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HYDROGEN STORAGE IN POROUS CARBON MATERIALS OBTAINED BASED ON SHUBARKOL COAL

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The aim of the research work was to study the hydrogen sorption properties of carbonized adsorbents obtained from coal from the Shubarkol deposit in Kazakhstan. The adsorbents were prepared by heat treatment with K_2CO_3. The morphological features of the obtained adsorbents were determined by the SEM method. The structure of the materials was confirmed using transmission electron microscopy (TEM). The results of the studies showed the largest specific surface area (653.024 m²/g), which determines its effective hydrogen sorption capacity. The adsorption-desorption isotherm of mesopores of the powdered carbonized adsorbent "Shubarkol:K_2CO_3" 1:0.5, 900ºC refers to a type I microporous material. The adsorption-desorption isotherm of the powdered carbonized adsorbent "Shubarkol:K_2CO_3" 1:1, 900ºC indicates that it has a macroporous or uneven solid surface of type II. In this regard, the powder "Shubarkol:K_2CO_3" 1:1 is recognized as the optimal material for storing hydrogen due to its high specific surface, developed microporous structure and ability to adsorb hydrogen.

Keywords: coal, adsorbent, porosity, carbonization, adsorption, hydrogen.

ШҰБАРКӨЛ КӨМІРІ НЕГІЗІНДЕ АЛЫНҒАН КЕУЕКТІ КӨМІРТЕКТІ МАТЕРИАЛДАРДА СУТЕКТІ САҚТАУ

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Зерттеу жұмысы Қазақстанның «Шұбаркөл» кен орнының көмірінен алынған карбонизацияланған адсорбенттерінің сутегіні сорбциялау қасиеттерін зерттеуге арналған. Адсорбенттерді K_2CO_3-мен өңдеп, термиялық процесс арқылы дайындалды. Алынған адсорбенттердің морфологиялық ерекшеліктері СЭМ әдісі арқылы анықталып. Өткізгіш электрондық микроскоп (ӨЭМ) әдісі арқылы материалдардың құрылымы дәлелденді. Зерттеу нәтижелері бойынша ең үлкен меншікті бетінің ауданы (653.024 м²/г) көрсетті, бұл оның сутекті тиімді адсорбциялау қабілетін айқындайды. «Шұбаркөл:K_2CO_3» 1:0,5, 900ºC ұнтақталған карбонизацияланған адсорбентінің мезо кеуектерінің адсорбция-десорбция изотермасым I типке микрокеуекті материалға жатады. «Шұбаркөл:K_2CO_3» 1:1, 900ºC ұнтақталған карбонизацияланған адсорбентінің адсорбция-десорбция изотермасым II типке макрокеуекті немесе тегіс емес қатты бетке ие екенін көрсетеді. Осыған байланысты «Шұбаркөл:K_2CO_3» 1:1 ұнтағы жоғары меншікті бетінің ауданына, дамыған микрокеуекті құрылымына және сутекті сіңіру қабілетіне байланысты сутегін сақтау үшін оңтайлы материал болып танылды.

Түйін сөздер: көмір, адсорбент, кеуектілік, карбонизация, адсорбция, сутегі.

ХРАНЕНИЕ ВОДОРОДА В ПОРИСТЫХ УГЛЕРОДНЫХ МАТЕРИАЛАХ, ПОЛУЧЕННЫХ НА ОСНОВЕ ШУБАРКУЛЬСКОГО УГЛЯ

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Целью научно-исследовательской работы было изучение водородосорбционных свойств карбонизированных адсорбентов, полученных из угля месторождения «Шубарколь» Казахстана. Адсорбенты были приготовлены путем термической обработки с K_2CO_3. Методом СЭМ определены морфологические особенности полученных адсорбентов. Структура материалов была подтверждена с помощью просвечивающей электронной микроскопии (ПЭМ). По результатам исследований показана наибольшая удельная поверхность (653,024 м²/г), что определяет его эффективную водородосорбционную способность. Изотерма адсорбции-десорбции мезопор порошкообразного карбонизированного адсорбента «Шубарколь:K_2CO_3» 1:0,5, 900ºС относится к микропористому материалу I типа. Изотерма адсорбции-десорбции порошкообразного карбонизированного адсорбента «Шубарколь:K_2CO_3» 1:1, 900ºС свидетельствует о том, что он имеет макропористую или неровную твердую поверхность II типа. В связи с этим порошок «Шубаркол:K_2CO_3» 1:1 признан оптимальным материалом для хранения водорода благодаря высокой удельной поверхности, развитой микропористой структуре и способности поглощать водород.

Ключевые слова: уголь, адсорбент, пористость, карбонизация, адсорбция, водород.

Introduction. There is a growing interest in renewable energy sources as a global strategy towards net-zero carbon emissions [1]. This is evident from a massive utilization of renewable energy sources to produce electricity in some parts of Europe [2]. More recently, the use of hydrogen as a clean alternate fuel has seen remarkable interest from the relevant stakeholders and the scientific community [3-5].

There are main four ways to store of hydrogen: liquefaction, compressed gas, metal hydrides, and adsorption. So far researches on hydrogen storage shows that pressurized tank (gaseous H_2), liquid hydrogen, metal hydride (solid hydrogen) and cryoadsorption (condensed phase of H_2) are the most promising alternatives. The hydrogen adsorption in porous solids and specially activated carbons, is still considered one interesting and safe alternative. Initially, carried out researches were based on the use of cryogenic systems, which are not useful from an economic point of view. Recently, research has focused on the search for the ideal adsorbent that can be used at room temperature as well as allows the storage of interesting amounts of H_2 such as activated carbons [6].

Nowadays, the hydrogen industry in Kazakhstan is in its infancy. Nevertheless, Kazakhstan is making significant strides in the field of hydrogen technol-ogies and production. In January 2023, President Kassym-Jomart Tokayev of Kazakhstan described green hydrogen as a ”promising direction” [7].

Hydrogen storage in carbon-based materials is considered a viable solution to increase hydrogen density, which is currently a major problem hindering the hydrogen supply chain, which becomes denser when stored in a porous solid as opposed to pure compressed gas.[8] The hydrogen density stored in nanoporous carbon materials can be approximated to the density of liquid hydrogen, i.e., 70 kg/m^3. To achieve such a value, which is four orders of magnitude higher than the density of gaseous hydrogen at room temperature and atmospheric pressure (0.089 kg/m^3), the system temperature needs to be significantly reduced. For example, at 77 K, hydrogen adsorption improves

due to enhanced interaction with the carbon surface via van der Waals forces. Thus, adsorption is the most effective storage method at 298 K and up to 20 MPa. This means that under these conditions, the amount of hydrogen stored is always higher in the presence of the adsorbent than in the case of hydrogen storage by simple compression in an empty vessel of the same volume. Therefore, based on carbon, storage will allow the use of a smaller volume hydrogen tank. Indeed, if 5 kg of hydrogen can be stored at 20 MPa and 298 K in an empty high-pressure tank of 340 L, the required volume decreases to 263 L in the presence of a carbon adsorbent for storing the same amount of hydrogen under the same conditions. Such advantages are provided by the unique texture of porous carbon [9].

Activated carbons are one of the widespread used porous carbon materials which usually have specific surface areas up to 3000 m^2/g^{-1} and wide pore sizes ranging from micropore to mesopore and even macropore, but with abundance of micropore size less than 1 nm. The highly developed porosity makes activated carbon a promising candidate for adsorption, separation, purification and gas storage, especially for hydrogen storage. In general, the hydrogen storage capacity of activated carbon has appeared to be proportional to the surface area and micropore volume. Experimental findings showed hydrogen uptake values in the range of 0.2–5.5 wt%, with a clear dependency on the activated carbons evaluated. Moreover, the majority of experimental results have demonstrated that H_2 uptakes of about 2.5 wt% at low pressures (1–10 bar) and 5.5 wt% at high pressures (up to 60 bar) and 77 K were achievable. Again, the highest H_2 adsorption measured at 100 bar and room temperature is below 1 wt%, even with highly developed pore structures and specific surface areas up to 2800 m^2/g^{-1} [10-13].

The hydrogen storage methods motivated us to study hydrogen adsorption on several porous carbon adsorbents of various origins that differed in the porous structure and chemical state of the surface at the near ambient temperatures and not-extreme high pressures. Therefore, this study was aimed to determine the factors affecting the efficiency of hydrogen adsorption-based storage with AC as an adsorbent, namely the influence of thermodynamic conditions and structural and energy characteristics.

