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ФИЗИКО-ХИМИЧЕСКИЕ И КАТАЛИТИЧЕСКИЕ СВОЙСТВА NiMo-COДЕРЖАЩИХ АЛЮМООКСИДНЫХ КАТАЛИТИЧЕСКИХ СИСТЕМ

Ал.С. Акимов, Т.В. Петренко, Е.Ю. Герасимов, А.С. Акимов

Альберт Софронович Акимов (ORCID 0000-0003-3567-8148)*, Татьяна Васильевна Петренко (ORCID 0000-0003-3457-3299), Аким Семенович Акимов (ORCID 0000-0001-7953-1477)

Лаборатория каталитических превращений легких углеводородов, Институт химии нефти СО РАН, пр. Академический, 4, Томск, Российская Федерация, 634055

E-mail: albertus98@mail.ru*, uvikon@ipc.tsc.ru, zerobox70@mail.ru

Евгений Юрьевич Герасимов (ORCID 0000-0002-3230-3335)

Институт Катализа им. Г.К. Борескова СО РАН, пр. Академика Лаврентьева, 5, Новосибирск, Российская Федерация, 630090

E-mail: gerasimov@catalysis.ru

Получены и изучены свойства NiMo-алюмооксидных каталитических систем для процессов гидроочистки углеводородного сырья. Оригинальность данной работы обусловлена двумя факторами: во-первых, в качестве носителя для системы была выбрана дельта модификация оксида алюминия; а во-вторых, при получении активного молибденового компонента применялись полиоксометаллатные соединения молибдена, полученные из дисульфида молибдена. В качестве промотирующего металла выступает никель. Исследованы физико-химические свойства полученных образцов с помощью методов рентгенофазового анализа, просвечивающей электронной микроскопии высокого разрешения с микроэлементным анализом поверхности и текстурных свойств по методу низкотемпературной адсорбции азота. Проведено сравнение полученной нанесенной каталитической системы с алюмооксидным носителем. Результаты рентгенофазового анализа и микроскопических исследований подтверждают нанесение активного компонента на поверхности оксида алюминия. По полученным результатам сделан вывод о необходимости дальнейшей оптимизации условий прокалки. Полученные результаты по текстурным свойствам показывают, что по удельной площади поверхности дельта модификация оксида алюминия при использовании дополнительных компонентов не соответствует технологическим требованиям. Исследование каталитических свойств полученных систем на модельном сырье (дибензотиофен в н-декане с содержанием в 1000 ррт в перерасчете на атомарную серу), показывает существенную десульфирующую активность биметаллической системы. В итоге удалось снизить содержание серы с 1000 ррт до 94 ррт, то есть на 90,4% по сравнению с исходным модельным сырьем. Было также выявлено по результатам метода хромато-масс-спектрометрии, что процесс гидродесульфирования модельного сырья протекает по маршруту прямого десульфирования.

Ключевые слова: гидроочистка, оксид алюминия, полиоксометаллаты, молибденовые сини

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PHYSICOCHEMICAL AND CATALYTIC PROPERTIES OF NiMo-CONTAINING ALUMINA-OXIDE CATALYTIC SYSTEMS

Al.S. Akimov, T.V. Petrenko, E.Yu. Gerasimov, A.S. Akimov

Albert S. Akimov (ORCID 0000-0003-3567-8148)*, Tatyana V. Petrenko (ORCID 0000-0003-3457-3299), Akim Yu. Akimov (ORCID 0000-0001-7953-1477)

Institute of Petroleum Science, Akademicheskiy ave., 4, Tomsk, 634055, Russia E-mail: albertus98@mail.ru*, uvikon@ipc.tsc.ru, zerobox70@mail.ru

Evgeny Yu. Gerasimov (ORCID 0000-0002-3230-3335)

Boreskov Institute of Catalysis of the SB of the RAS, Ac. Lavrentieva ave., 5, Novosibirsk, 630090, Russia E-mail: gerasimov@catalysis.ru

