), given in [20], was used to calculate the useful power of the pump:

$$N_p = \rho V g H, \quad (6)$$

where N_p is the pump power output; ρ is the density of the pumped liquid; V is the volumetric flow rate (capacity) of the pump; g is the acceleration of gravity; H is the head.

During the calculations, an assumption was made about the constancy of the mass of the sample during processing; for this purpose, it was necessary to take into account the change in the density of the sample after each exposure cycle. In all cases, the volumetric flow rate of the initial sample was assumed to be 0.1 m^3/s.

It follows from equation (6) that an increase in pressure (by 2, 3, etc. times) or an increase in the number of processing cycles (by the same number of times) leads to the same increase in energy consumption. The relationship between the energy costs of creating cavitation under different conditions of the process is shown in Fig. 3 along with the yield of the fraction T_{IBP}–400°C.

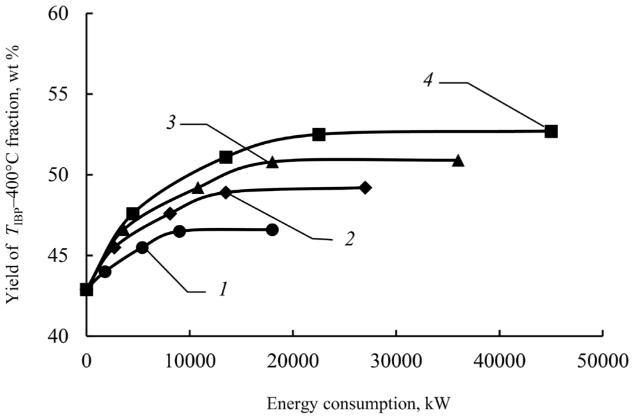

Fig. 3. Influence of energy consumptions and pressure on the yield of fractions T_{IBP}–400°C of a vacuum gasoil sample in cavitation processing: *1* – treatment pressure 20 MPa; *2* – treatment pressure 30 MPa; *3* – treatment pressure 40 MPa; *4* – treatment pressure 50 MPa.

Similar results were obtained for other samples. It can be seen that energy consumption increases comparably both with an increase in pressure and with an increase in the number of processing cycles. However, a greater effect (an increase in the yield of fractions of T_{IBP}–400°C) is achieved with an increase in pressure.

CONCLUSIONS

As a result of the conducted research, an equation describing the effect of pressure and the number of cycles on the yield of the fraction T_{IPB}–400°C after cavitation treatment of dark oil products is proposed. The connection of some of the coefficients of this equation with the physicochemical characteristics of the feedstock is established. The equation can be used to predict the maximum possible yield of the fraction T_{IBP}–400°C as a result of cavitation treatment under various conditions of the process according to the physicochemical characteristics of the feedstock with a prediction error less than 12%. The analysis of the equation and the comparison of energy consumptions between different process regimes shows that a higher yield of the target product can be achieved by increasing pressure gradient rather than the number of processing cycles.

Authors' contribution

All authors equally contributed to the research work.

The authors declare no conflicts of interest.

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The article was submitted: March 01, 2022; approved after reviewing: June 20, 2022; accepted for publication: November 17, 2022.

Translated from Russian into English by N. Isaeva
Edited for English language and spelling by Thomas Beavitt