Materials and methods. There are various approaches to producing carbon materials, which include the preparation and modification of the initial coal, carbonization, and subsequent activation using gas or chemical agents. One of the promising methods for obtaining porous carbon materials from carbonaceous feedstock is the use of activating agents during thermal processing. When in contact with salt, the lignite structure begins to rearrange even at room temperature, and upon heating, the salt promotes the development of specific surface area, as well as an increase in total pore volume and micropore volume. K_2CO_3 is considered a more effective activating agent compared to Na_2CO_3. The enhanced efficiency of K_2CO_3 is attributed to the larger ionic radius of potassium (0.267 nm) in comparison to that of sodium (0.190 nm). The activation atmosphere (N_2, CO_2, or H_2O) also influences the structural properties of the activated carbon. It has been found that, compared to CO_2 and steam, nitrogen serves as a good alternative as an activation medium. Increasing the mass ratio of salt to coal, the heating temperature, and the holding time leads to higher porosity and a larger specific surface area of the resulting carbon.

The experimental setup and procedure (hydrogen adsorption) were as follows: The hydrogen saturation unit for porous carbon material consisted of several sections. The hydrogen source was a QL 500 series hydrogen generator with a maximum output of 500 cm^3/min, and the hydrogen generator used water from a Thermo Scientific deionizer. The total flow rate was monitored using a rotameter.

An autoclaved glass reactor with a working volume of up to 0.5 liters was used as a laboratory reactor. The reactor vessel base has stainless steel legs. The reactor vessel design is based on a glass cylinder, which is fixed between the top cover and the metal bottom with a bottom drain valve. Temperature control is achieved by circulating thermostatically controlled water through a jacket

at the bottom of the reactor.

The pressure was measured every minute. The initial pressure was -0.75 bar, and a vacuum environment was created using a pump. The H_2 absorption process was carried out at temperatures of 298 K, 313 K, 343 K. The mass of the porous carbon material was 97 g. The process was continued until the pressure in the reactor reached a constant value. The absorption capacity was calculated from the gas balance (based on the measured amount of H_2 and the known gas flow rate).

The aim of the work is to study the method for obtaining carbon sorbents from oxidized coal ”Shubarkol” with a developed structure and high adsorption characteristics, as well as the use of the obtained adsorbents for hydrogen storage.

Chemical analysis and surface morphology were studied by energy-dispersive X-ray spectroscopy using a SEM (Quanta 3D 200i) with an EDAX energy-dispersive analysis attachment. Specific surface area analysis was performed using a 3Flex 3500 high-performance adsorption analyzer (Micromeritics, USA) with a standard SmartVacprep programmable degasser.

Results and discussion. The results of the physicochemical characteristics of the samples and the elemental composition are presented in Tables 1 and 2.

Table 1 - Results of physicochemical analysis of ”Shubarkol/K_2CO_3” 1:0.5; 1:1 adsorbents

Name of adsorbents	W^r_t,%	A^r,%	V^d, %	$V\Sigma_{(water)}$, cm^3/g	ρ_{bulk}, g/cm^3	$pH_{aqueous\ extract}$	$A_{m.o.}$, mg/g	$A_{m.b.}$, mg/g
”Shubarkol-K2CO3” (1:0.5, 900°C) powder carbonized adsorbent	12.73	8.83	52.95	1.63	0.76	7.41	33.23	34.31
”Shubarkol-K2CO3” (1:1, 900°C) powder carbonized adsorbent	11.45	8.85	51.25	1.83	0.72	7.05	38.45	40.12

Table 2 - Results of the elemental analysis of the samples

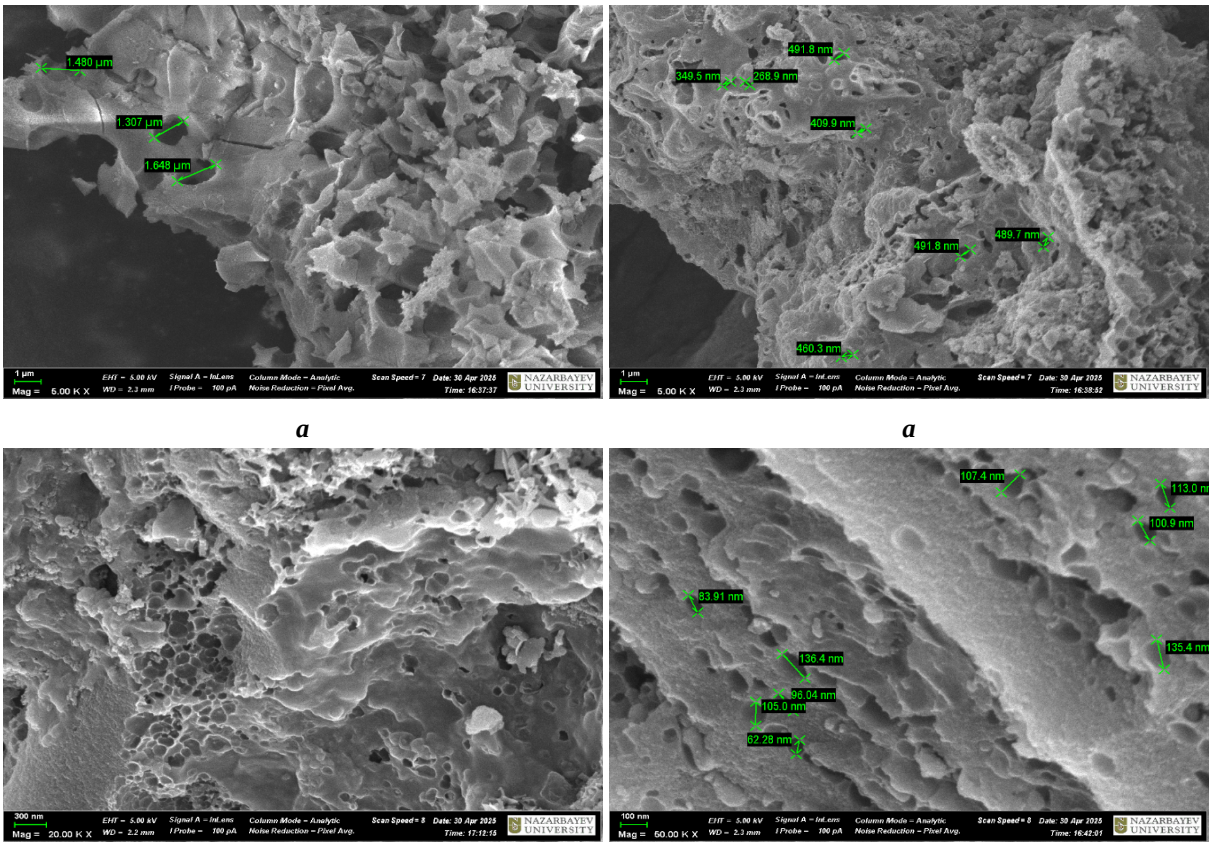
Name	Elemental content, mass %									
	C	O	Na	Mg	Al	Si	S	K	Ca	Fe
”Shubarkol-K2CO3” (1:0.5, 900°C) powder carbonized adsorbent	53.01	18.69	0.27	0.35	1.81	1.07	0.44	11.56	6.70	6.10
”Shubarkol-K2CO3” (1:1, 900°C) powder carbonized adsorbent	68.24	13.88	0.15	0.54	1.01	1.03	0.31	1.53	8.28	5.03

The physicochemical properties of porous carbon materials obtained as a result of the carbonization process were determined by the adsorption capacity according to methylene blue and methyl orange indicators. As a result, the adsorbent ”Shubarkol-K_2CO_3” in the ratio of 1:1 showed a relatively high adsorption capacity. In terms of elemental composition, the adsorbent in the ratio of 1:1 had a higher carbon content. The higher the carbon content, the more porous the adsorbent obtained and the more suitable it is for further use as an adsorbent.

The morphology of the obtained adsorbents was investigated at various scales using scanning electron microscopy (SEM). Figures 1 and 2 show

the results of SEM analysis of the ”Shubarkol-K_2CO_3” 1:0.5 900°C powder carbonized adsorbent and the ”Shubarkol-K_2CO_3” 1:1 900°C powder carbonized adsorbent.

