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EFFECTIVENESS OF LOW-TEMPERATURE CATALYTIC DEGRADATION OF POLYSTYRENE WITH THE USE OF ALUMINOSILICATE CATALYSTS

Introduction. *The global plastic pollution crisis has necessitated the development of efficient recycling strategies to mitigate environmental harm. Polystyrene, due to its chemical inertness and resistance to natural degradation, has posed a particular challenge.*

Problem Statement. *Although promising advances in catalytic depolymerization have been achieved, the high cost and limited availability of platinum group metals have hindered their large-scale application. Transition metals represent more affordable yet effective catalytic alternatives; however, a gap has remained in understanding how catalyst composition and process conditions influence the efficiency of polystyrene degradation.*

Purpose. *This study has aimed to evaluate the performance of synthetic aluminosilicate catalysts and natural Ukrainian zeolite from the Sokyrnytsia deposit in the low-temperature catalytic degradation of polystyrene.*

Materials and Methods. *Catalysts have been prepared via acid treatment (for natural zeolite) and impregnation with Ni and Co salts (for synthetic Y-type zeolite). X-ray diffraction and low-temperature*

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nitrogen adsorption–desorption methods have been employed to characterize catalyst structure and porosity. Catalytic degradation of polystyrene (at 169—200 °C) has been carried out under reduced pressure or under a H_2—N_2 (1 : 1) flow.

Results. *Under reduced pressure, acid-activated natural zeolite (Zeo-1) has achieved the highest total yield of target compounds (up to 72%), with a particularly high yield of methylstyrene (32.5%). In a hydrogen atmosphere, the overall yield of valuable products has increased (to 78% for certain catalysts), although the total liquid yield has decreased. Cobalt-containing catalysts have been established to boost particularly the hydrogenation of styrene to ethylbenzene. Natural zeolites have demonstrated performance comparable to that of synthetic aluminosilicates in plastic degradation. Proposed reaction mechanisms have shown that transition metals (Ni, Co) enhance C—C bond cleavage, yielding valuable monomers and partially hydrogenated products.*

Conclusions. *The findings obtained have paved the way for developing cost-effective, high-performance catalysts for polystyrene utilization.*

Keywords: polystyrene, catalytic degradation, low-temperature process, aluminosilicates, natural zeolite, gas-liquid chromatography.

The rapid and irresponsible pollution of the environment with plastics has become one of the global environmental threats to humanity and the planet as a whole. Due to such properties of polymers as chemical, thermal, and corrosion resistance, low density, and the ability to create any product design, the production volumes of plastics have significantly increased in recent decades, making plastic more applicable as packaging material than wood, aluminum, or other metals. The active use of plastics and the unwillingness of manufacturers to spend resources on its disposal have created a huge amount of plastic waste that accumulates as garbage in landfills and in the natural landscape [1].

Among various technologies, pyrolysis and gasification are considered promising technologies for converting plastic waste into fuel [2, 3], but the products of such technologies are multicomponent mixtures of organic substances that require a complex process of separation and purification to obtain commercial fuel products. Therefore, research into these processes to obtain fuel hydrocarbons is a relevant task for creating effective plastic waste processing technologies.

From the perspective of efficiency, catalytic degradation of plastics is considered more desirable, as the use of catalysts allows the manipulation of the final product composition and ensures desired selectivity for target products. It is known that the most active hydrogenation catalysts are platinum group metals (PGMs). For example, in [4], the successful conversion of polyethylene terephthalate (PET) into *p*-xylene and methylbenzene on a Ru/Nb_2O_5 catalyst, which is also suitable for the hydrogenolysis of other aromatic plastic waste with C—O and C—C bonds, including polystyrene, poly(*p*-phenylene oxide) (PPO), and mixed aromatic plastic waste, is demonstrated. However, the large-scale use of PGMs is hindered by their high cost and low abundance in the Earth's crust [5]. Therefore, scientific research aimed at finding inexpensive yet effective catalysts for the plastic recycling process via catalytic degradation is a highly relevant task today.

