






Thermal Dissolution of Coal: a Pathway to High-Value Carbon Materials

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Abstract. This study investigates the thermal dissolution of bituminous coal to produce extracts suitable for manufacturing of high-quality carbon materials, particularly carbon binders and needle coke. The research focuses on the composition and properties of coal extracts, their distillation fractions, and the structural features of the resulting carbonized products. The extracts exhibited low benzo(a)pyrene levels, making them environmentally favorable compared to traditional feedstock for coal tar pitches manufacturing. Distillate fractions obtained from these extracts primarily consisted of aromatic hydrocarbons. Carbonized products derived from the distillates are predominantly composed of turbostratic structures, with a minor proportion of well-ordered graphite-like domains. The study confirms that the choice of solvent for coal dissolution critically affects both distillate yield and final coke quality. Structural characterization against reference data demonstrated that the distillate obtained from coal extract in a mixture of coal tar and heavy cyclic oil yielded a coke with a morphology most similar to standard needle coke.

Keywords: Thermal Dissolution, Coal Extracts, Carbonization, Needle Coke

1 Introducing

Modern environmental protection requirements are driving a gradual transformation of the carbon industry's feedstock base. Numerous studies have focused on identifying alternative precursors. Such materials must contain minimal levels of carcinogens, notably benzo[a]pyrene (BaP). Additionally, these alternative feedstocks should primarily consist of polycyclic aromatic compounds, which are critical for producing carbon materials with high anisotropy.

Coal tar pitch and residual petroleum fractions serve as the primary feedstocks for industrial needle coke production now. In contrast to electrode coke, needle coke demonstrates superior properties, including low thermal expansion coefficient, high electrical conductivity, exceptional mechanical strength, and oxidation resistance [1,2]. These characteristics render it indispensable for steelmaking applications [3]

and the production of high- and ultra-high-power electrodes [4]. This enhanced performance originates from its distinctive needle-like microstructure and advanced degree of graphitization [5].

In this context, the approach of thermal coal dissolution under mild conditions (without hydrogen or catalysts) is of particular interest. Studies [6,7] have demonstrated that thermal dissolution of bituminous coals in anthracene oil (400–420°C) yields polyaromatic products suitable for manufacturing various carbon materials, including anodes and carbon fibers.

A key advantage of this process is the high yield of coal extracts (>85%), significantly exceeding conventional technologies (5–40%) [8]. The main limitation hindering widespread implementation is the high ash content of the resulting products. Developing processing technology presents a key challenge: converting coal extracts into precursors containing minimal mechanical inclusions and ash impurities while meeting needle coke production requirements

Distillation, along with solvent extraction using media of varying polarity, represents widely employed separation methods in both laboratory and industrial settings. These techniques effectively remove not only ash components but also sulfur-, oxygen-, and nitrogen-containing compounds [9].

Multiple studies [10–12] have demonstrated that the thermal behavior of toluene- and quinoline-insoluble substances, as well as β -resins, significantly influences coke structure formation. This occurs because different components play distinct roles in mesophase development during liquid-phase carbonization of feedstock components [13].

Producing high-quality needle coke requires meticulous feedstock composition selection. The optimal blend must contain both thermally active compounds (alkanes, alkyl chains) and thermally stable polyaromatic structures.

The aim of this work is to study the composition of coal extracts, distillate fractions isolated from the products of coal thermal dissolution, their carbonization and study the structure of carbonized products.

2 Experimental

Prior to thermal dissolution, the coal was ground to a particle size of less than 0.2 mm. The powdered coal was then mixed with high-boiling hydrocarbon fractions in a 1:2 mass ratio (coal-to-solvent) to form paste-like slurry. The following fractions derived from petroleum and coal processing were used as solvents: coal tar (CT), the anthracene fraction (AF) isolated from CT (supplied by Altai-Koks LLC), and heavy cyclic oil (HCO) obtained from a catalytic cracking unit (produced by Gazprom Neft-Omsk Refinery).

The experimental work yielded three distinct extracts: two extracts obtained using pure solvents (CT and AF separately) and one extract produced using a mixed solvent system consisting of HCO and CT in a 1:1 mass ratio (designated as HCO/CT).