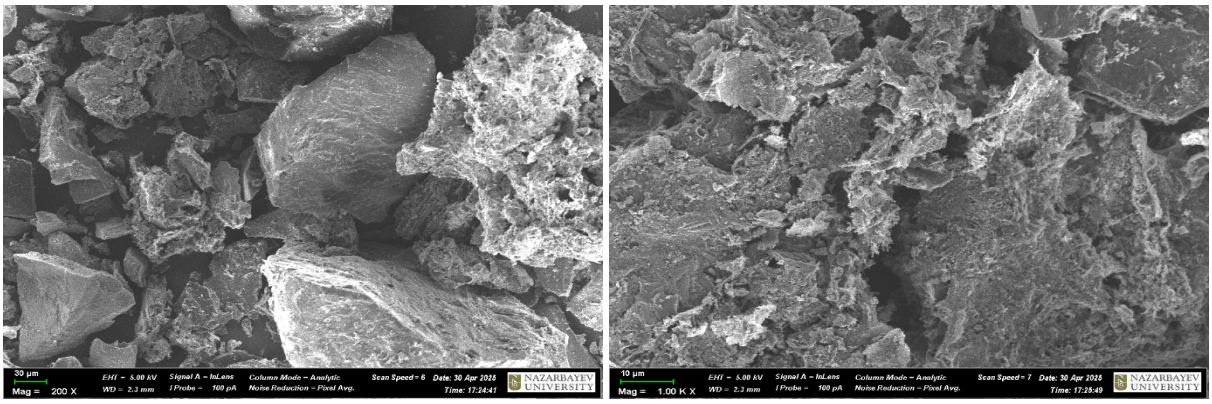
As a result of the SEM study, porous structures consisting of large and small particles are clearly visible in the samples carbonized at a temperature of 900°C. It is known that the presence of developed micropores on the surface layer contributes to an increase in the adsorption capacity. Figures 3 and 4 show the results of TEM analysis of the ”Shubarkol-K_2CO_3” 1:0.5 900°C powder carbonized adsorbent and the ”Shubarkol-K_2CO_3” 1:1 900°C powder carbonized adsorbent.



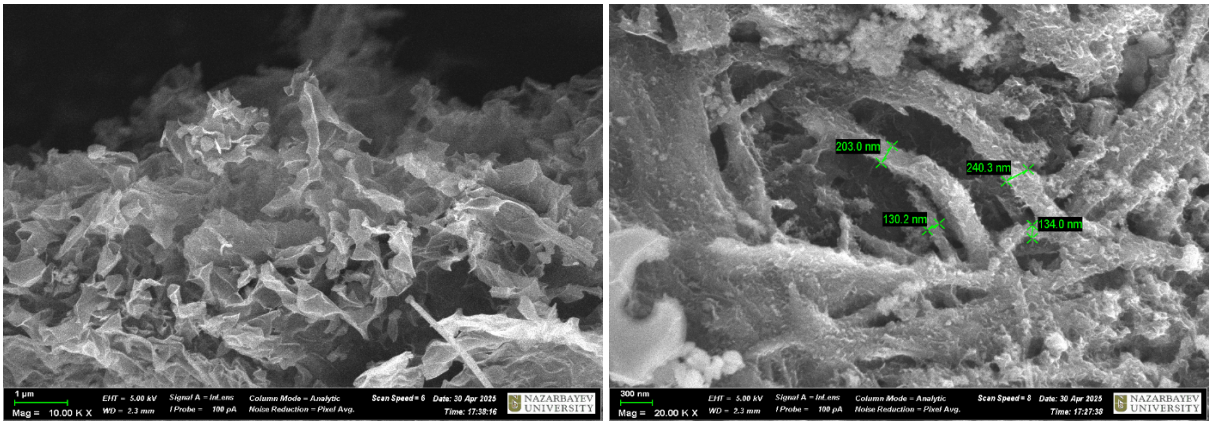
a ***a***

a ***a***

Fig.1 - SEM results of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” 1:0.5 at 900°C: a,b-x5000; c-x20000; d-x50000

