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THE RESULTS OF THE SPECIALISTS' AND SCIENTISTS' RESEARCHES

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Development of new methods for energy technology processing of Kyrgyzstan coals

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ABSTRACT

Introduction. This study explores methods for determining the yield of volatile matter from Kyrgyz coal and obtaining ultra-pure carbon for potential applications in modern carbon nanotechnologies used in the construction industry. Both organic and inorganic components of various coal types were analyzed, along with the composition of the released volatile substances. **Methods and materials.** We used in the research empirical methods (observation, experimentation, measurement, and comparison), alongside chemical methods involving acid treatment (for the removal of metallic impurities) and a transport reaction method (for the removal of silicon oxide impurities). The study focused on obtaining ultra-pure carbon from bituminous coal deposits in Kyrgyzstan. The tested raw materials included grey and brown coals from deposits in the southern region of Kyrgyzstan. Pre-weighed samples were placed in a stainless-steel reactor and subjected to slow pyrolysis under sealed conditions across specific temperature ranges. For brown coal, pyrolysis was conducted between 100 °C and 550 °C, while for bituminous coal the range was 100 °C to 1100 °C. The process continued until all liquid and gaseous pyrolysis products ceased to be released. **Results.** Pyrolysis was used to remove volatile liquid and gaseous impurities from the coal samples. The qualitative and quantitative composition of the volatile gases was determined. During pyrolysis in the 100 °C to 850 °C range, pyrogenetic water was formed, and gaseous products such as NO, CO_2, CO, H_2S, CH_4, and others were released. For brown coal, the yield of volatile substances at 150–170 °C was 61.9%. For bituminous coal, at 380–400 °C, the yield was 15.5%. Post-pyrolysis, the remaining coal contained only solid impurities – primarily metallic elements and silicon dioxide (SiO_2). These were removed using a chemical method involving a mixture of concentrated sulfuric and nitric acids in a 1:3 ratio. Silicon dioxide impurities were removed via a transport reaction facilitated by gas convection. As a result of this two-stage purification, ultra-pure carbon consisting solely of carbon atoms (C–C–C–) was obtained. **Conclusion.** The proposed experimental setup and technological scheme for impurity removal and carbon purification – including the use of transport reactions – enable industrial-scale production of ultra-pure carbon from coal. This purified carbon can be used as a component in advanced construction nanomaterials. The use of such materials significantly enhances the performance characteristics of construction structures and coatings, while also reducing the environmental impact of combustion by-products, ultimately lowering costs associated with environmental protection.

KEYWORDS: Nanotechnology, ultra-pure carbon, nanomaterials, graphene, carbon nanotubes, construction, milling, grinder, sieve, pyrolysis, brown coal, reactor, volatile gases, washing, neutralization, pH environment, purification, impurities, transport reaction, bituminous coal, coke, gas convection, filtration, drying

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THE RESULTS OF THE SPECIALISTS' AND SCIENTISTS' RESEARCHES

Разработка новых способов энерготехнологической переработки углей Кыргызстана

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АННОТАЦИЯ

Введение. В настоящей работе исследованы определение выхода летучих веществ из угля Кыргызстана и получение из него особо чистого углерода с целью возможного применения его в современных углеродных нанотехнологиях в строительстве. Определены органические и неорганические составляющие выхода различных видов углей и проведен анализ полученных летучих веществ. **Методы и материалы.** Процесс исследования основывался на применении эмпирических (наблюдение, эксперимент, измерение, сравнение) методов, а также химического с использованием кислот (на этапе очистки исследуемого угля от примесей металлов) и метода транспортной реакции (на этапе очистки исследуемого угля от примесей оксида кремния). Рассмотрены методы, позволяющие получить особо чистый углерод из месторождений каменного угля Кыргызстана. В качестве исследуемого материала, при определении выхода летучих веществ из исходного исследуемого сырья, использованы серые и бурые угли месторождения южного региона Кыргызстана. В ходе исследования заранее взвешенное сырье помещали в реактор и после его герметичного закрытия производили медленный пиролиз исследуемого угля в диапазоне заданных температур. Конструктивные элементы реактора выполнены из нержавеющей стали. Когда за объект исследования принимали бурый уголь, то процесс пиролиза проводили в диапазоне температур 100–550 °С. Исследования пиролиза каменного угля проводились в диапазоне температур 100–1100 °С. Исследования процессов пиролиза вышеуказанных углей проводились до момента полного прекращения выделения из объектов исследования жидких и газообразных продуктов распада. **Результаты.** Очистили исследуемые угли от жидких и газообразных примесей пиролизом. Определены количественный и качественный составы, а также содержание летучих газов исследуемых углей. В процессе пиролиза в интервале температур от 100 °С до 850 °С произошло разделение веществ с образованием пирогенетической воды, а также выделились газообразные вещества NO, CO_2, CO, H_2S, CH_4 и др. При пиролизе бурого угля в температурном диапазоне 150–170 °С выход летучих веществ составил 61,9%. При пиролизе каменного угля в диапазоне 380–400°С выход летучих веществ составил 15,5%. Получили в результате пиролиза в реакторе уголь, в составе которого остались только твердые примеси металлов и оксида кремния (SiO_2), входящих в состав его макро- и микроэлементов. Очистили исследуемые угли от твердых примесей соединения различных металлов, применив химический метод с использованием смеси концентрированной серной и азотной кислот в соотношении 1:3. Очистили полученные исследуемые угли от твердых примесей оксида кремния, применив транспортную реакцию (за счет конвекции газов). Получили в результате очистки из исследуемых углей особо чистый углерод, содержащий только атомы углерода С–С–С–. **Заключение.** Использование предложенной экспериментальной установки и технологической схемы очищения угля от примесей для получения чистого углерода с использованием транспортных реакций в промышленном масштабе позволяют более эффективно производить переработку и получение угля, содержащего чистый углерод, входящий в состав строительных наноматериалов и использование которого в строительстве с применением нанотехнологий позволяет значительно улучшать характеристики строительных конструкций и покрытий, а также снизит вредное воздействие продуктов сгорания на окружающую среду, что сократит затраты на природоохраняемые мероприятия.