Thermal solvolysis was performed in a 2-liter stainless steel autoclave at 380°C under autogenous pressure conditions. The reactor system was equipped with a paddle-type agitator operating at a constant rotational speed of 160 rpm. The reaction duration, measured from the point of reaching the target temperature, was maintained

at 1 hour. A detailed description of the experimental methodology is provided in Reference [14]. The resulting coal-derived extracts were subsequently subjected to distillation.

The coal extracts were distilled using a laboratory-scale setup. Approximately 150 g of extract was loaded into a 500 mL flask and heated to 250°C. The vapors were condensed using a 500 mm air condenser. During the process, the condenser was periodically heated with a gas burner flame to prevent crystallization of products on its inner walls.

The fraction boiling between the initial boiling point and 230°C was collected at atmospheric pressure. After phase separation into aqueous and hydrocarbon fractions, their masses were measured. The system pressure was then gradually reduced to 15 mmHg while increasing the heating intensity until the vapor temperature reached 300°C (equivalent to ~450°C at atmospheric pressure).

The target fractions for subsequent studies were those with boiling points between 230–450°C, obtained by combining the 230–350°C and 350–450°C subfractions.

The obtained distillate fractions were subjected to carbonization in the autoclave under conditions of 475 °C and 8 atm for 5 hours. The calcination process was performed in the apparatus shown in Figure 1. The quartz tube (12 mm inner diameter) was loaded with 8 g of the 230–450°C fraction and placed in a tubular metal reactor. Prior to heating, the system was purged with nitrogen to remove oxygen. The temperature was increased at a rate of 5 °C/min followed by a 1-hour isothermal hold at 1100 °C. Temperature was monitored using a thermocouple immersed directly in the sample bed. Finally, heating was discontinued and the reactor was cooled under a gentle nitrogen flow.

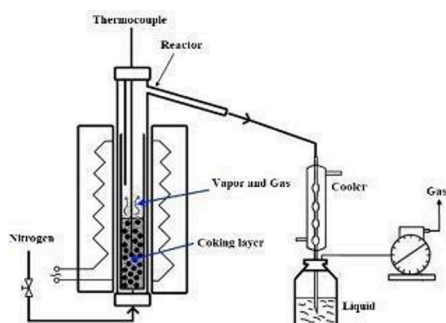


Fig. 1. Scheme of the installation for carbonization

The elemental composition of coal extracts and 230–450°C fractions was determined using the FlashEA™ 1112 analyzer. Oxygen content was calculated as the difference between 100% and the sum of C, N, H, and S percentage.

¹³C NMR spectra were acquired using the inverse-gated decoupling technique, accumulating 4500 scans per spectrum with a 15 s relaxation delay. All samples were analyzed under identical conditions, including sample weights and receiver gain

settings (rg = 2050). It enables direct quantitative comparison of integration results. Aromaticity (f_a) was calculated as:

$$f_a = (C_{ar-O} + C_{ar-C} + C_{ar-H}) / 100, \quad (1)$$

where C_{ar-O} , C_{ar-C} , and C_{ar-H} represent the relative concentrations of corresponding structural groups.

X-ray diffraction analysis of calcined cokes was performed on a PANalytical X'Pert PRO diffractometer using Cu K α radiation. Measurements covered the angular range of 5-90° (2θ) with a scanning step of 0.2° and exposure time of 25 seconds per point. The acquired diffractograms were processed using computational methods for quantitative component analysis and crystallographic parameter determination. Structural parameters were calculated using established equations.

The interlayer spacing (d_{002}) was determined by

$$d_{002} = \lambda / 2 \sin \theta_{002}, \quad (2)$$

where λ represents the radiation wavelength and θ_{002} is the (002) reflection angle. The stack height (L_c) was calculated according to equation

$$L_c = 0.91 \lambda / \beta_{002} \cos \theta_{002}, \quad (3)$$

where β_{002} is the full width at half maximum (FWHM) of the (002) peak. Similarly, the stack diameter (L_a) was derived from

$$L_a = 0.9 \lambda / \beta_{100} \cos \theta_{100}, \quad (4)$$

where β_{002} is the full width at half maximum of the (100) reflection. θ_{100} is the diffraction angle of the (100) plane. The number of layers (N) in the stacks was then determined as $L_c/d_{002} + 1$.

3 Results and discussion

The initial material for thermal dissolution was bituminous coal from the Chadansk deposit, belonging to the Ulug-Khem coal basin (Russia). The coal contained 84.7 wt.% carbon and 5.5 wt.% hydrogen, with an ash content of 7.5 wt.%.