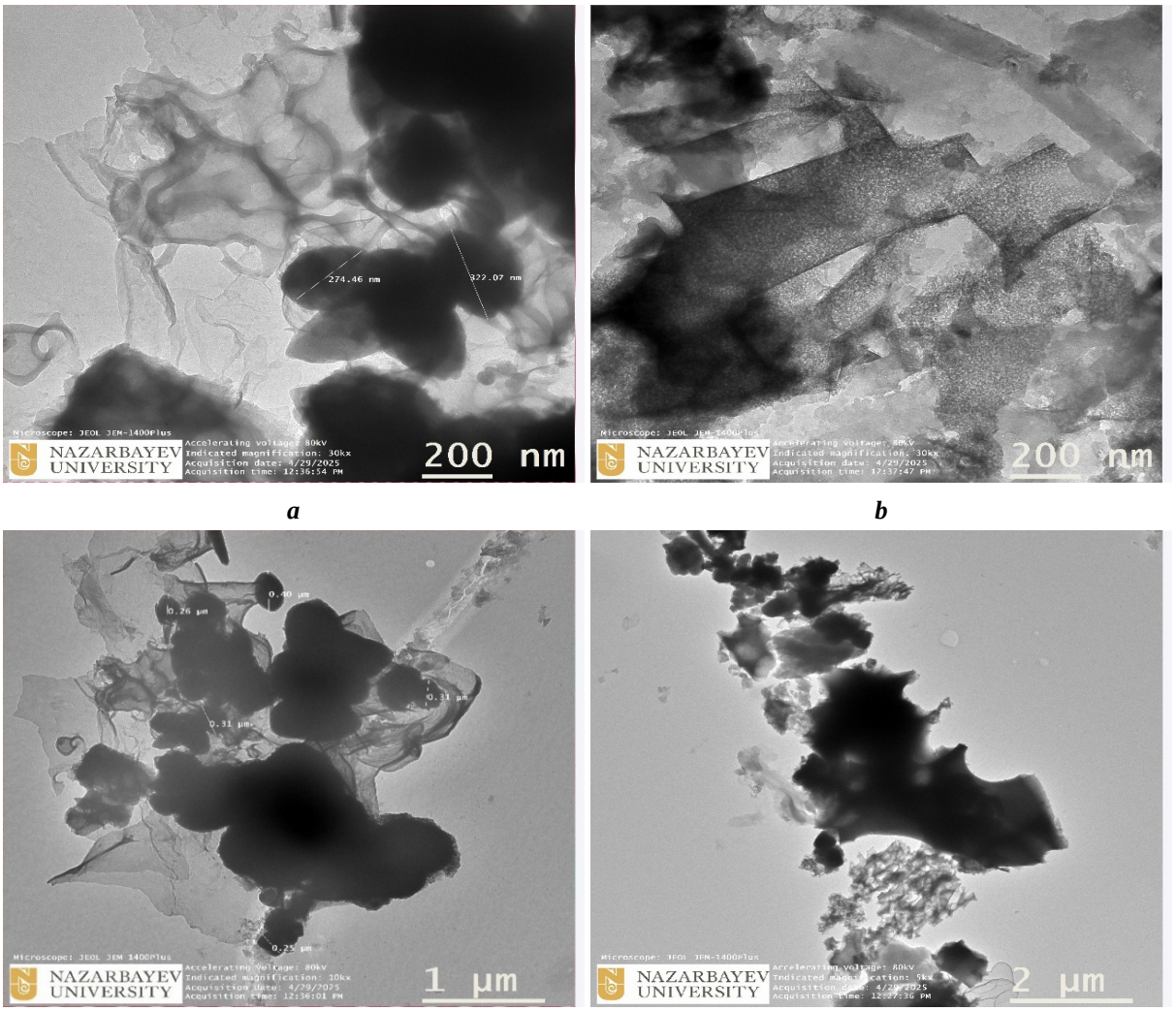


a ***b***



c *d*

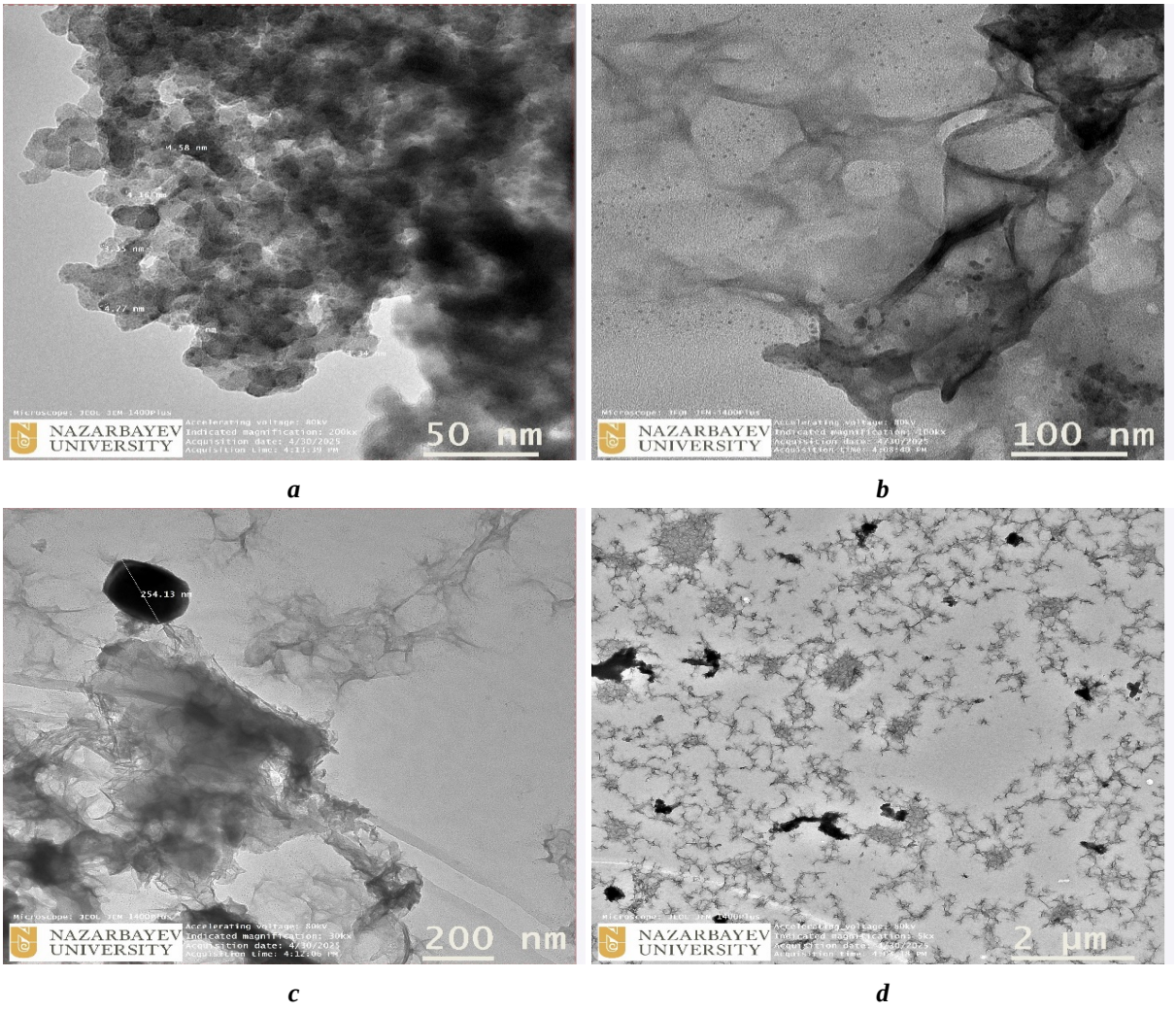
Fig.2 - SEM results of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” 1:1 at 900°C: a-x200; b-x1000; c-x10000; d-x20000



a *b*

c *d*

Fig.3 - TEM results of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” 1:0.5 at 900°C



a *b*

c *d*

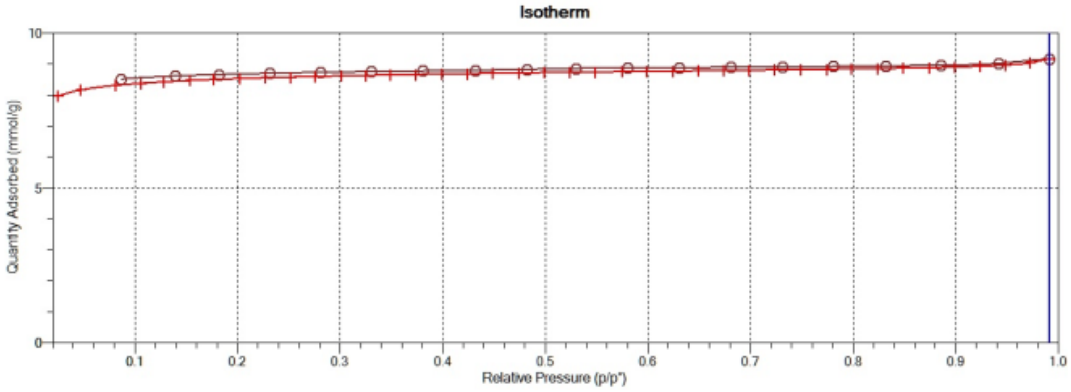
Fig.4 - TEM results of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” 1:1 at 900°C

Table 3 - Adsorption characteristics of samples (N_2)

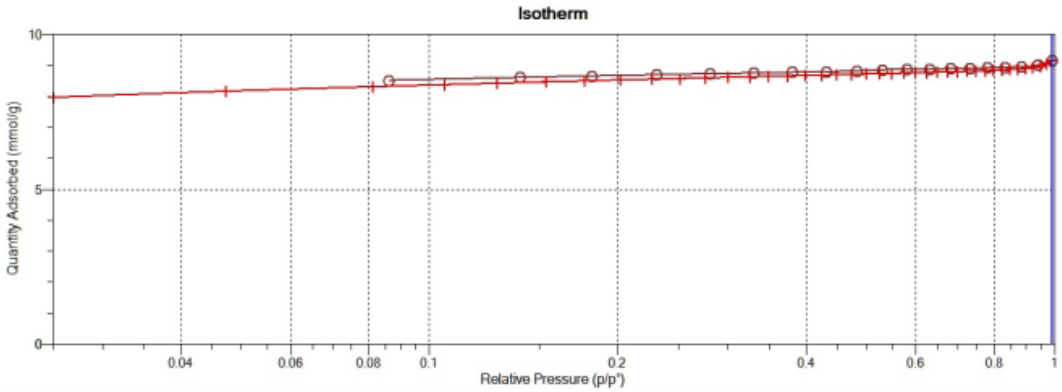
Name	SBET, m^2/g	Total pore volume, cm^3/g	Micro pores, cm^3/g	Meso pores, cm^3/g	Macro pores, cm^3/g	SBJH, for pore width from 17,000 Å to 3,000,000 Å, m^2/g	Average width of adsorption pores BJH (4V/A), Å
”Shubarkol-K2CO3” (1:0.5, 900°C) powder carbonized adsorbent	676.889	0.318	0.276	0.036	0.006	42.2087	37.616
”Shubarkol-K2CO3” (1:1, 900°C) powder carbonized adsorbent	653.024	0.435	0.205	0.183	0.048	137.2048	62.144

The results of the TEM images provide clear images of the internal structure of the carbon adsorbent. As shown in Figure 3, the particles are assembled in the form of large agglomerates, and at their edges there are clearly visible graphitized layers and curved structures. These graphitized structures may increase the

thermal stability of the adsorbent. The images presented in Figure 4 show the formation of nanostructured particles, as well as clearly visible flaky and layered structures. This indicates that the carbonization process contributed to the formation of nanoparticles with different morphologies within the carbon matrix. In general, the obtained microscopic data indicate that the carbon materials synthesized using Shubarkol coal and K_2CO_3 are highly structured, multi-porous and nanostructured. Such properties allow these adsorbents to be effectively used in gas or hydrogen storage.