КЛЮЧЕВЫЕ СЛОВА: Нанотехнологии, особо чистый углерод, наноматериалы, графен, углеродные нанотрубки, строительство, измельчение, мельница, сито, пиролиз, бурый уголь, реактор, летучие газы, промывка, нейтрализация, pH-среда, очищение, примесь, транспортная реакция, каменный уголь, кокс, конвекция газов, фильтрация, сушка

ДЛЯ ЦИТИРОВАНИЯ:
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INTRODUCTION

Carbon nanotechnologies in construction present a promising field of materials science and engineering, involving the application of nanomaterials based on pure carbon: graphene, carbon nanotubes (CNTs), fullerenes, nanodiamonds, and others. These materials possess unique properties that significantly enhance the performance of structural elements and protective coatings. Carbon-based nanomaterials are used to develop self-diagnostic construction materials capable of detecting damage at early stages [1]. These materials exhibit exceptional characteristics, enabling substantial improvement of building components and surface layers.

Carbon fibers (carbon fiber reinforced polymer – CFRP) are lightweight, strong, and corrosion-resistant, which makes them suitable for use in construction as reinforcement for concrete (as a substitute for steel), for strengthening structural elements (such as old bridges, columns, beams, slabs), in façade panels and interior elements. CFRPs offer high strength-to-weight ratio, are insensitive to moisture and chemically aggressive environments, and have a long service life (unlike metals, they do not rust).

Graphene is a monolayer of carbon atoms arranged in a hexagonal lattice, where each atom is bonded to three neighboring atoms [2]. Due to its exceptional strength and thermal conductivity, graphene is used to enhance construction materials and in paints and coatings to create self-sensing surfaces. When added to concrete, graphene increases strength and resistance to cracking [3]. Its high thermal conductivity and mechanical strength make it a promising material for energy-efficient structural systems [4]. Graphene coatings are used to protect structures from corrosion and mechanical damage [5]. Graphene-based nanomaterials are also utilized in the development of flexible sensors and smart home systems embedded into building materials [6]. However, at present, graphene remains too expensive for widespread commercial use.

Carbon nanotubes (CNTs) possess high strength and electrical conductivity, which makes them suitable for reinforcing concrete and enabling the creation of self-diagnostic structures. The incorporation of CNTs into concrete improves its mechanical performance and enables the development of materials capable of detecting internal damage. CNTs are applied in the fabrication of lightweight, high-strength composite materials for construction [7]. Due to their exceptional mechanical and electrical properties, CNTs are considered a promising reinforcement component for building materials [8]. The addition of CNTs enhances concrete's structural integrity and supports the development of self-monitoring capabilities [9]. CNTs are also used to manufacture antistatic or self-sensing materials capable of crack detection [10]. Graphene-based materials with high thermal conductivity are employed in energy-saving façades and underfloor heating systems. The use of graphene or CNT composites in 3D printing of structural elements provides advantages such as light weight, shape flexibility, and durability.

Fullerenes are closed-cage polyhedra composed of three-coordinated carbon atoms and exhibit unique physicochemical properties [11]. In construction, fullerenes are used to modify cementitious composites, improving their strength and resistance to aggressive environments [12]. They are also used to develop materials with enhanced thermal insulation properties [13]. Due to their nanoporous structure, fullerenes can reduce heat loss.

Fullerenes and carbon nanotubes are added to paints and coatings to impart anti-corrosion and antibacterial properties [14]. They also enhance the UV resistance of building materials [15]. Carbon nanomaterials improve coatings by making them resistant to ultraviolet radiation, imparting anti-corrosive and antibacterial effects, and enabling electrical conductivity for antistatic or thermo-protective applications.

The main challenges and limitations hindering the widespread adoption of carbon-based nanotechnologies in construction include their high cost, the technological complexity of achieving uniform dispersion in matrices, lack of standardized mass-production protocols, and the need for comprehensive long-term environmental impact assessments.

Pure carbon used in nanotechnology (e.g., for the production of fullerenes, graphene, CNTs, etc.) is synthesized by various methods depending on the desired allotropic form. Obtaining pure carbon from coal is a complex task, as coal is a heterogeneous mixture of carbon, volatile compounds, moisture, ash, and sulfur. To extract high-purity carbon, coal must undergo multiple purification stages. Although this does not always result in ideal graphite, it yields technically pure amorphous carbon or semi-crystalline graphite-like carbon.