The primary candidates to replace PGMs are transition metals, such as *3d*-metals (nickel, cobalt, etc.), which show great potential [6]. Cobalt (Co) and nickel (Ni) are characterized by their ability to exchange electrons with reagents, possessing various oxidation states that they can easily switch by absorbing or donating electrons, significantly enhancing their catalytic ability [7—9]. The most widely used and studied transition metal in almost all fields of catalysis is Co. Cobalt-based catalysts are predominantly used in energy and environmental protection technologies, to the extent that the European Union has included cobalt in the list of critical raw materials. The high catalytic activity of Co is due to its partially filled

d-orbital (3d7), which typically exhibits oxidation states of Co^{2+} and Co^{3+} [10].

However, on the other hand, one of the main stages in the processing of high-polymer materials is the breaking of C—C bonds (characteristic of polyethylene (PE), polypropylene (PP), and polystyrene (PS)), which is an extremely challenging task, because it is known that depolymerization of polymers containing heteroatoms, such as oxygen (C—O bond, typical for PET), is more energy efficient than the cleavage of the C—C bond. Among the known methods for breaking C—C bonds, acid catalysis using solid acids as catalysts is considered promising and has found widespread industrial application in petrochemistry. There are successful technologies using ZSM-5 zeolites, FAU-type zeolite, and *BEA zeolite, in which acid-catalyzed degradation occurs at significantly lower temperatures. However, the excessively high acidity of the zeolite and limitations due to the pore size of the zeolite lead to the formation of lower hydrocarbons (C_1—C_4), while the formation of more valuable C_5 products is limited [11]. Therefore, combining aluminosilicates, characterized by high acidity, with transition metals, such as nickel and cobalt, may be an effective way to create highly active and selective catalysts for catalytic degradation of plastics.

Unfortunately, in the literature, there has been little attention devoted to the recycling of polystyrene (PS) compared to other types of plastics. However, PS is extremely inert to effective degradation under mild natural conditions, which is why the use of chemical methods for its processing, among which catalytic degradation appears to be the most promising method for recycling plastic waste, has increasingly attracted the attention of scientists in recent times. This method allows the production of smaller molecular weight organic compounds that can be precursors for organic synthesis, as well as additives to motor fuel. Such an approach has great potential to become commercially viable and environmentally sustainable. Successful degradation of PS in the presence of a Ni/Al_2O_3 catalyst has already been reported, yielding synthesis gas with the following composition: 62.26 mmol H_2/g polystyrene and 36.10 mmol CO/g polystyrene [12]. In the study [13], the targeted conversion of polystyrene to ethylbenzene in a fixed-bed reactor under pressure in the presence of a Co—N—Ni catalyst was conducted. The conversion of PS reached 95% with an ethylbenzene yield of 92%. Therefore, further research on the catalytic degradation of PS using low-cost catalysts is a highly relevant issue that requires further in-depth studies to understand the chemistry of catalytic degradation and methods for influencing the efficiency of the entire process.

The aim of this work is to study the catalytic processing of polystyrene under reduced pressure and in a hydrogen atmosphere using catalysts based on CaY-type aluminosilicate and natural zeolite from the Sokyrnytsia deposit (Ukraine).

For the modification and activation of aluminosilicate catalysts, the following reagents were used: nickel(II) chloride hexahydrate ($NiCl_2$—$6H_2O$), cobalt(II) chloride hexahydrate ($CoCl_2$—$6H_2O$), hydrochloric acid (HCl), and nitric acid (HNO_3). All reagents were of analytical grade.

For the modification and application of catalytic additives, synthetic CaY-type aluminosilicate was used. Before modification, the CaY aluminosilicate was first converted to its H-form according to the method described in [14]. The modification of HY was carried out by impregnation method, using solutions of nickel and cobalt salts ($NiCl_2 \cdot 6H_2O$ and $CoCl_2 \cdot 6H_2O$). The modification process was conducted so that the theoretical metal ion content constituted 1% by mass of the catalyst in all cases. The HY was then soaked in the corresponding salt solutions for 24 hours, dried, and washed with distilled water to remove any remaining $NiCl_2$ and $CoCl_2$. The catalysts obtained in this way were dried for 5—6 hours at a temperature of 120 °C and then calcined for 1 hour at a temperature of 600 °C. This process yielded the catalysts NiHY, CoHY, and NiCoHY.

