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This paper reports a study into the effect of cavitation on the octane number of gas-condensate gasoline with the addition of isopropanol in the amount of 0–12 % by volume. The papers that confirm the impact of cavitation on the intensification of oil cracking reactions have been analyzed. Cavitation also initiates reactions of interaction between free radicals and alcohols. A laboratory installation scheme has been proposed to investigate the cavitation treatment process on the characteristics of gasoline modified with alcohols. A methodology has been devised for studying the effect of cavitation treatment intensity on the octane number of gasoline. A 0.3–0.9-point increase in the octane number of gas-condensate gasoline modified with isopropanol was experimentally proven following its cavitation treatment. The effect of the number of cavitation treatment cycles on the octane number indicator has been studied; it is shown that the stable value of an increase in the octane number is achieved over 7–8 ycles of cavitation treatment at a pressure at the outlet from the nozzle of 9.0 MPa. A reduction in the isopropanol additive, required to produce gasoline brands A-95 and A-98, when using a cavitation treatment technology was substantiated. It has been experimentally confirmed that compared to simple mechanical mixing of alcohol and hydrocarbon gasoline, the application of cavitation reduces the consumption of isopropanol by 17 % (from 3.0 % to 2.5 % by volume) in the production of gasoline brand A-95; and by 14 % (from 8.1 % to 7.0 % by volume) in the production of gasoline brand A-98. The effect of isopropanol concentration on the increase in the octane number of gasoline, measured by research method, under conditions of cavitation treatment is nonlinear in nature: with highs at concentrations of 1.0 % by volume, 3.5 % by volume, and 6.5 % by volume. Varying the initial concentration of isopropanol and the octane number of a hydrocarbon gasoline fraction can optimize the technological mode of production of gasoline brands A-95 and A-98 in terms of raw materials and energy consumption

Keywords: hydrodynamic cavitation, isopropanol, octane number, bioethanol, gas-condensate gasoline, octanometer, intensification

DETERMINING THE INFLUENCE OF CAVITATION TREATMENT ON THE OCTANE NUMBER OF GAS-CONDENSATE GASOLINE MODIFIED WITH ISOPROPANOL

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1. Introduction

The effect of hydrodynamic cavitation – the formation and subsequent collapse of liquid bubbles – is widely used in chemical technology to selectively supply energy to the reaction zone. Each bubble can be regarded as a separate reactor in which a change in the cavitation mode can control the temperature and pressure, increasing them locally by tens of

times. At a sufficiently intensive cavitation treatment of a liquid, it is possible to achieve significant acceleration of chemical reactions at relatively low energy consumption. Some processes in the chemical technology such as the cracking of hydrocarbon molecules and the recombination of radicals can be executed, under cavitation conditions, at room temperature; it is possible to achieve the results inherent in the processes of thermal and thermocatalytic cracking.

The cavitation treatment of gasoline modified with alcohols, aimed at increasing their octane number (ON), has proven effective. The effect of cavitation on alcohol-gasoline mixtures makes it possible to improve the ON indicators, defined both by the research (RON, research octane number) and motor (MON, motor octane number) methods. The use of cavitation makes it possible to devise an effective technology to produce gasoline brands A-95 and A-98. The new technology could reduce the cost of raw materials – a high-octane additive to fuel – compared to the conventional mechanical mixing of liquids.

In the future, that would reduce the cost of commercially available types of gasoline, as well as profits from selling them. These facts render relevance to the scientific and practical task to search for technologies and modes of effective cavitation treatment of alcohol-gasoline mixtures.

Isopropanol (IPA) is a promising raw material among other single-atomic alcohols for use in a mixture with gas-condensate gasoline.

Compared to methanol, the use of IPA is more appropriate. IPA has less toxicity than methanol. The DSTU 7687:2015 standard allows the use of a larger volumetric amount of IPA – 12 % by volume for the E10 type gasoline. The permitted amount of methanol is only 3.0 % by volume.

Compared to ethanol, the use of IPA is also appropriate because its production must not comply with strict legislative regulation. IPA is mostly made in the world by propylene hydration. Coming years may prove that on a global scale it is possible to make use of more propylene to produce IPA due to the general tendency to reduce the production of plastics, including polypropylene, which is also produced from propylene. Therefore, IPA may become a competitor for methanol and bioethanol as a high-octane additive to gasoline.

It is a relevant scientific task to devise technologies for modifying gasoline with isopropanol under the influence of cavitation; it is feasible enough to be rapidly implemented industrially.

2. Literature review and problem statement

Cavitation is an effective tool for the selective energy supply to a chemical reaction zone. In recent years, scientific areas related to the study of the influence of acoustic and hydrodynamic cavitation on the oil fraction treatment processes have been actively advancing.