Using coal as a source of pure carbon has several advantages, particularly in industrial or resource-limited settings:

1. Availability and low cost of raw materials. Coal is one of the most affordable and abundant carbonaceous fossil resources. It is widely available across the globe, especially in countries with a developed coal industry (e.g., Russia, China, India, USA). The cost of raw coal is significantly lower than that of pure graphite or synthetic carbon nanomaterials.

2. High carbon content. High-grade coal types (such as anthracite) contain up to 92–98% carbon after coking, making them suitable for producing technically pure carbon, provided proper purification is applied.

3. Stable source of technical carbon. Pyrolysis and coking products are extensively used for electrode production (in metallurgy), in batteries (as graphite), and as carbon fillers in construction and composite materials.

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4. Waste recycling potential. Low-grade coal or even coal mining waste (sludge, fines) can be processed to obtain technical-grade carbon, improving the ecological and economic efficiency of such processes.

5. Applicability in various nanotechnology domains. After thorough purification and thermal treatment, coal can serve as a source of graphite-like carbon, porous structures (e.g., activated carbon for supercapacitors), or catalyst carriers in chemistry.

6. Existing industrial infrastructure. Many countries already possess developed industrial bases for coking, thermal treatment, and chemical purification of coal, reducing investment costs for transforming raw materials into usable technical carbon.

More than 50% of the reserves of bituminous and lignite coals in Central Asia are located in Kyrgyzstan. These deposits form the basis of the country's fuel and energy resources (FER). The chemical composition and properties of fossil coals are diverse and depend on the conditions of formation and the subsequent metamorphic processes.

Coal metamorphism refers to the transformation of coal under geological factors such as increased temperature, pressure, and prolonged exposure. This process defines the physical, chemical, and textural properties of coal, increasing its carbon content and altering its energy potential.

Fossil solid fuels (excluding oil shales) are formed from the decomposition of organic matter, primarily of plant origin, and are the result of its transformation. Among these, peat is the youngest in geological terms. Its deposits consist of dense masses formed through the decay of marsh vegetation. Lignite is older and represents the next stage of coal formation. It is typically a homogenous mass varying from earthy to black in color. Prolonged exposure of lignite to the open air leads to partial oxidation (weathering) and transformation into powder form. Bituminous coal deposits are geologically older than lignite, have greater strength, and lower porosity. The oldest coals are anthracites, which have undergone the most intense transformation (over 90%). Anthracites contain up to 93% carbon, providing them with high hardness and strength.

When analyzing fuels as materials whose combustibility depends on their composition and structure in dry, ash-free form, the "daf" (dry, ash-free) index is used. This index considers all components of the organic mass, including pyritic sulfur, which combusts along with it. The chemical composition of any solid fuel is complex and variable. Since its precise composition is generally unknown, it is characterized using the total mass content of the elements it contains, which is determined via elemental analysis.

The following is derived from the results of elemental analysis:

$$C^{daf} + H^{daf} + O^{daf} + N^{daf} + S_c^{daf} = 100\%.$$

The combustion process of organic fuel occurs due to the burning of chemical elements—carbon, hydrogen, and sulfur—contained within the fuel, both in free and chemically bound forms. The age of a fuel is determined and characterized by changes in the percentage composition of certain chemical elements. Specifically, an increase in fuel age results in a rise in carbon content from 40% in wood to approximately 93% in anthracite, while the hydrogen content slightly decreases from around 6% to 2%.

Other chemical elements, such as oxygen, are present in the form of complex organic compounds. A clear trend is observed: the higher the oxygen content in the fuel, the more hydrogen and carbon atoms form chemical bonds with oxygen, becoming oxidized and effectively pre-burned. As a result, this reduces the net heat released per unit mass when such oxygen-rich fuel is combusted. Correspondingly, as the fuel matures, the oxygen content decreases from 42% in wood to about 2% in anthracite.

With proper combustion and an adequate supply of air, the complete combustion of 1 kg of carbon releases approximately 32.8 MJ of heat and results in the formation of carbon dioxide (CO_2), a relatively non-toxic gas. However, if combustion occurs under oxygen-deficient conditions, incomplete combustion takes place, producing only about 9.2 MJ of heat per kilogram of carbon and releasing carbon monoxide (CO), a highly toxic gas.

Sulfur is also a constituent of solid fuels, though its concentration varies and does not directly correlate with the coal rank or age. It depends primarily on the coal type and deposit. The combustion of sulfur within solid fuels results in the formation of toxic sulfur dioxide (SO_2) and, to a lesser extent, sulfur trioxide (SO_3), the latter being even more hazardous.

Nitrogen, though present in small amounts (typically up to 2% in dry, ash-free fuel), is one of the most harmful components. Combustion of nitrogen-containing compounds leads to the formation of highly toxic nitrogen oxides, such as nitric oxide (NO) and nitrogen dioxide (NO_2), which can also be generated from atmospheric nitrogen at combustion temperatures exceeding 1200 °C. Emissions of sulfur and nitrogen combustion products are major contributors to environmental pollution.

In engineering applications, fuels are characterized in their working state, indicated by the superscript "r". The general formula for the composition of solid fuel in its working state is:

$$C^r + H^r + O^r + N^r + S^r + A^r + W^r = 100\%.$$

For dry fuel components, the corresponding formula is:

$$C^d + H^d + O^d + N^d + S^d + A^d = 100\%.$$

Ash consists of mineral impurities that entered the coal seams during formation via wind or water transport, as well as minor amounts of minerals (typically 1–2%) originally present in the vegetation that formed the coal. Additionally, ash contains particles of rock introduced during coal mining.