The material balance of the coal thermal dissolution process is presented in Table 1. In all cases, the extract yield exceeded 94% (Table 1). The maximum extract yield was achieved when dissolving coal in the anthracene fraction of coal tar.

The use of pure coal tar as a solvent enhances the formation of volatile products during coal thermal solvolysis. In contrast, the addition of heavy cyclic oil as a co-solvent increases the extract yield by reducing the formation of liquid byproducts.

Table 1. Material Balance of Coal Thermal Dissolution in Technical Solvents

Solvent	Product, wt. %	Losses, %
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	Extract	Gas	Liquid products	
AF	98.8	0.35	0.45	0.4
CT	94.2	0.40	4.80	0.6
HCO/CT	97.3	0.60	1.70	0.4

The extracts obtained using CT and AF solvents showed nearly identical carbon and hydrogen content. Comparative analysis revealed that the AF-derived product contained reduced concentration of carbon but high hydrogen content (Table 2). The total heteroatom content in coal extracts obtained using AF, CT, and HCO/CT as solvents was 5.5 wt.%, 4.9 wt.%, and 4.7 wt.%, respectively. The extract produced with HCO/CT exhibited the lowest oxygen content combined with elevated sulfur concentration.

Table 2. Composition and Properties of Extracts Obtained by Thermal Dissolution of Coal in Technical Solvents

Solvent	Content, wt.% Based on daf					H/C atom.	BaP Content, mg/g	Softening Point, °C
	C	H	N	S	O			
AF	89.2	5.3	1.4	0.6	3.5	0.71	4.6	78
CT	89.7	5.4	1.3	1.0	2.6	0.72	3.2	86
HCO/CT	88.7	6.6	1.1	1.3	2.3	0.89	2.4	82

The primary products of thermal dissolution were pitch-like substances with softening points ranging from 78 to 86°C. The range corresponds to medium-temperature pitch. Spectroscopic analysis (IR, 1H and 13C NMR) revealed that these products predominantly consist of polyaromatic hydrocarbons [15], whose structural features depend on the solvent type used. 13C NMR spectra of pitch-like products, obtained after the thermal dissolution of the coal in AF, shows strong resonances in the aromatic region and very weak resonances in the aliphatic one. Most aliphatic protons are bonded to carbon atoms at α -position to one aromatic cycle and also to two cycles (like in fluorene or in 9,10-dihydroanthracene). The products obtained with CT solvent and with blended one are less aromatic. They show large variety of protons at various aliphatic carbon atoms, including those at α -position to aromatic rings. The integrated data on the proton distribution indicates that the average molecules of the extracts derived from the AF product are highly aromatic (f_a of 0.89), closely resembling typical coal-tar pitch. The data means the aromatic nuclei to consist of 4–5 condensed cycles, which are rarely substituted with short alkyl substituents. The aromatic nuclei of the CT product consist of 3–4 middle substituted condensed cycles with longer substituents. The aromatic hydrocarbons included in the composition of HCO/CT product contain the greatest number of substituents. The spectra show insignificant concentrations of the hydroxyl groups and olefinic substances in all samples.

After distilling off the light volatile fractions, the extracts yielded high-temperature pitches suitable for use as binding agents in aluminum anode production [8, 14]. Compared to conventional coal tar pitch, this extractive pitch offers significant

environmental advantages, containing several times lower benzo(a)pyrene content. Utilization of extractive pitches for carbon electrode manufacturing can help to improve ecology of their production through reduction of benzo(a)pyrene emission during preparation.

The fractions obtained through laboratory distillation exhibited distinct physical states and appearances. In all cases, the 230–350°C fractions consisted of liquid-crystalline mixtures, while the heavier (350–450°C) fractions solidified upon cooling. An exception was observed for the fraction derived from the HCO/CT coal extract, which remained liquid with minor crystalline precipitates.

As evident from Table 3, the distillate yields showed significant variation depending on the solvent type used in the coal thermal dissolution process.

The highest total distillate yield was obtained from the coal extract produced using the anthracene fraction as solvent. When coal tar served as the solvent, the yield of distillate fractions (DF) was significantly lower than that obtained in industrial coal tar processing. The addition of HCO to CT during thermal solvolysis significantly enhanced distillates yield.