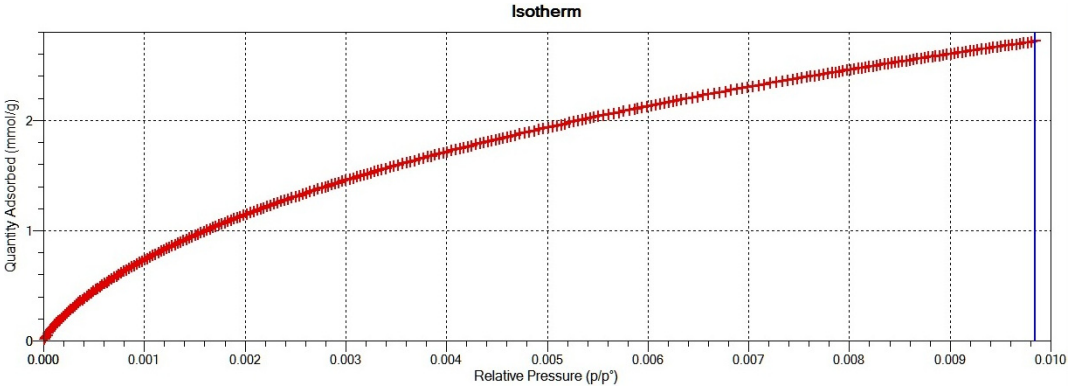


a

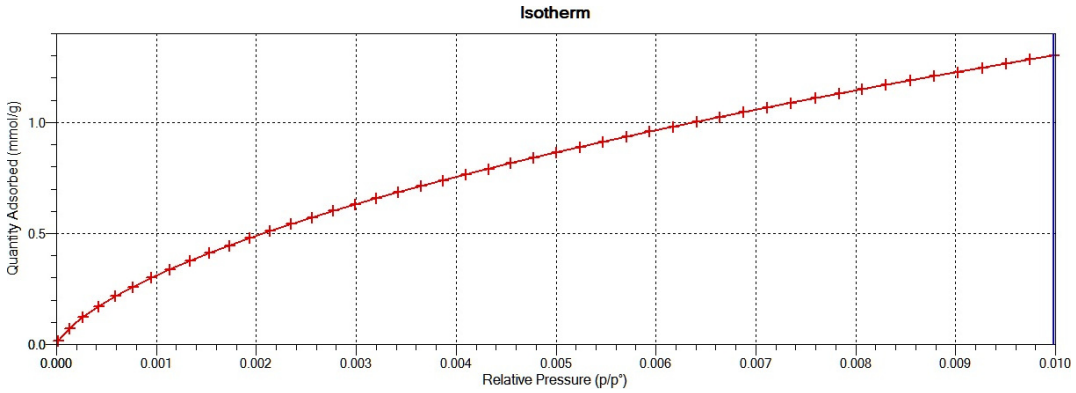


b

Fig.5 - Adsorption curves of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” a-1:0.5; b-1:1 (based on N_2, by the BET method)



a



b

Fig.6 - Adsorption curves of the powder carbonized adsorbent ”Shubarkol-K_2CO_3” a-1:0.5; b-1:1 (based on CO_2)

Table 4 – Results of the study of sorption of PCM (by CO_2)

Name	Dubinin-Radushkevich method			Dubinin-Astakhov method			
	Maximum capacity of micropores, mmol/g	Maximum volume of micropores, cm^3/g	Equivalent surface area, m^2/g	Maximum capacity of micropores, mmol/g	Micropore volume limitation, cm^3/g	Equivalent surface area, m^2/g	Average equivalent pore width, Å
”Shubarkol-K2CO3” (1:0.5, 900°C) powder carbonized adsorbent	7.9279	0.377916	811.635593	8.68047	0.413789	1359.46542	10.93346
”Shubarkol-K2CO3” (1:1, 900°C) powder carbonized adsorbent	4.3212	0.205985	442.386469	9.96985	0.475252	1308.89576	14.52375

As a result, the types of adsorption-desorption isotherms of the obtained adsorbents were determined and a conclusion was drawn. The adsorption-desorption isotherm of the mesopores of the powdered carbonized adsorbent “Shubarkol:K_2CO_3” 1:0.5, 900ºC belongs to type I. The isotherm of the obtained sample belongs to type I - this is a microporous material. The adsorption-desorption isotherm of the powdered carbonized adsorbent “Shubarkol:K_2CO_3” 1:1, 900ºC belongs to type II. The isotherm of the obtained sample belongs to type II - this type indicates that the adsorbent has a macroporous or uneven solid surface.

The time dependence of hydrogen adsorption was determined using a laboratory device for powdered carbonized adsorbents ”Shubarkol:K_2CO_3” 1:0.5; 1:1 900 ºC. During the study, the dynamics of the hydrogen adsorption process on porous carbon materials at temperatures of 298 K, 313 K, 343 K were studied. The time dependence of the amount of adsorbed hydrogen was considered, which allows

us to get an idea of the speed and efficiency of the hydrogen adsorption process. Analysis of the hydrogen adsorption rate at each time interval showed that the adsorption rate increases at the beginning of the process, reaching a maximum of 23 minutes at T=298 K, 18 minutes at T=313 K and 12 minutes at T=343 K, and then gradually stabilizes. This may indicate saturation of the adsorbent surface and a decrease in active centers available for hydrogen adsorption. The results of the study are shown in Table 5.

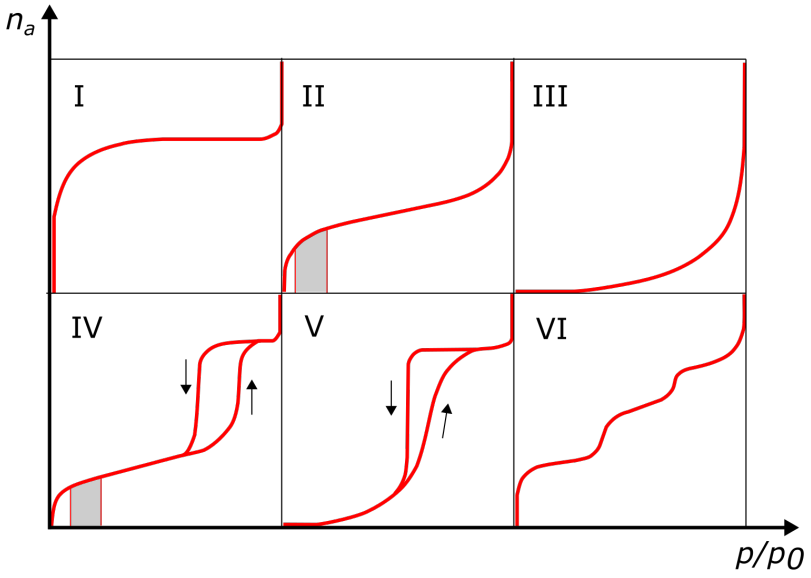


Fig.7 - Types of adsorption-desorption isotherms

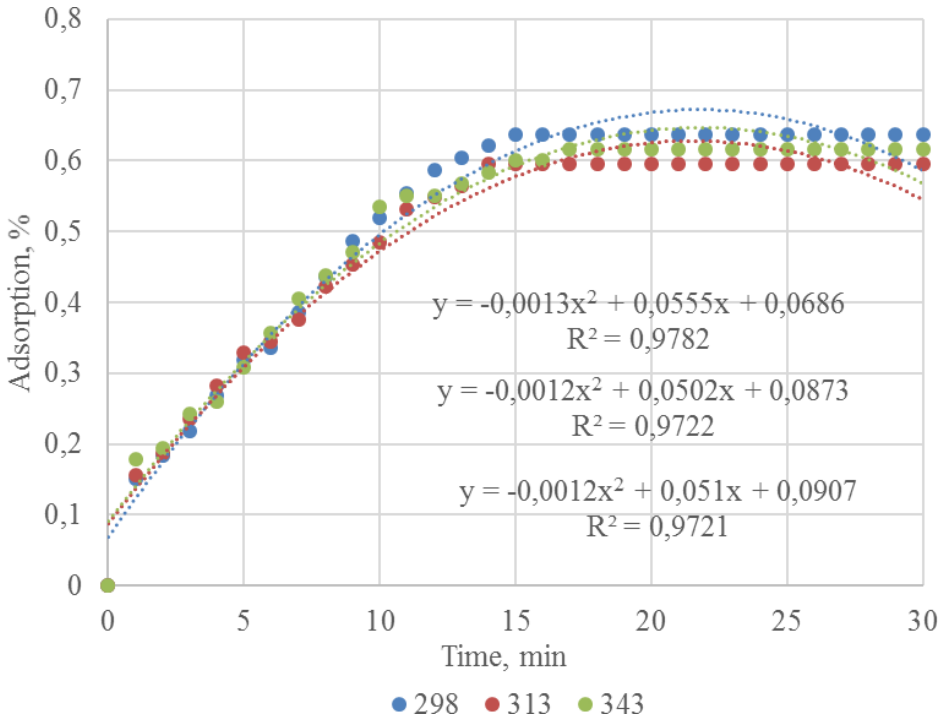


Fig.8 - Dynamics of hydrogen adsorption process on porous carbon material ”Shubarkol:K_2CO_3” 1:0.5 at temperatures of 298 K, 313 K, 343 K