Environmental regulations mandate the capture and disposal of ash produced during combustion. Ash disposal through transportation and storage increases operational complexity and cost. Therefore, it is more rational to utilize ash in civil and agricultural applications—as a cement additive, for soil liming, and as a mineral fertilizer.

Coal ash content can be significantly reduced via beneficiation, as the bulk of the ash is not chemically bound to the organic structure of coal. This process involves separating non-combustible rock from the coal matrix, which is economically viable only for coking coals due to the high cost of beneficiation.

Upon heating in the absence of oxygen, the organic matter in coal decomposes, producing gases, tar and water vapors, and carbon-rich inorganic residues. There is a direct relationship between temperature, residence time, and the total amount of volatile matter released during heating. This volatile matter yield – an important fuel characteristic - is inversely proportional to coal rank (i.e., it decreases with increasing coal age).

During heating, the organic mass undergoes several transformation stages, including viscous, fluid, and plastic states. Further heating and decomposition of the plastic mass leads to its resolidification. The presence and degree of coal plasticity, which vary by coal type, determine the physical and chemical properties of the resulting coke. The coke may be dense and sintered or porous and friable. Coals that form the dense, sintered coke are classified as coking coals, primarily used in metallurgy. These coals are scarce and serve as raw materials for producing metallurgical coke.

The quantity and composition of mineral impurities in coal are determined from the ash residue remaining after combustion. Ash content does not correlate with coal rank and can vary widely. The sources of these impurities include original plant-based minerals, sedimentary deposits introduced during coal formation, and rock materials introduced during mining.

Coal consists of both organic and inorganic components, including compounds of phosphorus, arsenic, water, sulfur, and other mineral impurities. The primary components of coal ash are oxides of silicon and various metals such as iron, aluminum, calcium, magnesium, and others.

Currently, the balance reserves of coal in the Kyrgyz Republic – at depths of up to 600 meters – are estimated at 1303.5 million tons. The total predicted and balance resources are estimated at approximately 6391 million tons. About 20% of the balance reserves (~1 billion tons) have been explored under categories A+B+C1, while over 3.12 billion tons fall under category C2 [16, 17]. Lignite reserves constitute the largest portion of Kyrgyzstan's total coal reserves.

The Kara-Keche and Minkush deposits are the primary large lignite reserves in the northern part of the country, with total reserves of 557.1 million tons. Of these, the Kara-Keche deposit holds 438.1 million tons (194.61 million tons accessible via open-pit mining and 243.39 million tons via underground mining), while the Minkush deposit contains 118.99 million tons, with a stripping ratio limit of K = 19.

However, the majority of lignite reserves are located in southern Kyrgyzstan, comprising the largest share of the country's coal reserves. Major southern coalfields include: Sulyukta – 113.9 million tons, Shurab – 140.335 million tons, Besh-Burkhan – 38.124 million tons, Kyzyl-Kiya – 88.221 million tons, Almalyk – 19.29 million tons, Bel-Alman – 90.1 million tons.

The southern deposits of Kok-Yangak, Tash-Kumyr, Dzhergalan, Kara-Tyty, and Tegenek are notable for producing energy-grade coals such as long-flame and gas coals. The Uzgen basin contains reserves of anthracite and coking coals; however, industrial-scale mining of these coals has not yet commenced.

The development of new methods for energy-technological coal processing requires a systematic approach to studying and combining the processes involved, as well as designing technologies and equipment for producing new coal-derived products [18].

One of the key modern processes for coal conversion is pyrolysis, which involves heating coal to temperatures between 400 °C and 1200 °C in the absence of air. This process includes two primary types of chemical reactions:

1) thermal decomposition reactions, in which the complex organic structures in coal break down under the influence of heat, resulting in the formation of simpler compounds;

2) polycondensation reactions, leading to the formation of high-molecular-weight organic compounds, such as various types of tars, which, upon vaporization, are released from the heated zone.

During pyrolysis, coal undergoes several distinct stages:

– initial stage: as the temperature gradually increases from ambient to about 300 °C, moisture and some adsorbed gases (e.g., O_2, CH_4, CO_2, N_2) are released, particularly in the 100–110 °C range;
– intermediate stage (300–550 °C): at this point, more profound changes occur in the organic structure of the coal. Vapors of various tars and gases are released, and a plastic mass is formed. As heating continues, this plastic mass transitions into a solid intermediate product known as semicoke.

– final stage (550–1000/1200 °C): the release of volatile substances from the remaining solid mass ceases completely. Not all carbon present in the fuel converts into volatile products. The remaining carbon, combined with mineral impurities, forms a solid non-volatile residue-coke [11].

The ultimate product of pyrolysis is this solid residue, making pyrolysis the principal method for producing high-quality solid fuels such as coke and semicoke from coal.

Depending on the temperature range used, two main types of pyrolysis are distinguished:

– coking – a high-temperature pyrolysis process conducted in the range of 950–1000 °C;
– semicoking – a lower-temperature process that is subdivided into:
– medium-temperature semicoking: 650–750 °C;
– low-temperature semicoking: 450–500°C [17].

Currently, extensive international research is being conducted on the pyrolysis of various solid fuels, with new methods of semicoking under development [11].