Work [1] examined the effect of ultrasonic cavitation treatment of raw materials on the physicochemical properties and content of asphaltenes in oil residues. Intense cavitation action with an intensity of 24 kHz is shown to reduce the total number of asphaltenes from 13.5 to 7 %, as well as reduce viscosity characteristics. The decrease in asphaltenes demonstrates that cavitation was able to achieve the initialization of cracking reactions of highly molecular hydrocarbon molecules. The process was carried out at room temperature and pressure in compliance with the cavitation treatment time

longer than 15 minutes. However, the cited work does not reveal the mechanism of cavitation impact on the chemical composition of products.

Paper [2] studied the effect of hydrodynamic cavitation on the viscosity of heavy oil in the presence of metal nanoparticles and a hydrogen donor, which could be a gasoline fraction. It is shown that the addition of 0.01 liters of gasoline per 1 liter of heavy oil and 10-minute cavitation cracking process at 80 °C and above-the-atmospheric pressure reduces the viscosity of heavy oil by about 20 %. However, the cited paper does not show the effect of cavitation on the formation of catalytic activity of the metal, although the occurrence of active catalyst nanoparticles was claimed. Similar tasks were solved in work [3]; tetrahydronaphthalene was used as a donor of hydrogen. In that case, the use of cavitation also made it possible to redistribute hydrogen and reduce the viscosity of heavy oil, although the change in the composition and octane number of gasoline fraction of oil was not studied.

Work [4] effectively demonstrates the impact of cavitation on the cracking of hydrocarbon molecules with the number of a carbon atom from 8 to 26. The application of ultrasonic cavitation to the diesel fraction in the cited work led to the formation of soot nanoparticles. However, the authors did not associate the mechanism of soot formation with the intensification of reactions, which in parallel can increase the octane number of gasoline. Intensive cavitation treatment of raw materials under some technological modes can accelerate not only the reactions of cracking but also intensify the processes of polymerization. Paper [5] shows that during the cavitation treatment of heavy oil in the presence of nickel nanoparticles there was an increase in the viscosity of the product. The authors have not drawn conclusions about the required and sufficient intensity of the mechanochemical activation of raw materials through cavitation to prevent compaction reactions.

The effect of hydrodynamic cavitation on the composition of cracking products was confirmed even when cavitation is a by-parameter. Study [6] shows the ways the cavitation processes in a pump before the fracking column of the catalytic cracking plant can change the fractional composition of the products and the characteristics of gasoline; however, the impact of cavitation on the octane number has not been confirmed by experimental data.

Theoretical justification of the amount of energy needed to break chemical bonds in oil during its cavitation treatment is reported in work [7]. The increase in the light distilled products reached 5 % per raw material, that is, the number of heavy fractions that underwent cracking under the influence of cavitation amounted to 10 18 %. The authors showed that there is a possibility of executing the cracking processes of raw materials exclusively by the influence of cavitation but did not propose to separate this process for the manufacturing technology of individual components and commercially available gasoline brands.

The cavitation cracking of hydrocarbons was modeled in work [8]. The authors determined a liquid's flow rate of 43 m/s, sufficient for cavitation transformations in the centered cavitation chamber and showed the heterogeneity of cavitation processes in the apparatus. That is, the design of the cavitation device largely affects the effectiveness of the process of modification of oil fractions, in particular gasoline, although the impact of a liquid's flow rate on the chemical transformations of raw materials was not studied. A study reported in [9] demonstrated that hydrodynamic cavitation is a potentially attractive option as a technology to intensify

heavy oil modernization processes; although these processes are promising to modernize refineries, no specific proposals for the design of manufacturing processes were provided. The authors of review [10] explained the mechanism by which cavitation technologies intensify water de-emulgation in emulsions, reducing the viscosity of crude oil, oxidizing desulfurization, and demetallization of oil and individual fractions. This makes cavitation a promising technology for the comprehensive impact on oil fractions, which would simultaneously improve several necessary characteristics of products, although it is not shown how water impurities affect the chemical transformation of hydrocarbons under the influence of cavitation.

Work [11] explores various technological modes of oil fraction treatment when implementing a process of hydrocarbon hydraulic cracking; although the main product of these processes is a gasoline fraction, the change in its operational properties was not investigated. Paper [12] shows the effect of cavitation on fuel combustion processes but the processes of making fuels and their combustion under the influence of cavitation were not linked by a unified theory.

The original research, reported in [13], demonstrated the possibility of changing the octane number of A-92 gasoline by changing the cavitation treatment intensity. It is established that there is an optimal time of cavitation treatment over which the maximum impact of cavitation on the octane number is achieved. However, the cited research does not provide any theory that could relate the time of cavitation to the intensity of the mechanochemical activation of gasoline and does not consider the effect of cavitation on gasoline when adding alcohols. Another work [14] studied the impact of cavitation treatment on the characteristics of the gasoline fraction modified with bioethanol. It is shown that cavitation can significantly improve the anti-detonation characteristics of alcohol-gasoline mixtures; however, no experimental data are given to investigate the effect of cavitation in the modification of gasoline with other single-atomic alcohols.