Additionally, a natural zeolite (LLC "Sokyrnytsia Zeolite Plant") with a particle size of less than 1 mm, characterized by a high clinoptilolite con-

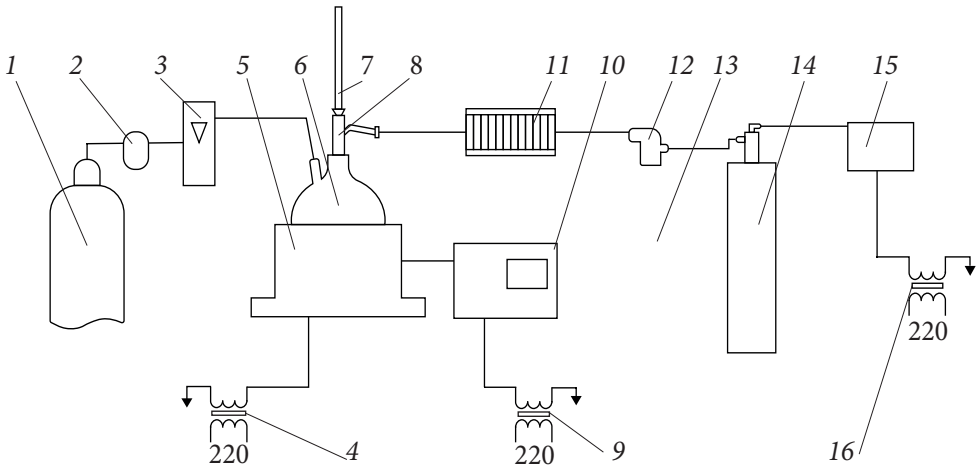

Fig. 1. Laboratory setup for catalytic degradation of polystyrene: *1* — N_2 gas cylinder; *2* — BVO-80DM hydrogen regulator; *3* — rotameter; *4, 9, 16* — power supply; *5* — flask heater; *6* — two-neck round-bottom flask; *7* — thermometer; *8* — Wurtz adapter; *10* — temperature controller; *11* — reflux condenser; *12* — distillation receiver; *13* — receiving flask; *14* — vacuum trap in liquid nitrogen; *15* — vacuum pump

tent (up to 85%), was chosen as a catalyst. Initially, the zeolite (Zeo-0) was treated with a 2M nitric acid (HNO_3) solution at a temperature of 40 °C under vigorous stirring for 4 hours. This process effectively removes impurities and calcium and magnesium ions, which can block active sites on the zeolite surface. After acid treatment, the zeolite sample was washed with distilled water until the pH of the wash water reached 6—7. The zeolite was then dried at 105 °C for 24 hours to completely remove moisture. This resulted in the acid-activated zeolite (Zeo-1).

The phase composition analysis of the catalyst samples based on CaY-type aluminosilicate and natural zeolite from the Sokyrnytsia deposit was performed using *X*-ray phase analysis (XRD) on a Rigaku Ultima IV *X*-ray diffractometer (Japan) with CuKα radiation (40 kW, 30 mA). The phase composition was automatically calculated using the PDXL software application based on standard reference cards.

The structural and adsorption properties of the catalysts were studied using a JWGB Meso 112 specific surface area and porosity analyzer (China) with corresponding software.

The catalytic degradation of polystyrene was conducted on a custom laboratory setup, the schematic of which is shown in Fig. 1.

The catalytic degradation was carried out under two conditions: under reduced pressure and in an H_2/N_2 (50/50) environment.

In the first setup, positions *1, 2*, and *3* were not used, and the process was conducted as follows. The shredded plastic, mixed with the appropriate catalyst in a 5:1 ratio, was loaded into the round-bottom flask *6*, which was connected to the vacuum system through the condenser *11*, the distillation receiver *12*, and the receiving flask *14*. After creating a vacuum in the setup, heating was started, and the catalytic cracking process was carried out for 4—6 hours.

For the catalytic cracking in an H_2/N_2 (50/50) environment, positions *15* and *16* were not used. Instead, after loading the plastic and catalyst (5:1 ratio), the round-bottom flask was purged with H_2/N_2 (50/50) gas, where hydrogen acted as a hydrogenation reagent. The gas flow from the cylinder was regulated by the BVO-80DM hydrogen regulator *2* and the rotameter *4*. The catalytic cracking process in the H_2/N_2 environment was then carried out as described above.