The properties of NiMo-alumina catalytic systems for hydrocarbon feedstock hydrotreating processes have been obtained and studied. The originality of this work is due to two factors: first, a delta modification of aluminum oxide was chosen as a carrier for the system and second, polyoxometallate molybdenum compounds derived from molybdenum disulfide were used in the preparation of the active molybdenum component. Nickel acts as the promoting metal. The physical and chemical properties of the obtained samples were investigated by X-ray phase analysis, high-resolution transmission electron microscopy with trace element analysis of the surface and textural properties by the low-temperature nitrogen adsorption method. The obtained applied catalytic system was compared with alumina carrier. The results of X-ray phase analysis with electron microscopy confirm the deposition of the active component on the surface of aluminum oxide. Based on the results obtained, it is concluded that further optimization of the calcination conditions is necessary. The obtained results on textural properties show that the specific surface area of delta modification of aluminum oxide using additional components does not meet the technological requirements. The study of catalytic properties of the obtained systems on model raw materials (dibenzothiophene in decane with the content of 1000 ppm in recalculation of atomic sulfur), shows a significant desulfurizing activity of the bimetallic system. As a result, it was possible to reduce the sulfur content from 1000 ppm to 94 ppm, i.e. by 90.4% compared to the original model feedstock. It was also revealed by the results of chromatography-mass spectrometry that the process of hydrodesulfurization of model feedstock proceeds by the route of direct desulfurization.

Keywords: hydrotreatment, aluminum oxide, polyoxometalate compounds, molybdenum blue

INTRODUCTION

In recent years, there has been a trend towards a reduction in light and medium oil reserves, leading to an increase in the involvement of heavy and extraheavy oil in the petrochemical industry. However, it is known that as oil becomes heavier, the content of heteroatomic compounds, particularly sulfur compounds, increases. In turn, the presence of sulfur-containing compounds in hydrocarbons adversely affects the service life of catalysts for hydrogenation transformations, negatively affects the operation of apparatus and units of oil refineries, etc.

There are many ways to reduce the content of heteroatomic compounds, but most of them involve interference in the operating technological schemes, which leads to negative consequences (increased capital expenditures, changes in technical documentation, retraining of personnel, etc.). In order to avoid such problems it is necessary to use such a method that would minimally affect the operation of existing technological lines. Improvement of properties of existing catalysts and/or optimization of their synthesis can be safely attributed to such methods. In this connection the development of catalytic systems for hydrotreating of hydrocarbon feedstock is an urgent task.

In the middle of the last century, the discovery of high hydrodesulfurizing activity of noble metals was the impetus for the appearance of the first hydrotreating catalysts based on them. Later they were widely used in industry until the discovery of $Co(Ni)Mo(W)S/Al_2O_3$ catalysts.

Thus, at present in the process of hydrodesulfurization of crude oil and petroleum products, alumina catalysts based on MoS_2 and WS_2 promoted by Ni or Co (Co(Ni)Mo(W)S/Al₂O₃) have a wider spread in comparison with catalysts based on noble metals (Pt, Pd). This is mainly due to their higher resistance to catalytic poisons and also because of their relatively low cost [1-8].