Our analysis of the scientific literature has revealed the possibility and prospects of implementing cavitation treatment technologies in the processes of fuel modification. It is promising to study the impact of cavitation on the ON of gas-condensate gasoline modified with IPA because that would open the possibility of devising a technology to industrially produce A-95 and A-98 gasoline brands at a reduced cost for a high-octane additive. Currently, isopropanol is cheaper in the market than such a common high-octane additive as MTBE. In addition, IPA is a real competitor to bioethanol because it has the prospect of being produced in large quantities from propylene obtained at catalytic cracking plants. The use of IPA and the cavitation treatment of alcohol-gasoline mixtures could make it possible to industrially produce gasoline brands at a lower raw material cost compared to conventional manufacturing processes.

3. The aim and objectives of the study

The aim of this work is to determine the impact of cavitation treatment on the ON of the mixtures of gas condensate and IPA of different concentrations in order to industrially produce A-95 and A-98 gasoline brands.

To accomplish the aim, the following tasks have been set:
– to investigate a change in ON due to the number of cavitation treatment cycles;
– to detect the impact of cavitation on the increase in ON for a mixture of gas-condensate gasoline with IPA at different concentrations;
– to provide recommendations on the manufacturing modes of cavitation treatment for the industrial production of A-95, A-98 gasoline brands from gas condensate and IPA;
– to compare the cost of IPA to industrially produce A-95 and A-98 gasoline brands at the mechanical mixing of IPA and gas-condensate gasoline and at the cavitation treatment of an alcohol-gasoline mixture.

4. The study materials and methods

A laboratory installation, designed to study the impact of the number of cavitation treatment cycles on the ON of gasoline modified with alcohols, is shown in Fig. 1: schematically in Fig. 1, *a*, and a photograph in Fig. 1, *b*.
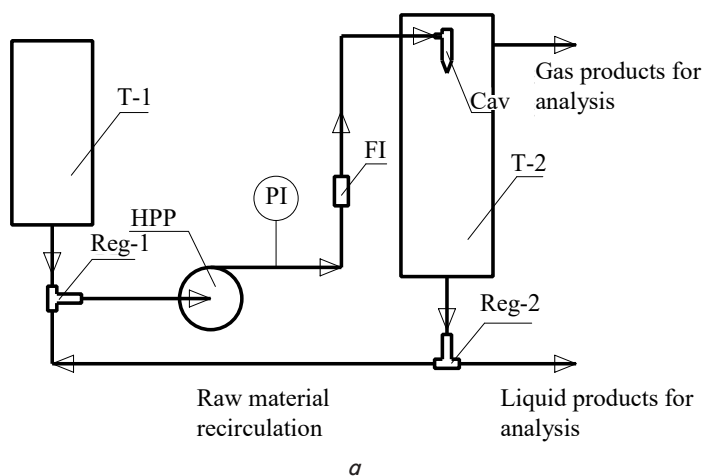

Fig. 1. Laboratory unit to study the impact of cavitation treatment on the ON and composition of gas-condensate gasoline with the addition of IPA: *a* — schematic of the unit ; *b* — a photograph of the unit ; T-1 — tank with raw materials (a mixture of GK-gasoline and IPA), T-2 — tank-separator for products, Cav — injector reactor that performs the cavitation treatment of raw materials, HPP — a high-pressure pump, Reg-1 — a three-way valve with control feature, Reg-2 —a three-way valve, PI — pressure gauge, FI — flow regulator

Before the experiment, we prepared an alcohol-gasoline mixture with a predefined concentration of IPA. Next, the finished mixture was loaded into a container (T-1) and, using a pump (HPP), was fed to a cavitation nozzle (Cav). The nozzle generates a pressure at the outlet from the nozzle of 9.0 MPa controlled by a pressure gauge (PI); cavitation cavities form at the outlet of the injector nozzle that act as the mini-reactors in which chemical transformations take place.

Cavitation cavities also form in the collision of raw materials droplets with the reactor walls and with a cone-shaped reflector. The collision rate exceeds 140 m/s.

One cycle of cavitation treatment includes the movement of raw materials along the contour "(T-1)-(Reg-1)-(HPP)-(FI)-(Cav)-(T-2)-(Reg-2)-(Reg-1)-(T-1)". The number of cavitation treatment cycles ensures the achievement of a stable value of ON under these conditions. A mixture of gasoline products and IPA, degassed in a separator (T-2), is analyzed for the indicators of RON and MON.