When coal is heated, thermally unstable organic molecules undergo decomposition, and hydrocarbon bonds within the combustible mass break down. This process results in the release of a range of combustible gases (CH_4, CO, H_2) and non-combustible gases (O_2, CO_2, N_2, SO_2), which are collectively referred to as volatile substances. Importantly, these volatiles are not intrinsic components of coal but rather products of its thermal decomposition. This distinction emphasizes that volatile matter is characterized by its release from coal, not by its inherent presence in it.

To experimentally determine the volatile matter yield, a sample of the fuel is weighed and placed in a muffle furnace under oxygen-free conditions. The temperature is maintained in the range of 830–870 °C, and strict control is exercised over the heating duration, temperature profile, and other parameters. These factors have a direct impact on the formation and evolution of volatile components during the pyrolysis process [14].

EXPERIMENTAL PART

The raw materials used in this study were coals from the southern region of the Kyrgyz Republic, specifically from the Kozhokelen, Sarymogol, and Kichi-Alai deposits of the Alai Basin, as well as the Changet deposit of the Uzgen Basin.

To determine the yield of volatile matter, the coal sample must be in a dry state. A 1,000 g sample of the coal under investigation was placed in a sealed horizontal pyrolysis reactor made of stainless steel. This reactor was then inserted into a contact-type tubular electric furnace (see Fig. 1). For the purpose of thermal decomposition (thermodestruction) of the coal feedstock, the reactor was heated inside the furnace to the required temperature.

The reactor used in the experiment for conducting pyrolysis of the coal feedstock was a multifunctional system, designed to ensure precise control over the operating parameters of the entire experimental setup. This configuration enables efficient and comprehensive processing of the investigated coal material, aiming to maximize the yield of liquid and gaseous decomposition products-namely, pyrolysis tar, pyrolysis gas, and coke (see Fig. 2).

To support this process, the system was equipped with a thermocatalytic gas purification unit, a condenser, and a liquid product collection reservoir. The condenser serves to cool and condense volatile pyrolysis products, which are then collected in the liquid product tank.

In order to quantify the flow rate and volume of gaseous products generated during pyrolysis, the setup was supplemented with a pyrolysis gas flow analysis unit.

The objects of study were lignite and bituminous coals.

Pyrolysis of lignite was carried out in the temperature range of 100–550 °C, while that of bituminous coal was

Fig. 1. Electric furnace

Fig. 2. Pyrogenetic water, resin and gases obtained as a result of coal pyrolysis

conducted over a broader range of 100–1100 °C, continuing until the complete cessation of release of liquid and gaseous products.

For the purpose of thermal processing analysis, 1,000 g of the lignite sample was loaded into the reactor. During the initial stage of semicoking, in the temperature range of 100–110 °C, physico-chemical moisture and a portion of adsorbed gases were released from the coal. As heating continued, and the temperature reached the range of 300–550 °C, more profound physical and chemical transformations occurred within the organic structure of the coal. These changes were accompanied by the evolution of tar vapors and gases, along with the formation of a plastic mass.

The total pyrolysis duration ranged from 65 to 80 minutes, with an average heating rate of 12–15 °C/min up to the target temperature of 1000 °C.

The quantitative and qualitative analysis of the resulting gases was conducted using an electrochemical method in accordance with GSPK 02.00.00.000 RE [15], employing a set of selective gas analyzers of various modifications:

- "Signal-4N": selective for nitrogen oxide (NO);
- "Signal-4E": selective for hydrogen sulfide (H_2S);
- "Signal-4": selective for carbon monoxide (CO) and methane (CH_4);
- "Signal-4M SO_2": selective for sulfur dioxide (SO_2) and total hydrocarbons (C_1–C_{12});
- carbon dioxide (CO_2) concentration was determined using indicator tubes.

The concentration of carbon dioxide in volumetric percent and mg/m³ was calculated using the following formula [16, 17]:

$$X = \frac{M \cdot a \cdot n \cdot 1000}{22{,}4},$$

where X_1 – the gas concentration in volume fractions %;

M – the molar mass of carbon dioxide ($M_{(CO_2)}$) = 44);
a – the amount of substance found in 1 liter of air;
n – the number of strokes of the flywheel pump;
22,4 – the volume of 1 g of gas molecule.

$$X_1 = \frac{44 \cdot 0{,}0006 \cdot 2 \cdot 1000}{22{,}4} = 2{,}3\%;$$

$$X_2 = \frac{44 \cdot 0{,}00052 \cdot 1 \cdot 1000}{22{,}4} = 1{,}0\%.$$

The calculation results showed that the carbon dioxide (CO_2) content in the coke-oven gas of lignite was 2,3%, while for bituminous coal, it was 1,0%.

The results of the experiment on the gas (volatile matter) content released from lignitein the temperature range of 110–550 °C, expressed in mg/m³, are presented in Table 1 and Fig. 3.

During the pyrolysis of brown coals, 61,9% volatile substances are formed, solid residue - coke 36% and liquid substances – 2,1% (tar and pyrogenetic water).

Experimental data on determining the content of gases (volatile substances) of coals at 250-1100°C, (mg/m³) are given in Table 2 and Fig. 4.

During the process of coal pyrolysis, 15,5% of volatile substances are formed, a solid residue – coke 83% and a liquid substance – 1,5% (tar and pyrogenetic water).