The identification of the products obtained from the catalytic degradation of polystyrene, specifically the liquid phase, was carried out using H^1NMR spectroscopy and GC/MS method. H^1NMR spectra were recorded on a Varian Unity Plus 400 spectrometer (at a frequency of 400 MHz). Tetramethylsilane was used as the internal standard. GC/MS was conducted on an HP Agilent 5890/5972 gas-liquid chromatograph with a mass detector (EI, 70 eV).

CATALYST CHARACTERIZATION

The *X*-ray diffraction patterns of the NiHY, CoHY, and NiCoHY catalysts presented in Fig. 1 indicate a weak degree of crystallinity, which confirms the presence of an amorphous phase in all samples. All diffraction patterns are similar to each other, indicating the absence of an influence from the modifier on their structural characteristics and emphasizing the determining role of the synthetic aluminosilicate in forming the structural-phase morphology of the CaY-based samples.

The *X*-ray diffraction patterns of Zeo-0 (natural zeolite) and Zeo-1 (acid-activated zeolite) indicate a well-defined crystalline structure of the zeolite and, upon comparison, show slight differences in peak intensities, suggesting minimal structural-compositional changes due to acid activation (Fig. 2).

The BET method evaluation of the structural-adsorption properties of the catalyst samples (Table 1) indicates a decrease in the specific surface area of the cobalt-nickel catalyst based on CaY-type aluminosilicate, specifically CoNiHY (213.5 m^2/g), compared to the NiHY and CoHY catalysts (366.8 m^2/g and 340.7 m^2/g, respectively), which requires further investigation.

The specific surface area of the natural zeolite Zeo-0 is relatively low at 12.1 m^2/g, but after acid activation with nitric acid, the specific surface area increased more than threefold, and the pore volume increased fivefold. At the same time, acid activation of the natural zeolite and modification of the NaY aluminosilicate did not significantly affect the pore diameter of the resulting samples.

RESULTS OF THE PRODUCTS OBTAINED FROM CATALYTIC DEGRADATION OF POLYSTYRENE UNDER REDUCED PRESSURE

The results of the products obtained from the catalytic degradation of polystyrene under reduced pressure are presented in Table 2. It should be noted that in this study, the target products of catalytic degradation of polystyrene were styrene, methylstyrene, and ethylbenzene. Therefore, the analysis of the data presented in Tables 3 and 4 was conducted with these considerations in mind.

From the data presented in Table 2, it can be seen that the use of the NiHY catalyst results in the production of target products such as styrene and ethylbenzene with a combined percentage of 52.05% in the reaction products. The use of cobalt-containing catalysts in this case, specifically CoHY and CoNiHY, allows obtaining target products such as styrene and methylstyrene, which can be exp-

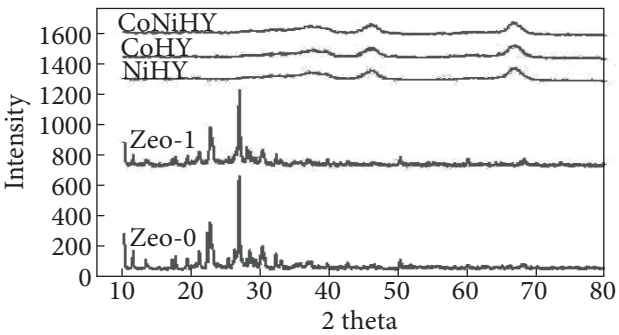

Fig. 2. *X*-ray diffraction patterns of CoNY, NiCoNY and NiNY samples and Zeo-0 and Zeo-1 samples

Table 1. **Structural-Adsorption Properties of the Catalyst Samples**

Catalyst Name	Pore Diameter, nm	Pore Volume, cm^3/g	Specific Surface Area, m^2/g
NiHY	2.2	0.1	366.8
CoHY	2.3	0.1	340.7
CoNiHY	2.2	0.05	213.5
Zeo-0	3.1	0.004	12.1
Zeo-1	2.3	0.02	38.9

lained by the presence of cobalt in these catalysts. The total percentage of target products is 37.74% and 57.9% for CoHY and CoNiHY catalysts, respectively. Therefore, it can be concluded that the presence of cobalt leads to the formation of the valuable product methylstyrene, while nickel contributes to an increased yield of target products.

Based on the data obtained, it can be assumed that by varying the nickel and cobalt content in the catalyst and the conditions of the catalytic degradation of polystyrene, the yield of valuable products, in particular methylstyrene, which is a precursor for the production of cumene, can be controlled.