The ON of raw materials and products is measured by the octanometer SHATOX SX-150 (manufactured at the Institute of Petroleum Chemistry, Tomsk, Russia, 2009; supplied by TOV Veritas, Mykolaiv, Ukraine). The device principle of operation is to determine the antidetonation resistance of gasoline by measuring their dielectric permeability and specific volumetric resistance. Control method implies modeling the electrical parameters equivalent to the electrical parameters of the analyzed mixture. The instrument can measure ON (RON and MON) in a range of 40–135 points with a measurement error of ±0.5 and a deviation from parallel measurements of ±0.2. The measurement time is 1–5 s. The values of RON and MON, acquired from this device, meet the standards ASTM D 2699-86, ASTM D 2700-86, EN 228-99.

5. Results of studying the intensity of cavitation treatment on the ON of gas-condensate gasoline

We have solved the task of studying a change in octane number (RON and MON) due to the number of cavitation treatment cycles for different concentrations of IPA in gas-condensate gasoline by acquiring experimental data given in Table 1 where columns 2–12 show the actual ON indicators after a certain number of cavitation treatment cycles.

The study aimed to find the IPA concentrations and cavitation regimes suitable for increasing RON to 95 and 98 points. These RON values correspond to the indicators of commercially available A-95 and A-98 gasoline brands.

We have solved the task of studying the impact of cavitation on the ON increase in a mixture of gas-condensate gasoline and IPA

at different concentrations by comparing the achieved increment (RON) and (MON) with the initial indicators. The data are given in Table 2. The accepted stable (RON) and (MON) indicators are the ON values, which do not change after 7–8 or more cycles of cavitation treatment at a nozzle with a pressure of 9.0 MPa.

After a certain number of cavitation treatment cycles, a stable value of (RON) and (MON) was reached, which no longer changed in subsequent cycles at the same pressure at a nozzle. For the isopropanol additive, 7–8 cycles of cavitation treatment in the interval of IPA concentrations from 0.5 to 12.0 % by volume are sufficient at a pressure at a nozzle of 9.0 MPa

Table 1

A change in RON and MON due to the number of cavitation treatment cycles for gas condensate with an IPA additive

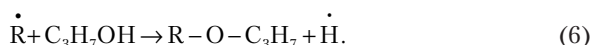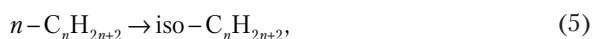| ON	The number of cavitation treatment cycles										
	0	1	2	3	4	5	6	7	8	9	10
1	2	3	4	5	6	7	8	9	10	11	12
Gas condensate without an IPA additive											
RON	92.3	92.4	92.4	92.6	92.6	92.8	92.9	92.9	92.5	93.0	93.1
MON	83.3	83.5	83.5	83.7	83.7	83.7	83.8	83.8	83.8	83.8	83.8
Gas condensate with an IPA additive in the amount of 0.5 % by volume											
RON	93.0	93.3	93.0	93.4	93.4	93.4	93.5	93.4	93.5	93.5	93.7
MON	83.8	83.8	83.8	83.8	83.8	83.8	83.9	83.8	83.9	83.9	83.9
Gas condensate with an IPA additive in the amount of 1 % by volume											
RON	93.2	93.8	93.8	93.8	93.7	93.9	93.6	94.0	94.0	94.2	94.1
MON	83.8	84.0	84.0	84.0	83.9	84.0	83.9	84.0	84.1	84.2	84.1
Gas condensate with an IPA additive in the amount of 1.5 % by volume											
RON	94.0	93.9	94.1	94.2	94.2	94.4	94.4	94.5	94.2	94.5	94.6
MON	84.1	84.0	84.1	84.2	84.2	84.4	84.4	84.5	84.2	84.5	84.6
Gas condensate with an IPA additive in the amount of 2 % by volume											
RON	94.6	94.6	94.7	94.7	94.7	94.7	94.8	94.9	94.9	94.9	95.0
MON	84.6	84.6	84.7	84.7	84.7	84.7	84.8	84.9	84.9	84.9	85.0
Gas condensate with an IPA additive in the amount of 2.5 % by volume											
RON	94.9	94.9	94.8	95.0	95.0	95.0	95.0	95.1	95.5	95.7	95.8
MON	84.9	84.9	84.8	85.0	85.0	85.0	85.0	85.1	85.5	85.7	85.8
Gas condensate with an IPA additive in the amount of 3 % by volume											
RON	95.0	95.0	95.1	95.1	95.4	95.1	95.4	95.6	95.7	95.8	95.9
MON	85.0	85.0	85.1	85.1	85.4	85.1	85.4	85.6	85.7	85.8	85.9
Gas condensate with an IPA additive in the amount of 3.5 % by volume											
RON	94.9	95.3	95.5	95.7	95.7	95.8	95.8	95.8	95.8	95.8	95.8
MON	84.9	85.3	85.5	85.7	85.7	85.8	85.8	85.8	85.8	85.8	85.8
Gas condensate with an IPA additive in the amount of 4.0 % by volume											
RON	95.8	96.0	96.1	96.1	96.2	96.2	96.2	96.2	96.3	96.4	96.3
MON	85.8	86.0	86.1	86.1	86.2	86.2	86.2	86.2	86.4	86.5	86.3
Gas condensate with an IPA additive in the amount of 5.0 % by volume											
RON	96.5	96.5	96.7	96.7	96.8	97.0	97.1	97.0	97.1	97.0	97.1
MON	86.7	86.8	87.1	87.1	87.2	87.2	87.2	87.2	87.2	87.2	87.2
Gas condensate with an IPA additive in the amount of 7.0 % by volume											
RON	97.6	97.9	97.9	98.0	98.0	98.1	98.1	98.1	98.2	98.3	98.5
MON	87.6	87.9	87.9	88.0	88.0	88.1	88.1	88.1	88.3	88.4	88.7
Gas condensate with an IPA additive in the amount of 10.0 % by volume											
RON	101.5	101.7	101.7	101.8	102.0	102.0	102.0	102.1	102.2	102.2	102.1
MON	91.2	91.4	91.4	91.5	91.7	91.7	91.7	91.7	91.9	91.9	91.7
Gas condensate with an IPA additive in the amount of 12.0 % by volume											
RON	104.3	104.2	104.3	104.3	104.4	104.5	104.5	104.6	104.6	104.6	104.5
MON	93.8	93.7	93.8	93.8	93.9	94.0	94.0	94.1	94.1	94.1	94.0