Table 5 - Results of the study of hydrogen sorption with PCM

”Shubarkol-K_2CO_3” (1:0.5, 900°C) powder carbonized adsorbent		
Temperature	Adsorption H_2, %	Adsorption H_2, cm^3/kg
25 ºC	0.637538	0.714043
40 ºC	0.595036	0.666440
70 ºC	0.616287	0.690241
”Shubarkol-K_2CO_3” (1:1, 900°C) powder carbonized adsorbent		
Temperature	Adsorption H_2, %	Adsorption H_2, cm^3/kg
25 ºC	0.727543	0.814849
40 ºC	0.679041	0.760525
70 ºC	0.703292	0.787687

Table 6 - Calculation of the hydrogen adsorption process on porous carbon material ”Shubarkol:K_2CO_3” 1:0.5, %

Temperature, K	**Time, min**			
	10	**12**	**14**	**16**
273	0.350	0.557	0.786	1.037
278	0.318	0.524	0.754	1.008
283	0.288	0.494	0.725	0.982
288	0.261	0.466	0.699	0.960
293	0.235	0.441	0.677	0.941
298	0.211	0.419	0.657	0.926
303	0.189	0.399	0.640	0.914
308	0.169	0.381	0.627	0.907
313	0.152	0.367	0.617	0.902
318	0.136	0.354	0.610	0.902
323	0.122	0.345	0.606	0.905
328	0.110	0.338	0.605	0.911
333	0.100	0.333	0.607	0.922
338	0.093	0.331	0.612	0.936
343	0.087	0.332	0.621	0.953
348	0.083	0.335	0.632	0.974
353	0.081	0.341	0.647	0.999
358	0.081	0.350	0.665	-
363	0.084	0.361	0.686	-

368	0.088	0.374	0.710	-
373	0.094	0.390	0.737	-
378	0.102	0.409	0.768	-

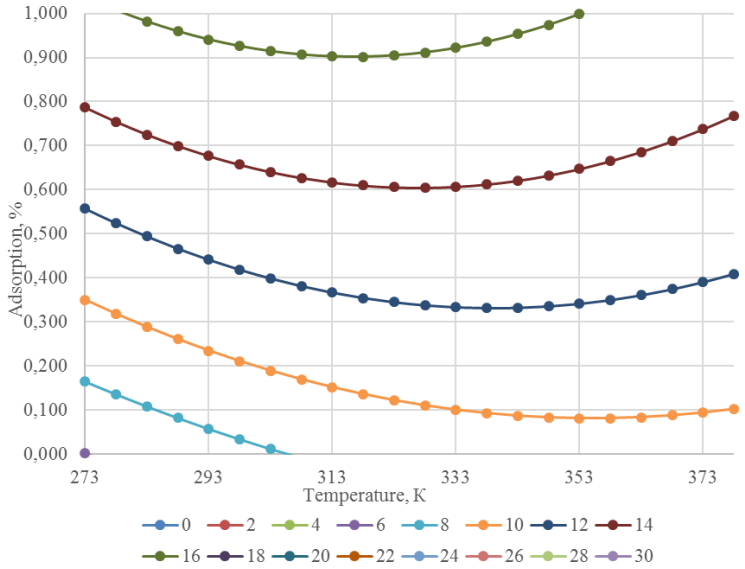


Fig.9 - Dynamics of hydrogen adsorption process on porous carbon material of ”Shubarkol:K_2CO_3” 1:0.5 adsorbent

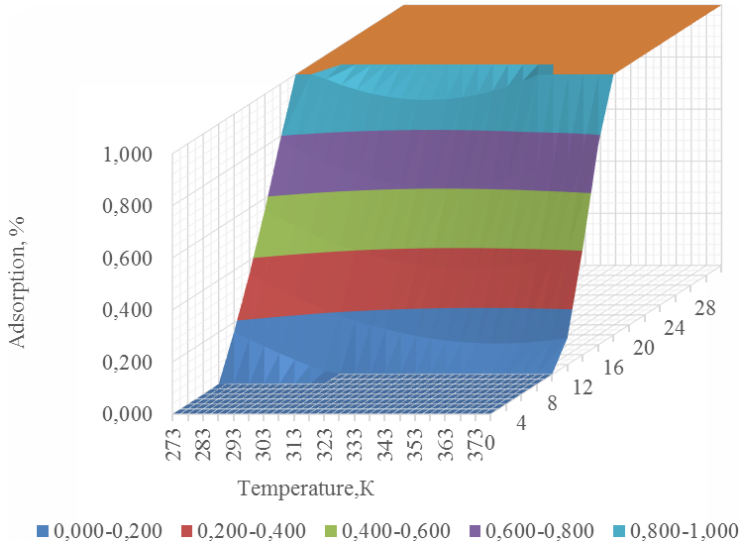


Fig.10 - Dynamics of the process of hydrogen adsorption on porous carbon material ”Shubarkol:K_2CO_3 1:0.5”

This porous carbon from Shubarkol coal (chemical activation K_2CO_3 1:0.5) is capable of absorbing up to ~0.8 wt% hydrogen at room temperature (~298 K) for ~15 minutes, indicating its suitability for rapid hydrogen sorption. Increasing the temperature to 343 K reduces the adsorption threshold by about 10% relative to 298 K, confirming the negative effect of temperature

on hydrogen storage in carbonaceous materials. Thus, for maximum hydrogen adsorption efficiency, low temperatures and sufficient retention times (about 15 minutes to saturation) are suitable for this material. These results may be useful when designing hydrogen storage systems, indicating the need to cool the adsorbent to increase its capacity and take into account the kinetic characteristics of pore filling.

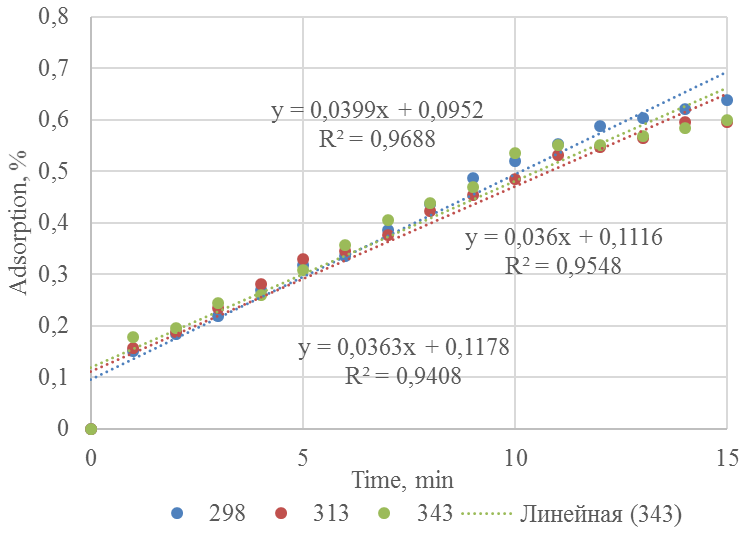


Fig.11 - Dynamics of hydrogen adsorption process at temperatures of 298 K, 313 K, 343 K on a porous carbon material weighing 97 g

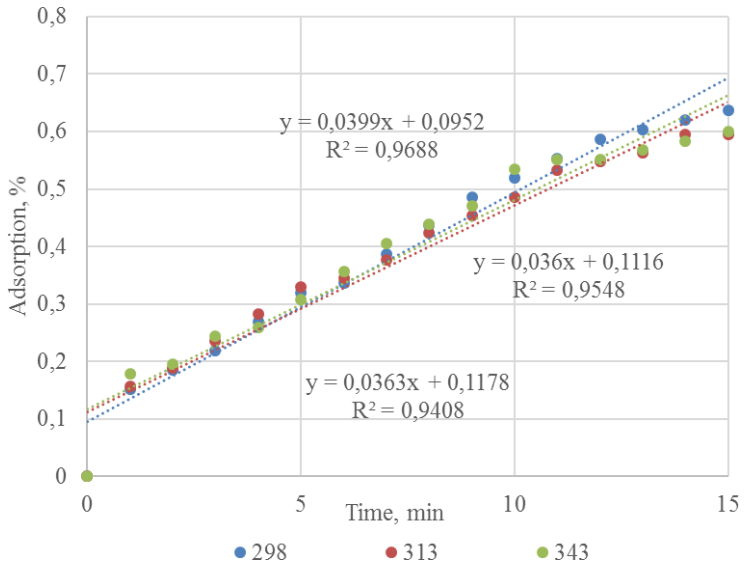


Fig.12 - Dynamics of the process of hydrogen adsorption on porous carbon material ”Shubarkol:K_2CO_3 1:0.5” at temperatures of 298 K, 313 K, 343 K

If we calculate it in a similar way, the activation energy of hydrogen adsorption on this carbon material is approximately -1.6 kJ/mol–1.6 kJ/mol. The negative value of Ea indicates that the adsorption rate decreases with increasing temperature. This behavior is typical of exothermic processes of physical adsorption: as the temperature increases, it becomes more difficult for molecules

to attach to the surface, and the efficiency of adsorption by the adsorbate decreases. A practically negative (close to zero) activation energy indicates the absence of a significant energy barrier for adsorption - the process proceeds practically without an activation limit, and the slight decrease in the rate with increasing temperature is due to thermodynamic factors (weakening of the binding to the adsorbate). Based on the Arrhenius plot and linear regression, the calculated activation energy of hydrogen adsorption is approximately 1.6 kJ/mol (with a minus sign). This is a very low absolute value, close to zero, which is consistent with the idea of physical adsorption of hydrogen on porous carbon without a significant energy barrier.