Table 2. **Results of the Products Obtained from the Catalytic Degradation of Polystyrene under Reduced Pressure**

Catalyst	T_{max}, °C	Liquid fraction yield, %	Reaction products	
			Product name	Yield, %
NiHY	178	55.08	Styrene	46.9
			ethylbenzene	5.15
			1,3-diphenyl-but-2-ene	5.92
			2,4,6-triphenyl-hex-1-ene	11.12
			others	30.88
CoHY	160	45.26	Styrene	29.6
			1,3-diphenyl propane	13.79
			methylstyrene	8.14
			others	48.49
CoNiHY	200	52.2	Styrene	51.9
			1,3-diphenyl-but-2-ene	5.32
			2,4,6-triphenyl-hex-1-ene	14.37
			methylstyrene	6.00
			others	22.37
Zeo-0	182	61.38	Styrene	38.0
			1,3-diphenyl-but-2-ene	4.87
			2,4,6-triphenyl-hex-1-ene	15.59
			methylstyrene	5.67
			others	35.87
Zeo-1	175	52.33	Styrene	39.6
			1,3-diphenyl-but-2-ene	2.94
			2,4,6-triphenyl-hex-1-ene	9.19
			methylstyrene	32.45
			others	15.82

The results of catalytic degradation of polystyrene using catalysts based on natural zeolite of Ukrainian origin and its activated form (Zeo-0 and Zeo-1, respectively) proved to be interesting. The use of natural zeolite Zeo-0 resulted in the highest liquid fraction yield among the catalysts studied, namely 61.38%, which confirms the ability of natural zeolites to create conditions for C—C bond cleavage [15]. Furthermore, this catalyst is almost as effective as the CoNiHY sample in terms of methylstyrene yield.

A simple and inexpensive acid activation step of the natural zeolite (Zeo-1) allowed the highest yield of methylstyrene, specifically 32.45%. The total percentage of target products for this catalyst was also the highest at 72.05%. In addition, the mass fraction of aromatic dimers, trimers and unidentified organic products decreased in the presence of Zeo-1, indicating a shift in selectivity toward target products.

Liquid phase yield analysis, which is valuable in this process, shows similar levels in all cases, ranging from 45.26% to 61.38%.

RESULTS OF THE PRODUCTS OBTAINED FROM THE CATALYTIC DEGRADATION OF POLYSTYRENE IN A HYDROGEN ATMOSPHERE (H_2 TO N_2 MIXTURE 1 : 1)

The results of the products obtained from the catalytic degradation of polystyrene in a hydrogen atmosphere (H_2—N_2 mixture 1 : 1) are shown in Table 3. From the data presented, it can be observed that in the degradation products in hydrogen atmosphere, in the presence of CoHY, CoNiHY and Zeo-1 catalysts, ethylbenzene appears together with styrene and methylstyrene. In contrast, styrene and methylstyrene are present in the products when NiHY and Zeo-0 are used. This may indicate different mechanisms of catalytic reaction for polystyrene conversion in these different environments.

It should be noted that the yield of styrene does not decrease but rather increases for all catalysts except NiHY and CoNiHY, which may indicate a

mechanism of C—C bond cleavage at acidic sites and warrants further investigation. At the same time, the yield of valuable products in the hydrogen atmosphere increases significantly, ranging from 47.51% to 78.1%, which is associated with the potential for hydrogenation processes.

The analysis of the liquid phase yield in the hydrogen atmosphere shows that it ranges from 37.11% to 56.5%, which is lower than in the reduced pressure mode. However, the quality of the valuable products in the liquid phase is higher in terms of target product content. These observations indicate the positive effect of both the hydrogen atmosphere and the reduced pressure mode on the catalytic degradation of polystyrene, suggesting that the combination of these two factors could improve its efficiency. Therefore, it can be concluded that in the hydrogen atmosphere, the yield of valuable components increases while the yield of the liquid phase decreases, with cobalt exhibiting greater catalytic capability for hydrogenation of the C—C double bond, which is consistent with literature data [10].

It should be noted that the temperature for the catalytic degradation of polystyrene in the presence of the studied catalysts is consistently within the range of 169 °C to 200 °C. This confirms the viability of low-temperature catalytic recycling of polystyrene with these catalysts.