As a rule, catalysts in which the active component is deposited on an inert carrier are used in the hydrotreating process. Most often it is gamma modification of aluminum oxide (γ -Al₂O₃). In addition to deposited catalysts, array catalysts are also used. However, in industrial realization the number of names of applied massive catalysts is much inferior to the applied analogs. Among the most effective and industrially implemented samples are such catalysts as NEB-ULA and Celestia. The activity in the hydrodesulfurization process of these catalysts significantly exceeds traditional applied catalysts. Their high activity is mainly due to the large number of active centers per unit area of the catalyst. And the large number of active centers in massive catalysts is achieved due to the fact that, in fact, their entire surface is a MoS₂ phase. However, not the entire surface can be used to participate in hydrotreating processes. Moreover, most of the MoS₂ is deep in the phase and does not participate in the target processes. It follows that the consumption of active metal is much higher in massive catalysts than in applied catalysts - 55-65 wt% on average in massive catalysts, while 10-15 wt% is used for applied catalysts. These problems of massive catalysts are known, and researchers from different countries are working on increasing the surface area and pore volume values. Basically the increase of these parameters is provided by finding the optimal ratio between the length of molybdenum disulfide crystallite and the number of plates in the crystallite, as well as by large dispersion of these crystallites. In contrast to massive catalysts, there is more room for synthesis in the applied catalysts, since more process parameters can be varied. Improvement of properties of existing active components, optimization of technology of their obtaining or search of new ways of synthesis, selection of carriers, promoters, plasticizers, possibility of modification of carriers by different elements, mixing of different carriers and their joint use, use of different ways of application of active component on the carrier – all this together is only a part of those ways of improvement of applied catalysts, which is used for obtaining laboratory catalytic systems and industrial catalysts. Despite the fact that the present research team has chosen to synthesize specifically applied catalytic systems, it is important to note that the study and improvement of both applied and arrayed catalysts is currently an urgent and important task. Both concepts have the right to exist, and the choice of one of them often depends on the preferences and logistics of research teams.

As applied to the present work, the methods of optimization of active component synthesis and carrier selection are considered. Thus, commercial molybdenum disulfide powder was chosen as the precursor of the active component instead of traditionally used heptamolybdates. Mainly, the choice of commercial MoS_2 is due to the ease of obtaining the target active phase from this precursor relative to the traditionally used precursor. It is known that the synthesis of active phase from heptamolybdates is characterized by a relative multistep process, the use of a certain amount and volume of solvents, and the complexity of the process. Complexity in this case means the need for strict execution of all stages of the process without exception, the appearance of error or sloppiness even in the extreme stage of synthesis leads to the loss of the results of all previous stages.

This work is more of a fundamental nature. In this connection it was decided to take as a carrier delta modification of aluminum oxide. To study the physicochemical properties of this carrier and the prospects of its use. As it is known, traditionally gamma aluminum oxide is used as a carrier for hydrotreating processes. This modification was widely used in industrial realization of catalysts due to the fact that it has relatively high values of surface area, and the values of pore volume and pore diameter correspond to the existing technical regulations. In addition, this modification of aluminum oxide has good forming ability and high thermal stability. In contrast to gamma delta oxide, the modification has almost half the value of specific surface area with equal values of pore diameter and pore volume. Moreover, these values are outside the limits of the technological norms established in production.

But at the same time delta modification of aluminum oxide has moderately pronounced acidity. Literature sources note that this property plays a positive role in deepening of hydrotreating processes. For example, [9] compared the catalytic properties of CoMoS catalysts with three different modifications of aluminum oxide as carriers. According to the results of this work, it was found that the catalyst deposited on δ -Al₂O₃ shows the best hydrodesulphurizing activity of hard-to-remove sulfur compounds. Similar results were published in [10], where a series of similar catalysts were synthesized, but where Ni was used as the promoting metal. It was found that when NiMo/ δ -Al₂O₃ was used, the conversion of dibenzothiophene was almost twice as high as with NiMo/ γ -Al₂O₃; the higher efficiency of NiMo/ δ -Al₂O₃ is also manifested in the process of hydrodesulfurization of dimethyl substituted homologues of dibenzothiophene – in their case, catalysts with delta-modification of aluminum oxide demonstrate almost fourfold advantage. Such an advantage of NiMo/ δ -Al₂O₃ in the hydrodesulfurization of aromatic organosulfur compounds is most likely due to the presence of acid centers initiating side processes. For example, isomerization processes of dibenzothiophene homologues may contribute to the partial neutralization of steric hindrances caused by alkyl groups. This may facilitate access to the sulfur atom for the active surface, which will contribute to an increased degree of dehydrodesulphurization.

The use of delta modification of aluminum oxide together with gamma modification is considered as a promising way to obtain such systems. In this regard, the present work, in which the use case is considered will be the basis for future studies related to the use of δ -Al₂O₃ in the composition of the carrier.