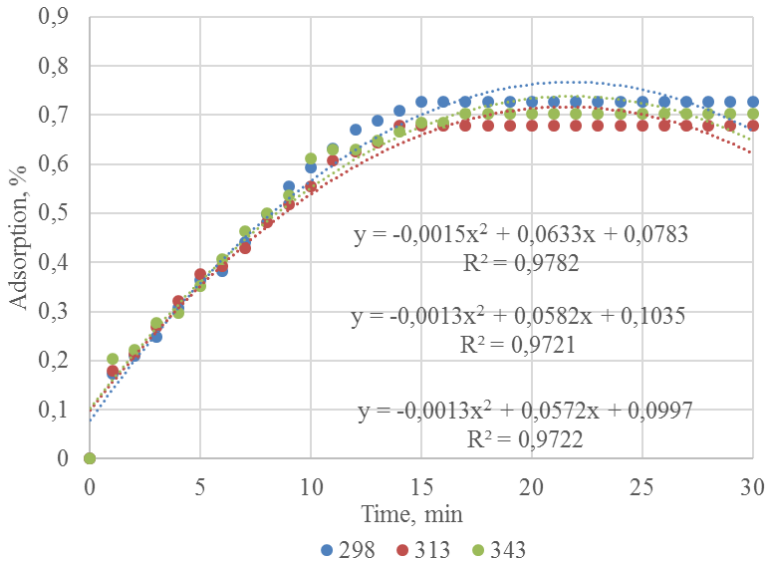


Fig.13 - Dynamics of hydrogen adsorption process on K_2CO_3 1:1 porous carbon material of ”Shubarkol” coal at temperatures of 298 K, 313 K, 343 K

Table 7 - Dynamics of the hydrogen adsorption process in porous carbon material of coal ”Shubarkol:K_2CO_3 1:1”, %

Temperature, K	Time, min									
	0	1	3	7	10	15	19	22	25	30
273	0	0	0.104	0.302	0.432	0.615	0.731	0.799	0.853	0.907
280	0	0.004	0.099	0.274	0.392	0.564	0.679	0.752	0.815	0.894
287	0	0.012	0.094	0.248	0.355	0.517	0.632	0.710	0.780	0.880
294	0	0.017	0.088	0.225	0.322	0.476	0.590	0.671	0.748	0.867
301	0	0.021	0.083	0.204	0.294	0.440	0.554	0.637	0.720	0.854
308	0	0.022	0.077	0.186	0.269	0.409	0.522	0.608	0.694	0.840
315	0	0.022	0.070	0.170	0.248	0.383	0.496	0.583	0.672	0.827
322	0	0.020	0.064	0.157	0.231	0.362	0.474	0.562	0.654	0.814
329	0	0.016	0.057	0.146	0.218	0.347	0.458	0.546	0.638	0.801
336	0	0.009	0.050	0.138	0.209	0.336	0.446	0.534	0.625	0.787

343	0	0.001	0.043	0.133	0.204	0.331	0.440	0.526	0.616	0.774

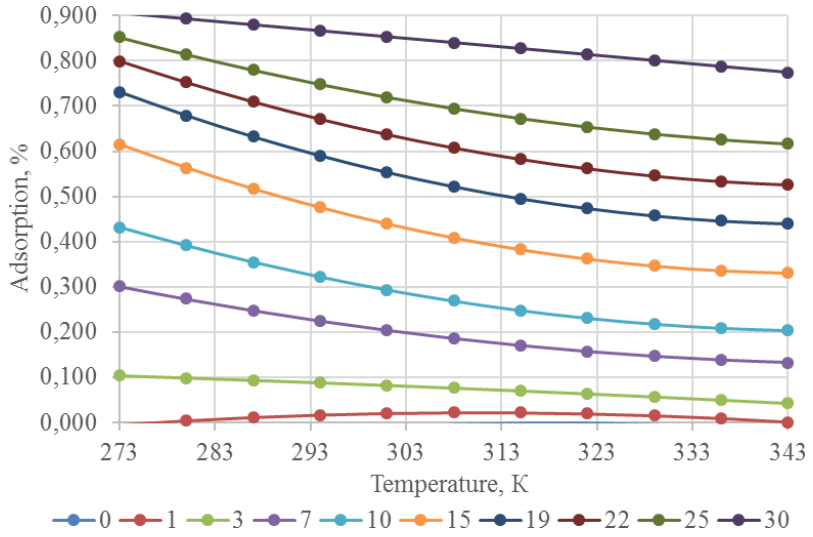


Fig.14 - Dynamics of the hydrogen adsorption process on porous carbon material of the adsorbent ”Shubarkol:K_2CO_3 1:1” 30 min

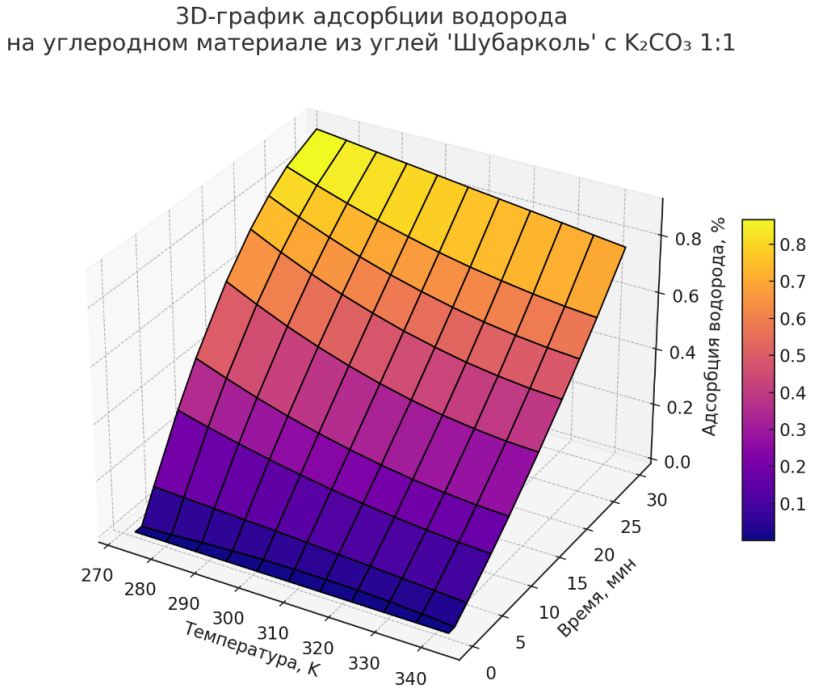


Fig.15 - Hydrogen adsorption (%) on porous carbon material containing K_2CO_3 (1:1) from ”Shubarkol” coal

In the initial stages (up to 10 minutes), the adsorption intensity increases especially rapidly. At low temperatures (273–294 K), maximum adsorption values are achieved - above 0.9%. As the temperature increases, the sorption capacity decreases, which indicates the physical nature of adsorption and possible desorption upon heating.