Experimental data on determining the yield and the temperature of the onset of the release of volatile substances are given in Table 3.

OBTAINING PURE CARBON

The use of pure carbon in construction primarily involves carbon-based materials with unique properties, such as carbon fibers, graphene, and diamond-like carbon (DLC).

It is well known that coal contains a significant amount of carbon, which is chemically inert under normal conditions. In its purer form, carbon naturally exists as simple substances in crystalline states, specifically as graphite and diamond. These two forms exhibit dramatically different physical properties.

Artificially produced graphite is a key structural material for nuclear reactors. Synthetic graphite is obtained by heating a compressed mixture of petroleum coke and coal tar pitch. Initially, the mixture is heated to 1500 °C, fol-

Table 1. The results of the experiment on the gas

Gas analyzers modifications	NO	H_2S	SO_2	CO	CH_4	CO_2	C_1–C_{12} (sum of hydrocarbons) Ethane, propane, butane, pentane, ethylene, propylene, butylene, benzene, toluene, xylene, etc.	
1. «Signal-4»	2.0	–	–	–	–		29	
2. «Signal-4»	–	–	–	7.4	20			
3. «Signal-4E»	–	0.4	–	–	–			
4. «Signal-4M-SO_2»	–	–	0.8	–	–	2.3		
Total, in %	2.0	0.4	0.8	7.4	20	2.3	29	61.9

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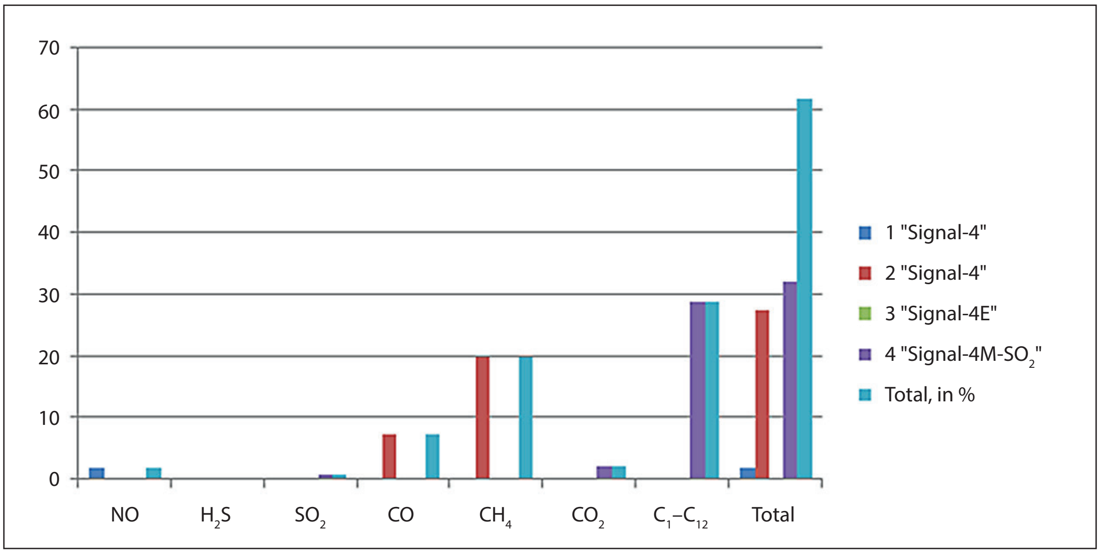

Fig. 3. Histogram of the experimental results on volatile matter release from lignite in the temperature range of 110–550 °C (mg/m^3)

Table 2. Experimental data on determining the content of gases

Gas analyzers modifications	**NO**	**H_2S**	**SO_2**	**CO**	**CH_4**	**CO_2**	**C_1–C_{12} (sum of hydrocarbons) Ethane, propane, butane, pentane, ethylene, propylene, butylene, benzene, toluene, xylene, etc.**	
1. «Signal-4»	0.2	–	–	–	–		5.05	
2. «Signal-4»	–	–	–	1.5	7			
3. «Signal-4E»	–	0.15	–	–	–			
4. «Signal-4M-SO_2»	–	–	0.6	–	–	1.0		
Total, in %	0.2	0.15	0.6	1.5	7	1.0	5.05	15.5