Based on the above, the aim of this work is to synthesize and study the physical and chemical properties of applied catalytic systems by using polyoxometalate compounds as an active component and δ -Al₂O₃ as a carrier.

EXPERIMENTAL TECHNIQUE

The methodology of the work can be divided into the following parts:

- obtaining nickel and molybdenum-containing active component;

- obtaining a carrier – aluminum oxide from a commercial product – pseudoböhmite (AlOOH);

- obtaining the catalytic system by applying the obtained active component on the aluminum oxide carrier.

Synthesis of the active component was carried out as follows: as a molybdenum-containing compound was used a class of polyoxometalate compounds known as molybdenum blues. Molybdenum blues in turn were synthesized according to the original methodology, the essence of which in brief consists in the following – commercial powder of molybdenum disulfide "Molysulfide" was placed in a laboratory vibrating mill and subjected to mechanoactivation for 8 hours in air. Then hydrogen peroxide (RUE "Belmedpreparaty") was added to mechanically activated molybdenum disulfide to obtain aqueous solutions of molybdenum blue. Further, bimetallic impregnation solution was prepared by adding nickel nitrate hexahydrate ("Reahim") and citric acid to the solution of molybdenum blue.

Preparation of the carrier is a thermal treatment of AlOOH pseudobemite (ISCPC) in a muffle furnace at 900 °C for 4 h. The application of the active component on the alumina carrier was carried out by the impregnation method according to the moisture capacity, followed by drying and calcination stages. The impregnation is single impregnation with a solution of two metal-containing compounds. Drying "slow", was carried out at room temperature. The necessary conditions of calcination were selected empirically. The obtained catalytic system was conventionally designated as KT-1.

It is known that molybdenum-containing catalysts are used in the processes of processing heavy native and residual raw materials mainly in sulfide form, in this connection the standard technique of catalyst sulfurization (ex situ) under laboratory conditions (hereinafter referred to as KT-2) was applied [11-14].

The obtained systems were investigated by a number of physicochemical methods of analysis: Xray phase analysis (XRD), high-resolution transmission electron microscopy (HRTEM), low-temperature nitrogen adsorption/desorption, X-ray fluorescence analysis, UV spectroscopy, and chromatography-mass spectrometry (CMS).

XRD was performed on a Bruker D8 Advance powder diffractometer equipped with a one-dimensional Lynx-Eye detector and a K_β-filter with CuK_α-radiation. Imaging was performed in the angle range 10° $< 2\theta < 86^{\circ}$. Refinement of structural parameters was carried out on powder diffractograms by the Rietveld method using Topas V4.2 software.

The structure and microstructure of the samples were investigated by high-resolution transmission electron microscopy (HRTEM) on a ThemisZ electron microscope (Thermo Fisher Scientific, USA) with an accelerating voltage of 200 kV and a resolution limit of 0.07 nm and in the scanning mode of electrons scattered at large angles (HAADF STEM). Images were recorded using a Ceta 16 CCD array (Thermo Fisher Scientific, USA). The instrument is equipped with an energy dispersive X-ray characteristic emission (EDX) SuperX spectrometer (Thermo Fisher Scientific, USA) with a semiconductor Si detector with an energy resolution of 128 eV. For electron microscope studies, sample particles were deposited on holey carbon substrates mounted on copper or molybdenum grids using an ultrasonic disperser UZD-1UCH2, which allowed to achieve a uniform distribution of particles on the substrate surface. The sample was placed in alcohol applied to the ultrasonic disperser, followed by evaporation and subsequent deposition of the sample particles on the copper mesh [15].

The specific surface of the samples was determined using the BET method of low-temperature nitrogen adsorption on the device "Sorbtometer M" of

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CATAKON company, in addition, the specific surface was determined on this device by the comparative method, as well as the specific pore volume by the limit filling and the volume of micropores.