Table 2

The indicators of RON and MON before and after cavitation treatment depending on the content of IPA in gas condensate

No.	IPA content, % by volume	RON		MON		ON increment, points	
		Before	After	Before	After	RON	MON
1	0	92.3	92.88	82.3	82.8	0.58	0.50
2	0.5	93.0	93.53	83.8	83.88	0.53	0.08
3	1.0	93.2	94.08	83.8	84.1	0.88	0.3
4	1.5	94.0	94.45	84.1	84.45	0.45	0.35
5	2.0	94.6	94.93	84.6	84.43	0.33	0.33
6	2.5	94.9	95.53	84.9	85.53	0.63	0.63
7	3.0	95.0	95.75	85.0	85.75	0.75	0.75
8	3.5	94.9	95.8	84.9	85.8	0.9	0.9
9	4.0	95.8	96.3	85.8	86.35	0.5	0.55
10	5.0	96.5	97.05	86.7	87.2	0.55	0.5
11	7.0	97.6	98.28	87.6	88.38	0.68	0.78
12	10.0	101.5	102.15	91.2	91.8	0.65	0.6
13	12.0	104.3	104.58	93.8	94.08	0.27	0.27

6. Analysis of experimental data and comparison of results with data from previous studies

The results from Table 1 suggest that the addition of IPA leads to increased (RON) and (MON) throughout the entire interval of our study. When the number of cavitation treatment cycles increases, the values of (RON) and (MON) initially increase, reach a certain value, and remain stable during the subsequent cavitation treatment cycles. That is, there is a certain amount of energy acquired by the system at which its equilibrium state is achieved. Most likely, the equilibrium concentrations of substances are established in this case.

Work [14] reports the composition of an alcohol-gasoline mixture before and after cavitation treatment, as well as suggests a path of chemical transformations, which explains the presence of ethers in a bioethanol-gasoline mixture. A similar scheme can be offered to explain the presence of ethers and olefins in the isopropanol-gas-condensate mixture. The following reactions lead to an increase in the mixture's ON: the cracking of hydrocarbons (1), (2), the formation of olefins, iso olefins, isoparaffins (3) to (5), the formation of ethers (6).

$$R_1\text{-}R_2 \rightarrow \dot{R}_1 + \dot{R}_2, \tag{1}$$

$$R_1 - H \rightarrow \dot{R}_1 + \dot{H}, \tag{2}$$

$$\dot{C}_n H_{2n+1} \rightarrow C_n H_{2n+1} + \dot{H}, \tag{3}$$

$$n - C_n H_{2n} \rightarrow iso - C_n H_{2n}, \tag{4}$$

$$n - C_n H_{2n+2} \rightarrow iso - C_n H_{2n+2}, \tag{5}$$

$$\dot{R} + C_3 H_7 OH \rightarrow R - O - C_3 H_7 + \dot{H}. \tag{6}$$

These reactions are only a part of all reactions of radical chain transformations. Chromatographic analysis of alcohol-gasoline mixtures shows an increase in the proportion of unsaturated compounds and isomers with a simultaneous reduction of n-paraffins, as well as an increase in the number of ethers and other oxygen-containing compounds.

We have solved the task of providing recommendations on the manufacturing modes of cavitation treatment for the industrial production of A-95, A-98 gasoline brands from gas condensate and IPA by building a system of regression equations, linking the RON indicators to the concentration of IPA in an alcohol-gasoline mixture under different modes of cavitation treatment.