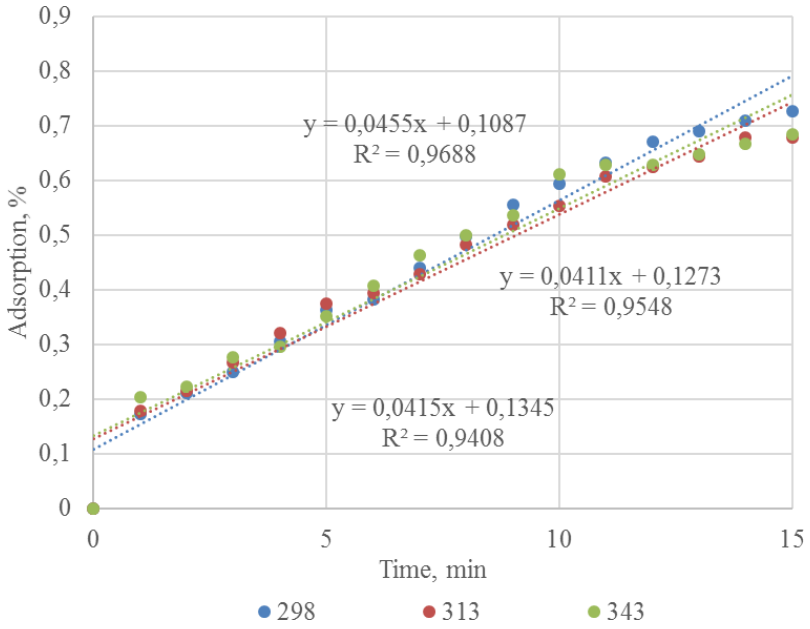


Fig.16 - Dynamics of hydrogen adsorption process on porous carbon material based on Shubarkol:K2CO3 1:1 at temperatures of 298 K, 313 K, 343 K

Table 8 - Experimental results

Temperature , K	Time, min	Adsorption, %	R^2
298	x, min	y = 0.0455*x + 0.1087	0.9688
313	x, min	y = 0.0411*x + 0.1273	0.9548
343	x, min	y = 0.0415*x + 0.1345	0.9408

Table 9 - Calculating activation energy

Temperature , K	Equation	Slope (k), %/min
298	y = 0.0455*x + 0.1087	0.0455
313	y = 0.0411*x + 0.1273	0.0411
343	y = 0.0415*x + 0.1345	0.0415

Table 10 - Data for linear approximation of the dependence of ln on 1/T

T (K)	1/T (1/K)	k (%/min)	ln(k)
298	0.003356	0.0455	-3.09004
313	0.003194	0.0411	-3.19175
343	0.002916	0.0415	-3.18206

Now let’ s find the slope for the line using the least squares method: $\ln k = -E_a/R \quad T + \ln A$

$k_1 = -Ea/R = \Delta \ln k / \Delta(1/T) = (-3{,}09004 + 3{,}11915)/(0{,}003356 - 0{,}003194)$

k_1=0,02911/0,000162≈179,69

Ea=−R k_1=−8,314 (179,69)≈ -1493,954 J/mol ≈-1,5 kJ/mol

Due to the negative activation energy, the process is thermodynamically unfavorable at high temperatures.

The highest adsorption is observed at low temperature (298 K). When the temperature increases to 313 K, the adsorption decreases slightly, which is typical of physical adsorption (which is exothermic). When further increasing to 343 K, a slight recovery of adsorption occurs, which may be due to additional activation of deeper pores or experimental error.

Table 11 - Comparative analysis

Parameter	K_2CO_3 1:1	K_2CO_3 1:0.5	Difference (%)
298 K Adsorption (cm^3/kg)	814.80	714.00	14.00%
313 K Adsorption	760.50	666.40	14.10%
343 K Adsorption	787.70	690.20	14.10%

Table 12 - Comparative analysis of adsorption, %

Temperature, K	Coal ”Shubarkol”/ K2CO3		Difference, %
	1:0,5	1:1	
298	0.637538	0.727543	12.37
313	0.595036	0.679041	12.37
343	0.616287	0.703292	12.37

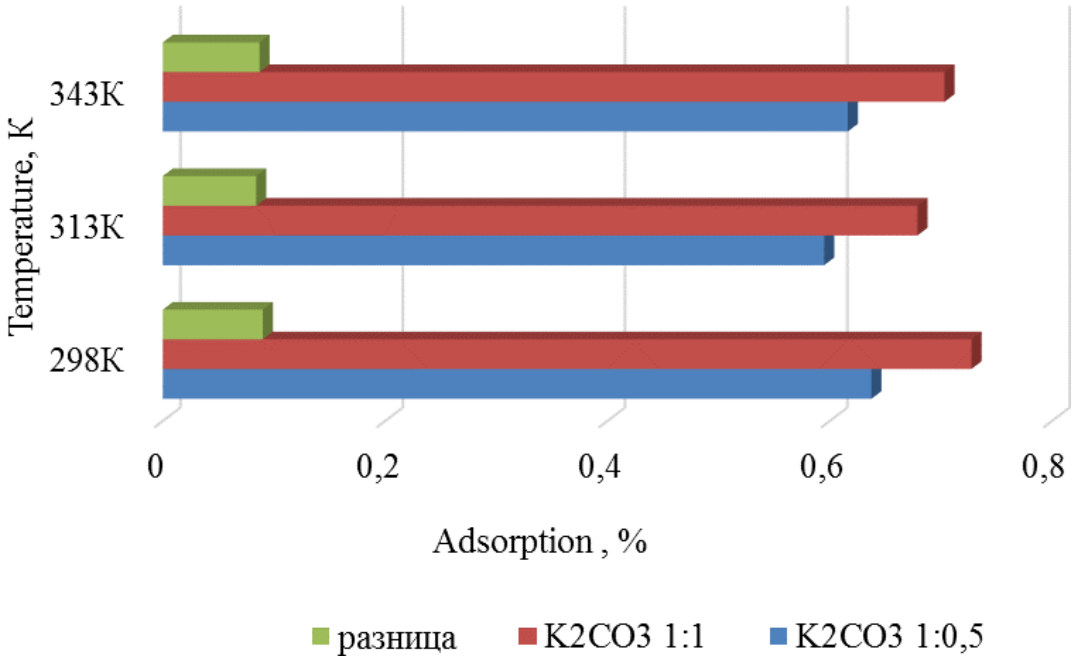


Fig.17 - Comparative analysis of hydrogen adsorption

Table 13 - Hydrogen adsorption calculation, %

Coal:K_2CO_3	Temperature, K								
	273	283	293	303	313	323	333	343	353
1:1	0.916	0.835	0.772	0.728	0.701	0.693	0.702	0.729	0.775
1:0.5	0.890	0.826	0.778	0.746	0.729	0.729	0.745	0.777	0.825
1:0.33	0.865	0.817	0.783	0.763	0.758	0.766	0.788	0.824	0.874
1:0.25	0.839	0.808	0.789	0.781	0.786	0.802	0.831	0.872	0.924
1:0.2	0.814	0.799	0.794	0.799	0.814	0.839	0.874	0.919	0.974
1:17	0.789	0.790	0.799	0.817	0.842	0.876	0.917	0.966	1.024
1:0.14	0.763	0.781	0.805	0.835	0.870	0.912	0.960	1.014	1.074
1:0.13	0.738	0.772	0.810	0.852	0.899	0.949	1.003	1.061	1.123
1:0.11	0.712	0.763	0.816	0.870	0.927	0.985	1.046	1.109	1.173
1:0.10	0.687	0.754	0.821	0.888	0.955	1.022	1.089	1.156	1.223

On average, increasing the mass fraction of K_2CO_3 from 1:0.5 to 1:1 leads to an increase in the adsorption capacity by ~14% in volume. This confirms that intensive activation of K_2CO_3 improves the sorption properties. Both materials show a characteristic physical adsorption property: high efficiency at low temperatures. At K_2CO_3:1:1, hydrogen adsorption is 10–15% higher than at 1:0.5. The difference is observed at all temperatures and is most noticeable at ~714 cm³/kg vs. ~815 at 298 K. This confirms that the high concentration of the activator (K_2CO_3) contributes to good porosity and high sorption capacity.

Conclusion. As a result of the conducted research, the physicochemical properties, morphological features, surface area of carbon adsorbents obtained using Shubarkol coal and potassium carbonate (K_2CO_3) were studied, and the hydrogen storage process was carried out in laboratory conditions. The results showed that the adsorbent "Shubarkol-K_2CO_3" (1:1, 900°C) showed the highest BET specific surface area (653.024 m²/g), which determines its ability to effectively adsorb hydrogen. TEM images confirmed the nanostructured nature of the material. Graphitized regions, layered structures, and agglomerated particles were detected. The results of scanning electron microscopy (SEM) and elemental analysis showed that carbon adsorbents have high porosity, which is an important factor improving their hydrogen storage capabilities.

The results of the conducted research can serve as the basis for the development of promising carbon adsorbents for hydrogen storage systems.

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