Determination of sulfur content in the studied samples was carried out using X-ray fluorescence energy dispersive analyzer of sulfur in oils and oil products "Spectroscan S" (GOST R 51947-2002). Measuring range of mass fraction of sulfur is from 0,0002% to 5%. The operating principle of the analyzer is that the analyzed sample is irradiated with low-power X-ray radiation emitted by the X-ray source (X-ray tube). At the same time, secondary radiation is emitted from the sample surface, the spectral composition of which adequately reflects the elemental composition of the sample. Using a proportional counter and a selective filter, the analyzer extracts the analytical sulfur line (K_{α}) from the secondary radiation and automatically converts its intensity into the mass fraction of sulfur in the sample. The mass fraction of sulfur is expressed either as a percentage or in milligrams per kilogram.

The rate constants of dibenzothiophene hydrogenolysis (hereinafter referred to as DBT) were determined on the assumption of the pseudo-first order of DBT transformation:

$$C_{DBT} = C_{0DBT} - e^{-kt}, \qquad (1)$$

From the tangent of the slope of the natural logarithm dependence ($\ln(C_{0DBT}/C_{DBT})$) on time (t), the corresponding values of the rate constant were obtained. Samples of 0.5 mL were taken from the reactor after 0.5; 1; 2; 3; 4; 6 hours [16-17].

The composition of DBT transformation products was identified (computer library of mass spectra NIST-5) by GC/MS chromatography-mass spectrometric analysis using a Thermo Scientific DFS magnetic chromatography-mass spectrometer with a Thermo Scientific quartz capillary chromatographic column of 0.25 mm inner diameter, 30 m length, TR-5MS stationary phase of 0.25 µm thickness. Chromatograph operation mode: carrier gas - helium, evaporator and interface temperatures - 250 °C; thermostat heating program: $t_0 = 80$ °C, isotherm – within 2 min, heating at a rate of 4 deg/min to $t_{max} = 300$ °C. Mass spectrometer operation mode: ionization method - electron impact; ionizing electrons energy 70 eV; ionization chamber temperature 250 °C; range of registered masses 50-500 Da; spectrum sweep duration 1 second.

RESULTS AND DISCUSSION

In the catalytic system, the presence of phases related to δ -Al₂O₃ was determined by XRD, but almost no reflexes related to the active component KT-1 are observed.

In both samples, a number of reflexes lying in the range of 30° to 70° are observed. Reflexes in the region of angles $2\theta \approx 32.92$; 37.44; 45.70; 46.81; 69.17° and planes corresponding to the above planes with indices (220), (311), (400), (0012), (440) confirm the presence of a metastable modification of aluminum oxide, δ -Al₂O₃ (PDF #56-1186) [19]. In addition, in the catalytic system, the XRD profile shows more significant amorphization, a decrease in the intensity of the reflections related to the carrier of the catalytic system and the appearance of a number of low-intensity reflections. The rows of low-intensity reflexes that appeared are related to the NiMo₂S₄ phase (PDF #21-1273). They are represented by low-intensity reflexes present only in the catalytic system. These reflections are located at angles $2\theta \approx 14.95^{\circ}$; 29.55° ; 33.28° ; 44.60° ; 50.26°; 58.76°; 60.50°; 70.60°.

This result is most likely due to the high dispersibility of the compounds comprising the active component, in other words, these parameters lie beyond the sensitivity of the device. The high dispersity is mainly due to the mechanical activation stage, during which the morphology of molybdenum disulfide is changed and mechanocomposites with higher dispersity are formed. The obtained mechanocomposites are a system, on the surface of which a layer of molybdenum oxides Mo_xO_y is formed, and in the core – molybdenum disulfide. Due to this, the surface of the mechanocomposite is hydrophilic in contrast to the inactivated molybdenum disulfide, which allows further reactions with hydrogen peroxide.