The effect of cavitation treatment intensity on the indicator of (RON) is well observed in Fig. 2. In all the examined intervals of IPA concentrations, increasing the number of cavitation treatment cycles increases the ON indicator. The higher the concentration of IPA in gasoline, the less noticeable the impact of cavitation on the increase in ON. In the range of IPA concentrations from 0 to 7.0 % by volume, the dependence of ON on the concentration of IPA $RON = f(C_{IPA})$ can be represented in the form of regression equations: for simple mechanical mixing of IPA and gas-condensate gasoline, equation 7; for 1 cycle of cavitation treatment, equation 8; for 5 cycles of cavitation treatment, equation 9; for 7–10 cycles of cavitation treatment, equation 10.

$$RON = 0.0109 \cdot C_{IPA}^3 - 0.1491 \cdot C_{IPA}^2 + \\ + 1.2679 \cdot C_{IPA} + 92.32, \tag{7}$$

$$RON = 0.012 \cdot C_{IPA}^3 - 0.1467 \cdot C_{IPA}^2 + \\ + 1.2077 \cdot C_{IPA} + 92.562, \tag{8}$$

$$RON = 0.0014 \cdot C_{IPA}^3 - 0.0375 \cdot C_{IPA}^2 + \\ + 0.9397 \cdot C_{IPA} + 92.909, \tag{9}$$

$$RON = 0.014 \cdot C_{IPA}^3 - 0.1712 \cdot C_{IPA}^2 + \\ + 1.2913 \cdot C_{IPA} + 93.069. \tag{10}$$

Equations (7) to (10) can be used to calculate the required concentration of IPA to achieve the RON indicators of 95 and 98 points at a different intensity of cavitation treatment.

We have solved the task of comparing the consumption of IPA to industrially produce A-95 and A-98 gasoline brands at the mechanical mixing and during the cavitation treatment of an alcohol-gasoline mixture by comparing data in Table 1. After 7–8 cycles of cavitation treatment (Table 1), a stable value of (RON) and (MON) is achieved, which does not increase during 10 treatment cycles or more. Fig. 2 shows that 3 % by volume of IPA is sufficient to reach a (RON) indicator of 95 points at the mechanical mixing of gas-condensate gasoline and IPA, which would suffice for the industrial production of A-95 gasoline brand according to DSTU 7687:2015. The use of cavitation treatment (more than 7 cycles at a pressure at the nozzle of 9.0 MPa) reduces the amount of IPA, sufficient to achieve the indicator of (RON) of 95 points, to 2.5 % by volume.
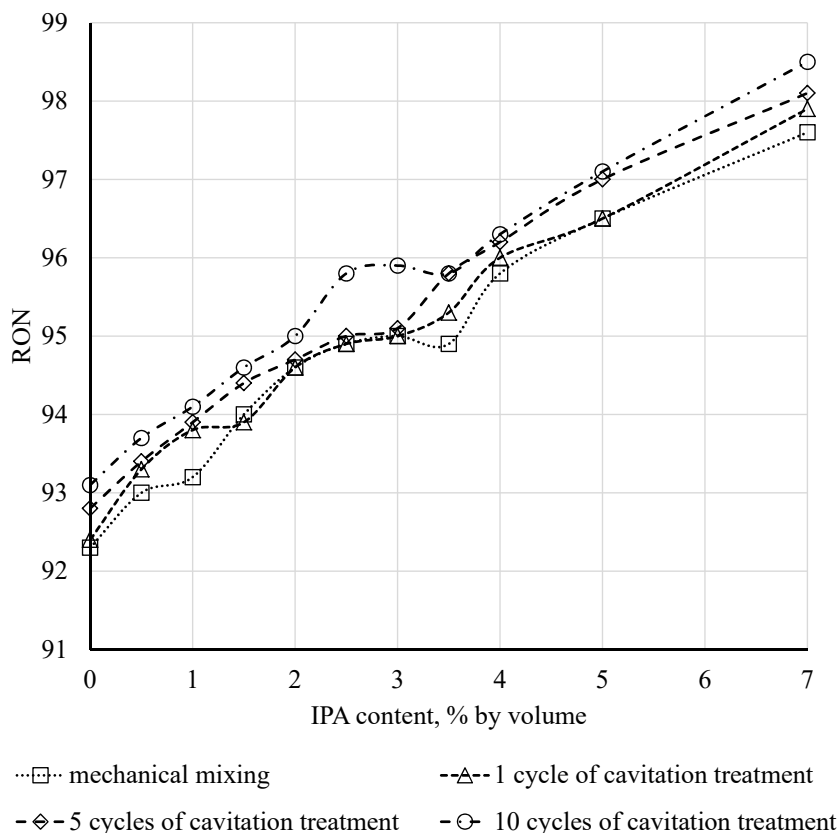
Fig. 2. Comparison of the intensity of cavitation treatment on the (RON) of gas-condensate gasoline at different concentrations of an IPA additive

of IPA for the (MON) indicator. Similar dependences were observed when studying the impact of cavitation on the ON of gasoline modified with bioethanol; however, there was one pronounced maximum there – at the concentration of bioethanol at the level of 1.0 % by volume. The presence of such highs can be explained by a change in the ratio of the rate of chemical reactions of different types, which simultaneously proceed in an alcohol-gasoline mixture during its cavitation treatment. There are some optimal concentrations of alcohol at which the effect of cavitation on the chemical transformations, mass exchange, ON, and other characteristics of gasoline becomes resonant. In this case, certain characteristics reach maximum values.