Based on the experimental data obtained in the study of catalytic degradation of polystyrene under different conditions and under the influence of different catalysts, several schemes for the formation of the main products have been proposed.

As is known, the study of the mechanisms of thermal and catalytic degradation of polystyrene has long been the subject of active research [16]. Recently, quantum-chemical methods have been most frequently used, which allow a more detailed study of the degradation sequence of the carbon chain of polystyrene, the structure and stability of intermediates, and an explanation of the conditions for the formation of specific reaction products [17]. However, the quality of these studies may vary, and some of these conclusions should be treated with great caution.

When assessing a particular destruction mechanism, it is necessary to take into account the stereoregular structure of the selected polymer, the conditions of destruction, primarily temperature, and the nature of the catalyst [18].

The type of stereoregular structure of polystyrene (isotactic, syndiotactic, and atactic) significantly affects the value of the C—C bond energy in the polystyrene molecule [17]. Since the type of polystyrene structure is unknown in our expe-

Table 3. **Results of the Products Obtained from the Catalytic Degradation of Polystyrene in a Hydrogen Atmosphere (H_2 to N_2 mixture 1 : 1)**

Catalyst	T_{max}, °C	Liquid fraction yield, %	Reaction products	
			Product name	Yield, %
NiHY	180	56.5	Styrene	41.14
			1,3-diphenyl propane	10.89
			styrene dimer	7.57
			styrene trimer	12.71
			methyl styrene	7.32
			other	20.37
CoHY	173	44.46	Styrene	52.8
			styrene dimer	3.23
			styrene trimer	2.28
			methylstyrene	10.1
			ethylbenzene	12.12
			other	19.47
CoNiHY	169	52.2	Styrene	44.97
			styrene dimer	3.28
			styrene trimer	0.98
			methylstyrene	11.02
			ethylbenzene	22.11
			other	17.64
Zeo-0	176	45.34	Styrene	39.95
			1,3-diphenyl propane	11.88
			styrene dimer	4.49
			styrene trimer	4.38
			methyl styrene	7.56
			other	31.74
Zeo-1	175	37.11	Styrene	49.16
			styrene dimer	9.36
			styrene trimer	9.2
			methylstyrene	6.65
			ethylbenzene	5.15
			other	20.48

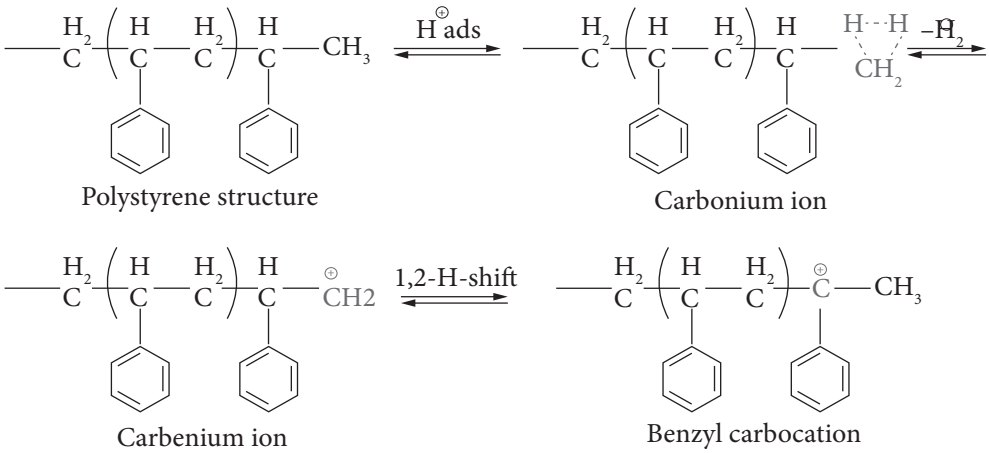

Fig. 3. Mechanism of formation of carbonium, carbenium, and benzyl cations

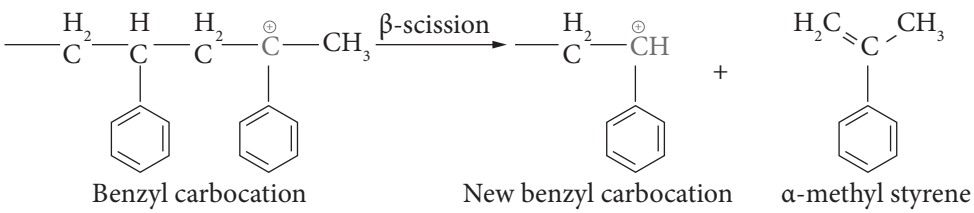

Fig. 4. Mechanism of formation of a-methyl styrene

riment, we can assume that we are dealing with the most disorganized atactic structure.