It is necessary to take into account the fact that in the process of impregnation the distribution of particles of the active component is more pronounced. In addition, in the process of calcination of catalytic systems in the redistribution and dispersion of molybdenum on the surface should occur the formation of bimetallic oxide precursors of the active component. This may be due to the fact that the formation of a sulfide bimetallic compound at the subsequent stage of preparation of the catalytic system (at the stage of sulfurization) from Mo or Ni atoms separated throughout the space is difficult to realize due to the low volatility of sulfides of the active and promoting metals. When analyzing literature sources, these data are indirectly confirmed – the dispersity of polymetallic catalysts is always higher than that of monometallic ones.

In addition to the above, the almost identical profile of X-ray diffractograms may be due to the low content of active metals. As it is known, in both monometallic and polymetallic catalytic compounds the processes of dispersion of applied metals are accompanied, along with the formation of sulfide bimetallic compound, by the formation of a number of surface compounds that do not directly participate in the target catalytic processes. On this basis, it can be assumed that in the process of calcination some fraction of the potential active metal is lost to the formation of inactive surface compounds.

Fig. 1 shows a comparison of X-ray diffractograms of the alumina carrier and the catalytic system based on it. The fact of the presence of phases of the active component is confirmed by the results obtained during catalytic tests, as well as by transmission electron microscopy (TEM).



Fig. 1. Comparison of diffractograms of δ-Al₂O₃ and KT-1:
1 - KT-1; 2 - carrier - δ-Al₂O₃. Triangles indicate reflexes corresponding to PDF #56-1186, circles indicate PDF #21-1279
Рис. 1. Сравнение дифрактограмм δ-Al₂O₃ и KT-1: 1 – KT-1;
2 – носитель - δ-Al₂O₃. Треугольниками обозначены рефлексы, соответствующие PDF #56-1186, окружностями - PDF #21-1279

After determining the activity (data are given below) of the compound, the phase composition was analysed, and its results show almost completely identical profiles. That is – absence of lateral shifts of reflexes, in the change of intensity of reflexes, broadening of separate reflexes or appearance of extraneous 'noises'.

The obtained experimental data agree with the literature data [18]. Since the high-temperature metastable crystalline modification of aluminium oxide (δ -Al₂O₃) used in this work is obtained only at heating above 900 °C (and stable α -Al₂O₃ at temperatures from 1200 °C), it is practically impossible to change the crystalline modification from δ -Al₂O₃ to another crystalline modification under the conditions of checking the activity of the systems, i.e. at 340 °C.

The wide particle size distribution is mainly due to the choice of moisture impregnation as the method of catalyst preparation.

Fig. 2 shows micrographs of the sulfurized catalytic system (KT-2). The micrographs clearly show the bundle structures of different length, direction and thickness of the bundle. They belong to the MoS_2 phase of the catalytic system. The average value of the interplanar distance of the selected region in Fig. 2 is 0.23 nm. In order to understand the relative distribution of elements with respect to each other, mapping (Fig. 3) by energy dispersive X-ray analysis (EDX) was carried out. It was found that molybdenum, nickel, and sulfur were uniformly distributed relative to each other, which may indicate the formation of sulfide phases on the surface of the alumina carrier. The uniform distribution of active components on the surface of the carrier is natural due to the use of moisture impregnation as a method of application.



Fig. 2. Transmission electron microscope (TEM) micrographs of the alumina-oxide system

Рис. 2. Микрофотографии алюмооксидной системы, сделанные в просвечивающем электронном микроскопе (ПЭМ)

The measured values of textural properties of δ -Al₂O₃ also confirm the literature data [17]. The values of specific surface area are on average almost twice as low as those for γ -Al₂O₃. It follows that the use of δ -Al₂O₃ as a single component of the carrier is inappropriate because the readings for textural properties do not meet the industrial requirements for catalysts. Therefore, firstly, the inexpediency of using monoalumina oxide systems based on delta-modification of aluminum oxide is shown, and secondly, the necessity of further studies of blended γ -Al₂O₃/ δ -Al₂O₃ systems is confirmed. The use of blended systems with the most optimal ratio of the used components should neutralize the unsatisfactory values of δ -Al₂O₃ textural characteristics for practical applications. Judging by the obtained data on textural properties, it can be assumed that in such systems the share of γ -Al₂O₃ will prevail over δ -Al₂O₃, which will provide on the one hand the level of textural properties required by technical regulations, and on the other hand will reduce the positive influence of δ -Al₂O₃ in the processes of hydrodesulfurization of dibenzothiophene and its homologues.