It should be noted that the phenomenon of the resonant effect of the intensity of mechanical activation, which includes cavitation, was observed for other technologies that employ mechanical methods for the selective energy supply to reaction centers. For example, a method known as "aerosol nanocatalysis" [15] implies the activation and formation of a constant concentration of the aerosol of hyperactive catalytic particles due to a change in the frequency of fluctuations of the catalytic system, consisting of a catalyst powder with initial dimensions up to 200 µm and a material that disperses this catalyst, whose dimensions are up to 1.2 mm. The study into various processes of hydrocarbon treatment involving this method revealed the presence of abnormal maximum dependences of the effective constant of cracking reaction rates at certain frequencies of fluctuations in the catalytic system, as well as a change in the yield of individual products.

Almost similar is the case for achieving the indicator of (RON) of 98 points. At mechanical mixing, it is necessary to add IPA in the amount of 8.1 % by volume (Fig. 2), while the use of cavitation during 4–7 cycles can reduce the amount of IPA to 7.0 % by volume. Extrapolating the results for the scale of an industrial installation shows that the use of cavitation could reduce the cost of raw material, IPA, by 17 %. The required amount of IPA in the mixture would decrease from 3.0 % by volume to 2.5 % by volume in the production of the A-95 gasoline brand. In the production of the A-98 gasoline brand, the reduction would be 14 % – from 8.1 % by volume to 7.0 % by volume.

Solving the task of studying the impact of cavitation on the increase in ON for a mixture of gas-condensate gasoline with IPA is supplemented with the visualization of data from Table 2 in Fig. 3.

It can be noted that the dependence is nonlinear in nature with several highs at certain concentrations – 1.0 % by volume, and 3.5 % by volume, and 7.0 % by volume of IPA for the (RON) indicator; 3.5 % by volume and 7.0 % by volume
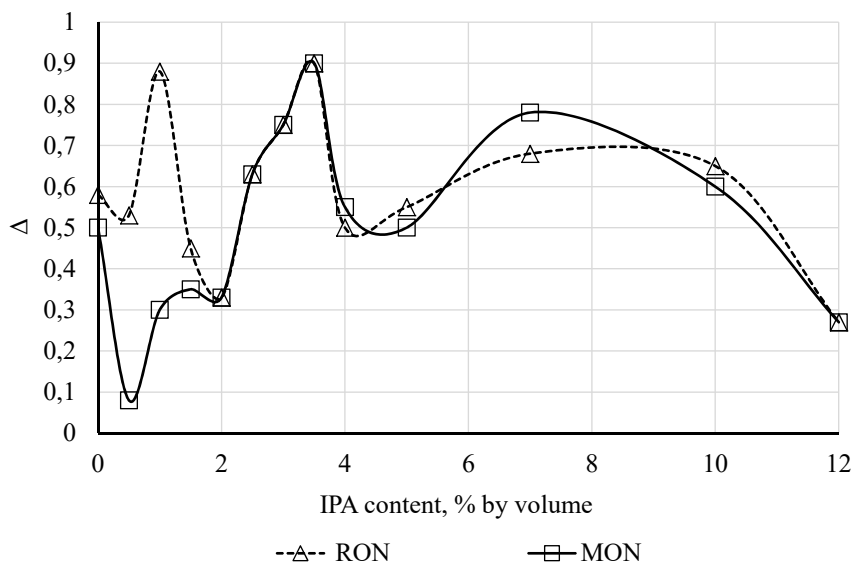

Fig. 3. The contribution of cavitation treatment to the increase in (RON) and (MON) indicators at the different concentrations of IPA in gas-condensate gasoline

As regards cavitation treatment, the phenomenon of resonance can be explained by achieving an optimal concentration of activated particles. In this case, the consumption rate of the activated particles in target reactions exceeds the consumption rate in side reactions. For the examined gas-condensate gasoline, the industrial development of the A-95 gasoline brand is possible when adding 2.0–3.5 % by volume of IPA and at a cavitation treatment intensity of 0–8 cycles at a pressure at the nozzle of 9.0 MPa. To produce the A-98 gasoline brand industrially, it is necessary to add 6.0–8.5 % by volume of IPA with a cavitation treatment intensity of 0–8 cycles at a similar pressure at the nozzle.