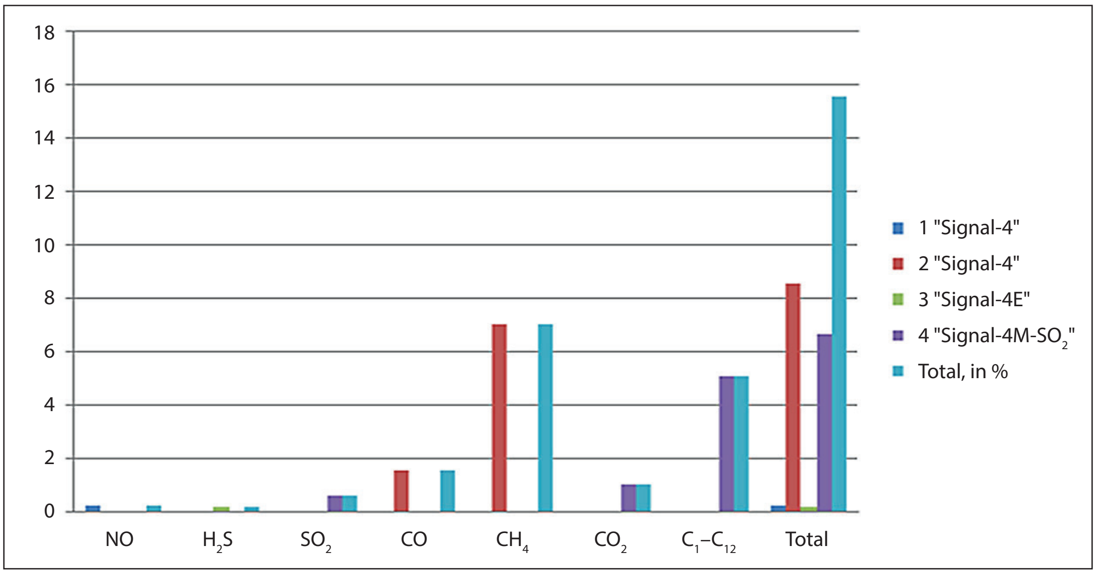

Fig. 4. Histogram of experimental data on the gas (volatile matter) content of bituminous coal in the temperature range of 250–1100 °C (mg/m^3)

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Table 3. Experimental data on determining the yield and the temperature

Fuel type	Volatile release V^{daf}, %	Temperature of the beginning of the release of volatiles, °C
1. Brown coals	61.9	150–170
2. Coals	15.5	380–400

lowed by a secondary heating to 2750 °C, after which it is gradually cooled. The resulting artificial graphite typically has an ash content of less than 0.1% [18].

Graphite is a grayish-black substance with a density of 2.2 g/cm³. Its characteristic physical properties include low hardness and relative softness, which cause it to exfoliate when rubbed, leaving a metallic gray trace on various hard surfaces. These properties make graphite ideal for use in pencil production.

The differences in the crystal lattice structures of graphite and diamond account for the variations in their properties, such as electrical conductivity, hardness, and melting point. X-ray diffraction studies of diamond show identical interatomic distances of 1.545 Å between carbon atoms in its crystal structure. The transformation of graphite into diamond requires an increase in temperature under constant pressure, with the following thermodynamic characteristics:

— sublimation temperature**: 3470 °C;
— melting point**: 3570 °C;
— heat of fusion (at 47,000 atm): 25 kcal/g-atom [19].

The relatively low heat of fusion of graphite suggests that only partial breaking of crystal lattice bonds occurs during melting. The heat of combustion of carbon is approximately 94 kcal/g-atom, and its vapor phase includes carbon atoms as well as more complex clusters (Cn). As temperature increases, the average value of n also increases, indicating the formation of larger molecular structures such as linear or branched carbon chains (C–C–C–C). The dissociation energy of these bonds reaches 144 kcal/mol, depending on the type of bond: single (C–C), double (C=C), or conjugated systems.

The heat of sublimation of carbon at 250 °C is 171 kcal/g-atom. It is believed that applying a pressure of 700,000 atm to graphite for several seconds can produce a new solid phase with a density exceeding that of diamond.

Carbon can also be produced via high-temperature pyrolysis of methane, according to the reaction [10]:

$$CH_4 = C + 2H_2.$$

A linear carbon polymer containing up to 99% carbon, known as carbyne, was synthesized by Academician V.V. Korshak via catalytic oxidation of acetylene (C_2H_2) [20].

Another allotrope of carbon-fullerene (C_{60})-is produced using the electric arc method and is obtained as a soot-like powder, from which fullerenes are extracted using solvent-based methods [21].

EXPERIMENTAL SECTION

For experimental purposes, bituminous coal from the Uzgen Basin was crushed using a screw crusher followed by milling in a ball mill to remove mineral impurities. The resulting powder was sieved using a brass sieve with 0.04 mm mesh size.

A 1,000 g sample of the sieved coal powder was mixed with 100 g of a 1:3 mixture of nitric acid and hydrochloric acid, and left to stand for 30 minutes. After that, the sample was thoroughly washed with distilled water. The cleaned sample was then filtered through cotton fabric, yielding a metal-impurity-free coal powder residue, which was dried in a drying oven at 110 °C until it reached constant mass.

To remove moisture, organics, and gases, the coal powder was loaded into a pyrolysis reactor and subjected to gradual heating from 20 °C to 1000 °C:

— stage 1 (up to 260 °C): moisture was released;
— stage 2 (280—387 °C): dark brown liquid (tar) and gaseous products evolved;
— stage 3 (400—1000 °C): final gas evolution occurred; pyrolysis ended, leaving behind carbonized coal.

To further purify the coal powder from silicon, calcium, and other impurities, a transport reaction method using gas convection was employed [16].

A schematic diagram of the experimental setup used to accelerate the convection process is shown in Fig. 5.