The second important factor that determines the choice of mechanism is the reaction temperature and/or the presence of a catalyst. Under high-temperature process conditions (temperatures above 350—400 °C), homolytic processes of C—C and C—H bond cleavage can be assumed, leading to the formation of free radicals. Then the formation of free radicals, their β-scission, hydrogen transfer, disproportionation, and free-radical addition processes are natural [18]. Under milder conditions, in the presence of heterogeneous acidic catalysts, a mechanism of heterolytic cleavage of C—H and C—C bonds can be assumed, which is accompanied by the formation of carbonium and then carbenium ions with subsequent isomerization and rearrangement processes [18].

Taking into account our conditions for the reaction of catalytic degradation of polystyrene, it is logical to assume that the process proceeds along a heterolytic path. As is known, the processes of catalytic transformations of hydrocarbons on the surface of acid catalysts begin with the splitting of the most accessible C—H bonds. This leads to the formation of carbonium ions first, and then carbenium ions (Fig. 3).

The subsequent fate of these ions depends on the structure of the carbon skeleton and the presence of appropriate cation-stabilizing substituents. The presence of aromatic rings effectively stabilizes benzyl carbocations, which can easily form as a result of the 1,2-hydride shift (Fig. 3). This suggests that this route may be the most preferable at the first stage of the reaction.

The resulting benzyl carbocations are then capable of splitting, stabilizing according to the b-scission with the formation of new carbocations with a lower molecular weight (Fig. 4). One of these routes allows obtaining a-methylstyrene.

The formation of styrene is possible even at the first stage of the formation of the primary carbe-

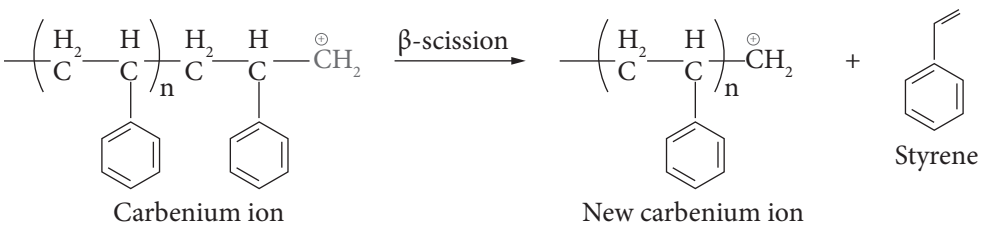

Fig. 5. Mechanism of formation of styrene

nium ion. In this case, instead of the expected 1,2-hydride shift, β-scission of the primary carbocation is observed (Fig. 5).

The formation of, for example, 1,3-diphenyl-but-2-ene and 2,4,6-triphenyl-hex-1-ene is the result of similar processes of β-scission and a sequence of 1,2-hydride shifts that occur with the products of deeper depolymerization of polystyrene. In addition, the formation of 1,3-diphenyl-but-2-ene indicates that the original structure of polystyrene is atactic.

The presence of saturated products in reaction mixtures indicates the occurrence of a hydrogenation reaction on the double C=C bonds, which result from carbocation stabilization processes. In experiments conducted in a hydrogen atmosphere, such products are noticeably more numerous.

An interesting feature is the occurrence of the hydrogenation reaction during catalytic degradation of polystyrene under reduced pressure in the presence of a NiHY catalyst. In this case, the amount of ethylbenzene can reach up to 5%. This may be an indirect confirmation of the mechanism involving the formation of carbonium ions, as well as the catalytic activity of NiHY in hydrogenation reactions. For all other cases, no formation of saturated products of the catalytic degradation of polystyrene has been reported.

In this study, the low-temperature degradation of polystyrene has been investigated with the use of catalysts based on synthetic NaY-type aluminosilicates (NiHY, CoHY, CoNiHY) and natural zeolite from the Sokyrnytsia deposit (Ukraine) with and without acid activation (Zeo-0, Zeo-1) under two conditions — reduced pressure and a hydrogen atmosphere. The catalysts were characterized by XRD analysis and low-temperature nitrogen adsorption-desorption methods, while the products of catalytic degradation were identified by NMR spectroscopy and chromatography.