A further increase in concentration leads to the acceleration of non-target reactions, for example, reactions of obtaining n-alkanes and compaction reactions.

Fig. 3 illustrates the possibility of establishing the optimal concentrations of alcohol at which the technology of cavitation treatment of raw materials produces a maximum effect. The initial ON of the gasoline fraction can be changed by compounding it with high-octane fractions. Further addition of IPA or other alcohols would help organize the process of obtaining A-95, A-98 gasoline brands at minimal energy consumption.

7. Discussion of results of studying the impact of cavitation intensity on the ON of gasoline modified with IPA

Our study has shown the effectiveness of cavitation to increase the ON of gas-condensate gasoline with an IPA additive. A 12-point increase in RON and a 10.5-point rise in MON when changing the concentration of IPA from zero to 12 % by volume are expected. It is proportional to the concentration of alcohol. However, the use of cavitation gives an additional effect of 0.3–0.9 points depending on the concentration of IPA and the intensity of cavitation treatment. This can be explained by a change in the chemical composition of the modified gasoline. The chromatographic analysis shows an increase in the content of olefins, iso alkanes, iso olefins, esters in an alcohol-gasoline mixture to 0.5 % by volume in total, compared to the composition of the mixture that was not subjected to cavitation treatment. They give an additional increase in the ON. The increase in gasoline's ON at different concentrations of IPA is shown in Fig. 2.

However, the increased cavitation makes it possible to increase the ON not linearly but resonantly. Fig. 3 clearly demonstrates the resonant nature of the impact of cavitation intensity on the ON. Such a character of the impact can be explained by different ratios of the rates of targeted and side reactions at the different concentrations of IPA.

Enhancing the ON through the addition of alcohol is a well-known technology. However, no previous manufacturing process so far has combined the mixing of IPA with gasoline and cavitation treatment. In contrast to works [1, 3, 9, 10], where it was possible to achieve chemical transformations of hydrocarbons and reduce the viscosity of heavy petroleum products, our study has demonstrated the possibility of increasing the ON of gasoline.

The impact of cavitation on fuel characteristics is only positive. The intensive mechanochemical activation of raw materials leads to an increase in the content of olefins, which reduces the stability of gasoline. Such gasoline would have a shorter shelf life without losing properties. However, the benefits of increasing ON outweigh this disadvantage.

Our results could be scaled to the processes of modifying gas-condensate gasoline fractions with an initial ON not exceeding 92 points based on a research method. For the proper scaling and optimization of the process in terms of alcohol consumption and energy costs, the industrial production of A-95 and A-98 gasoline brands should involve the amount of an IPA additive to an alcohol-gasoline mixture not exceeding 12 % by volume. The pressure at the cavitation nozzle should equal 9.0 MPa and the number of cavitation treatment cycles under these conditions does not exceed 10. The intensification of non-targeted compaction and coke reactions is possible at a larger number of cycles.

Further research will be aimed at examining the effects of cavitation treatment when modifying gasoline with higher molecular alcohols and mixtures of alcohols. It is also planned to study the effect of pressure at a cavitation nozzle on the ON of alcohol-gasoline mixtures and their chemical composition.

8. Conclusions

1. It has been established that a stable value of (RON) and (MON) for the gas-condensate gasoline modified with IPA is achieved over 7–8 cycles of cavitation treatment at an IPA concentration in the mixture of 0.5–12 % by volume. This makes it possible to optimize the manufacturing mode toward reducing energy consumption for a would-be industrial installation for the cavitation treatment of alcohol-gasoline mixtures.

2. It has been found that the effect of the concentration of IPA on the ON of the modified gasoline under cavitation treatment is nonlinear with several highs at certain concentrations – 1.0 % by volume, 3.5 % by volume, and 7.0 % by volume of IPA for the (RON) indicator; 3.5 % by volume and 7.0 % by volume of IPA for the (MON) indicator. Varying the initial concentration of IPA and ON of the gasoline fraction can optimize the technological mode to produce A-95 and A-98 gasoline brands in terms of raw materials and energy consumption.

3. It has been proven that the development of the A-95 gasoline brand is possible when adding 2.0–3.5 % by volume of IPA and at a cavitation treatment intensity of 0–8 cycles at a pressure at the nozzle of 9.0 MPa. To produce the A-98 gasoline brand, it is necessary to add 6.0–8.5 % by volume of IPA; the cavitation treatment intensity should equal 0–8 cycles at a similar pressure at the nozzle.

4. The use of cavitation treatment could reduce the consumption of a raw material, IPA, by 17 % (from 3.0 % by volume to 2.5 % by volume) in the production of A-95 gasoline brand; by 14 % (from 8.1 % by volume to 7.0 % by volume) in the production of A-98 gasoline brand.

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