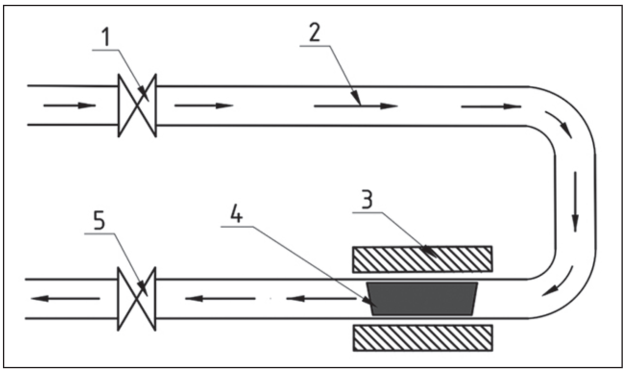

Fig. 5. Gas convection in the experimental setup:
1, 5 – valves; 2 – direction of gas convection (iodine);
3 – electric furnace; 4 – cuvette with purified substance

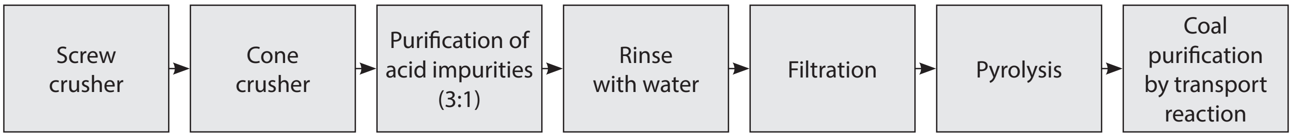

Fig. 6. Technological scheme of coal purification from impurities: 1 – screw crusher; 2 – cone crusher; 3 – coal purification from impurities using nitric-hydrochloric acid; 4 – washing with water; 5 – filtration; 6 – pyrolysis, coal purification from water, organic substances, and volatile gases; 7 – coal purification from silicon and other metals

The experimental apparatus is assembled using ground-glass joints, and the setup itself is fabricated from quartz. The composition of carrier gases must be of the highest purity. Prior to the experiment, quartz boats must be calcined to remove any residual impurities.

For gas transport at temperatures up to 950 °C, the apparatus can be constructed from high-temperature resistant glass.

The procedure begins by placing the quartz boats (4), containing the material to be purified, into the reactor. By opening valves (1) and (5), the system is evacuated under vacuum. During this stage, a slight evaporation of the substance into container (4) may occur, which facilitates its transportation.

Once vacuuming is complete, inert iodine (I_2) is introduced into the system by opening valve 1. After that, the electric furnace (3) is turned on, and container (4) with the substance is heated under closed valves.

During the transport reactions, volatile gaseous compounds are removed, and the following simultaneous chemical reactions take place:

$$SiO_{2(\text{тв})} + SiJ_{4(\text{газ})} = 2SiO_{(\text{газ})} + 4J_{(\text{газ})};$$

$$SiO_2 + 2SiJ_{(\text{газ})} = 2SiO_{(\text{газ})} + SiJ_{(\text{газ})}.$$

Using iodine, the transport reaction can be used to purify the coal being studied from metals such as Ni, Fe, Cr, Ti, Hf, V, Ta, etc.

$$\text{Me}_x Si + (n+4)J_{(\text{газ})} = \text{xMe}J_n\text{п}/\text{x}_{(\text{газ})} + SiJ_{4(\text{газ})}.$$

CONCLUSION

1. Although bituminous coal is not an ideal raw material for the synthesis of highly ordered carbon nanomaterials such as graphene or carbon nanotubes, it remains an effective and economically viable source of technically pure carbon. Its applications are particularly relevant in metallurgy, the production of activated carbon, the development of carbon-based composites, and the manufacture of low-cost carbon electrodes.

When the goal is large-scale production of carbon with acceptable purity, coal represents a practical alternative to more costly synthetic methods.

2. The experimental data obtained from our research on the quantitative and qualitative gas composition of lignite and bituminous coal from various coal deposits in Kyrgyzstan show the following:

- the content of combustible gases (methane, nitrogen oxide, hydrogen sulfide, carbon monoxide, and total hydrocarbons) in lignite is 58.8%, whereas in bituminous coal, it is 13.9%;
- the content of non-combustible gases (carbon dioxide and sulfur dioxide) in lignite is 2.8%, and in bituminous coal – 1.6%;
- during pyrolysis of lignite, the yield is: 61.9% volatile matter, 36% solid residue (coke), and 2.1% liquid products (tar and pyrogenic water);
- during pyrolysis of bituminous coal, the yield is: 15.5% volatile matter, 83% solid residue (coke), and 1.5% liquid products (tar and pyrogenic water).

3. To remove metallic impurities, the coal was treated with a concentrated nitric-hydrochloric acid mixture in a 1:3 ratio.

4. During pyrolysis in the temperature range of 100 °C to 850 °C, various components are released from the coal, including pyrogenic water (containing ammonia water, benzene, toluene, paraffin, acetic acid, etc.), volatile gaseous substances, and tar. After this stage, the remaining material in the reactor is pure carbon.

5. After pyrolysis, the residual solid product contains silicon dioxide (SiO_2), which is removed through a transport reaction with iodine, using gas convection as a transport mechanism.

6. As a result of sequential purification steps, a highly pure, homogeneous substance – pure carbon – is obtained, consisting exclusively of carbon atoms.

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ADDITIONAL INFORMATION

The authors declare that generative artificial intelligence technologies and technologies based on artificial intelligence were not used in the preparation of the article.

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CONTRIBUTION OF THE AUTHORS

Nurzhamal T. Aldasheva – scientific supervision, research concept, formulation of final findings and conclusions.

Baktybek S. Childebaev – conducting the experimental part, participation in the development of the research concept.

Aishakan S. Suyunbekova – scientific editing of the text, preparation of final findings.

Yuri A. Dyachkov – collection of material from literary sources

Yslamidin Tashpolotov – scientific consultation.

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