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Fig. 3. Dark-field imaging in high-angle scattered electrons and mapping of major elements of KT-2

Рис. 3. Темнопольное изображение в высокоугловых рассеянных электронах и картирование основных элементов КТ-2

The analysis of the porous structure of KT-2 shows that the specific surface area decreases by 24% and the total pore volume decreases by 26%, while the pore size changes insignificantly (by 2.5%). The decrease in specific surface area and total pore volume also indirectly confirms the presence of active component in the carrier. The results of textural characterization published earlier in [19, 20] are presented in Table 1.

Table 1

Texture characteristics of the carrier - delta modification of aluminum oxide and catalytic system - KT-1 *Таблица 1*. Текстурные характеристики носителя – дельта модификации оксида алюминия и каталитической системы – KT-1

Sample	S_{BET} , m^2/g	V _{por} , cm ³ /g	D _{por} , nm		
δ -Al ₂ O ₃	116.5	0.054	1.85		
KT-1	88.5	0.040	1.81		

After the sulfidation process, preliminary testing of hydrodesulphurising activity of the obtained samples on model raw materials was carried out. This information is a small addition to the above physicochemical methods. Since at this stage there is no question of comparison with any benchmark or industrial catalyst, and thus it is possible to consider these results as a precursor for further full-fledged catalytic tests. The test conditions are summarized in Table 2.

From its results, it is observed that the sulphur content was 94 ppm, which is about 91% lower than the original model mixture (1000 ppm). Using the results obtained by UV spectroscopy, a kinetic curve was

constructed. Based on the kinetic curve, the reaction rate constant was calculated, which was 0.68 h^{-1} .

Fig. 3 shows the results of the test. The average histogram characterizing the pure carrier clearly shows that it takes almost no part in the hydrodesulfurization of the feedstock and emphasizes that only after the addition of the active component the above results were achieved.



The results of gas chromatography-mass spectrometry (GC-MS) show the presence of such products as tetrahydrodibenzothiophene (THDBT), biphenyl (BP), cyclohexylbenzene (CHB) which may indicate. The process of hydrodesulphurization of model raw materials is carried out in both direct desulfurization (DDS) and hydrogenation (HYD) reaction pathways [21].

It can be observed that the maximum content of the component is biphenyl (97.28%), indicating the prevalence of the direct desulphurization route (DDS).

Table 2

Composition of dibenzothiophene transformation products in the model hydrodesulfurization

Таблица 2.	Состав продуктов і	превращения д	цибензо-
гиофена в мо	одельной реакции і	гидродесульфи	рования

Test parameters	The yield of products, %		
	THDBT	BP	CHB
Autoclave reactor with stirring T-340 °C Solvent: decane Duration: 6 h	0.40	97.28	2.32

CONCLUSION

A series of alumina NiMo-containing systems have been synthesized. The distinctive feature of the synthesis from similar works is the following point – using as Mo-containing precursor – a solution of molybdenum blues bound to a non-traditional carrier – δ -Al₂O₃. XRD and HRTEM results show the presence of the target phases. The results of textural characterization demonstrate that the specific surface area of the obtained catalytic system has a specific surface area of $88.5 \text{ m}^2/\text{g}$, pore volume and pore diameter are $0.040 \text{ cm}^3/\text{g}$ and 1.81 nm, respectively.

Preliminary testing of the obtained systems in the hydrodesulfurization of model feedstock was carried out. The sulfur-containing compound conversion was of the order of 91% and the residual sulfur level was of the order of 94 ppm. The reaction rate constant was 0.68 h⁻¹. The results of chromatography-mass spectrometry showed that the hydrodesulfurization reaction proceeded by the route of direct desulfurization (DDS)(biphenyl yield was 97%).

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