It has been found that the main products of catalytic degradation include styrene, ethylbenzene, methylstyrene, 1,3-diphenyl-but-2-ene, 1,3-diphenylpropane, and 2,4,6-triphenylhex-1-ene, with the target products being the first three compounds listed. The temperature of catalytic degradation ranged from 169 °C for CoNiHY in a hydrogen atmosphere to 200 °C for CoNiHY under reduced pressure.

The analysis of the liquid phase compositions has shown that natural zeolites are nearly as effective as synthetic zeolites: the highest yield of methylstyrene, specifically 32.45%, under reduced pressure, was observed for acid-activated natural zeolite (Zeo-1), with the highest total percentage of target products at 72.05%. The analysis of the liquid phase yield for Zeo-1 in a hydrogen atmosphere has also indicated high catalytic activity, second only to the CoHY catalyst in effectiveness.

The positive effect of both the hydrogen atmosphere and the reduced pressure on the catalytic degradation of polystyrene has been observed. This leads to a suggestion that the combination of these two factors may enhance the efficiency of polystyrene catalytic conversion.

A mechanism for the formation of valuable components in the catalytic degradation of polystyrene has been proposed. This testifies to a high catalytic activity of transition metals (Co, Ni) as hydrogenation agents and the potential of natural zeolites. This could be the subject of further research aimed at developing efficient and cost-effective catalysts for the degradation of polystyrene and possibly other types of plastics.

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ДОСЛІДЖЕННЯ ЕФЕКТИВНОСТІ НИЗЬКОТЕМПЕРАТУРНОГО КАТАЛІТИЧНОГО РОЗКЛАДУ ПОЛІСТИРОЛУ З ВИКОРИСТАННЯМ КАТАЛІЗАТОРІВ НА ОСНОВІ АЛЮМОСИЛІКАТІВ

Вступ. Глобальна криза забруднення пластиком вимагає ефективних стратегій його переробки для зменшення шкоди довкіллю. Зокрема, особливу проблему становить полістирол через свою хімічну інертність та стійкість до природного розкладання.

Проблематика. Незважаючи на досягнення у галузі каталітичної деполімеризації, висока вартість і дефіцит металів платинової групи перешкоджають їх широкомасштабному застосуванню. Перехідні метали є доступними і ефективними каталізаторами, проте залишається прогалина у розумінні того, як склад каталізатора та умови процесу впливають на ефективність розкладання полістиролу.

Мета. Дослідження ефективності синтетичних та природних алюмосилікатних каталізаторів у низькотемпературному каталітичному розкладанні полістиролу.

Матеріали й методи. Каталізатори було підготовлено шляхом кислотної обробки (для природного цеоліту) та просочення солями Ni й Co (для синтетичного цеоліту Y-типу). Рентгенівська дифракція, низькотемпературна адсорбція-десорбція азоту характеризували структуру та пористість каталізатора. Каталітичний розпад полістиролу (при 169—200 °C) виконано під зниженим тиском або при потоці H_2—N_2 (1:1).

Результати. За зниженого тиску кислотно-активований природний цеоліт (Zeo-1) досяг найвищого загального відсотка цільових сполук (до 72 %), що особливо помітно для метилстиролу (32,5 %). В атмосфері водню загальний вихід цінних продуктів збільшився (до 78 % для деяких каталізаторів), хоча загальний вихід рідкої фази зменшився. Каталізатори, що містять кобальт, особливо сприяли гідруванню стиролу до етилбензолу. Природні цеоліти продемонстрували майже однакову ефективність із синтетичними алюмосилікатами при розкладанні пластику. Запропоновані механізми реакції свідчать про те, що перехідні метали (Ni, Co) посилюють розрив зв'язків C—C, що призводить до утворення цінних мономерів і частково гідрованих продуктів.

Висновки. Отримані дані відкривають шлях до розробки економічно ефективних високопродуктивних каталізаторів для утилізації полістиролу.

Ключові слова: полістирол, каталітичний крекінг, низькотемпературний процес, алюмосилікати, природний цеоліт, газорідинна хроматографія.