Table 3. Yield of Distillate Fractions from Coal Thermal Dissolution Extracts

Solvent Used for Extract Preparation	Distillate Fractions, wt.%				Total, wt.%
	i. b.p.– 230 °C,	230 – 350 °C,	350 – 450 °C,	Water, wt.%	
AF	0.9	26.2	16.1	0.4	43.2
CT	4.2	9.8	18.1	1.0	32.1
HCO/CT	2.0	15.3	22.0	0.6	39.3

The elemental composition of the 230–450°C distillate fractions is presented in Table 4.

Table 4. Elemental Composition of Distillate Fractions (230–450 °C)

Sample	Content, wt.%					H/C atom.
	C	H	N	S	O	
DF AF*	89.03	5.98	1.55	0.59	2.85	0.81
DF CT**	87.66	6.76	1.30	0.65	3.63	0.92
DF HCO/CT ***	87.75	7.68	0.77	0.75	3.05	1.05

* - DF obtained by distillation of coal extract in AF solvent

** - DF obtained by distillation of coal extract in CT solvent

*** - DF obtained by distillation of coal extract in HCO/CT solvent

The carbon content in the distillate fractions exhibited minimal variation across samples. Compared to the elemental composition of the initial extracts, the distillates showed hydrogen enrichment. However, the calculated atomic H/C ratio indicated a predominantly aromatic hydrocarbon composition.

Comparative analysis of Tables 2 and 4 revealed that oxygen-containing compounds primarily concentrated in the distillation residue obtained from the extract

of coal in anthracene fraction. The other two samples demonstrated an opposite distribution pattern.

The molecular composition of DF was investigated using ^{13}C NMR spectroscopy. Figure 2 presents the ^{13}C NMR spectra of 230–450°C fractions derived from the extracts of coal dissolution. The spectrum integration results are presented in Table 5.

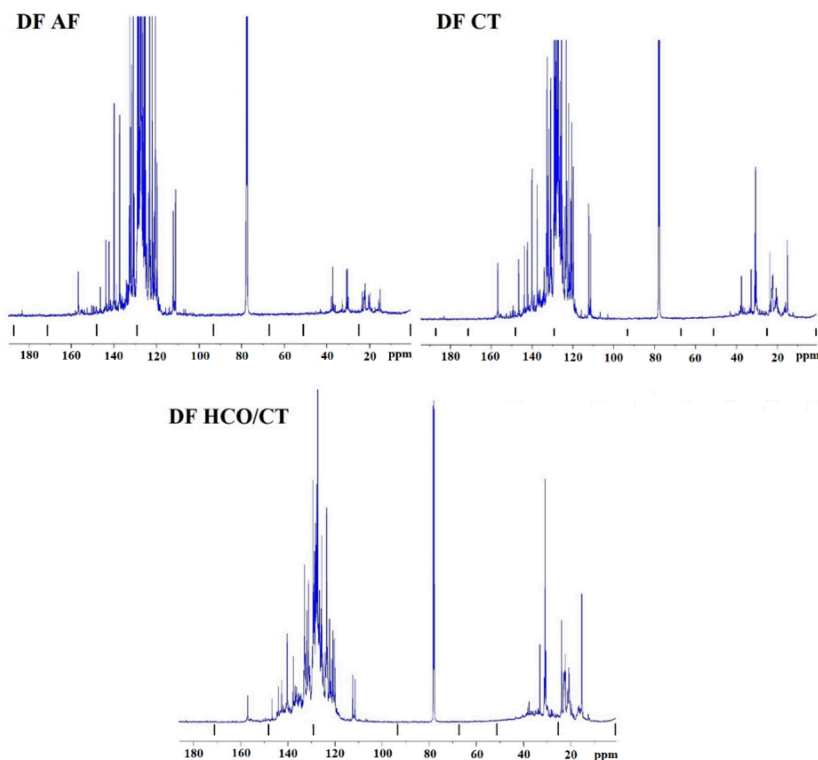


Fig. 2. ^{13}C NMR Spectra of 230–450 °C Fractions from Extracts of Coal Dissolution in Different Solvents

Table 5. Composition of Distillate Fractions According to ^{13}C NMR Spectroscopy Data

Sample	Integration range, ppm							fa
	0-25	25-51	51-93	93-129	129-148	148-171	171-187	
	Structural fragment, integral intensity, %							
	CH_3	CH_2	O-CH_3 , C-O-C	$\text{C}_{\text{Ar-H}}$	$\text{C}_{\text{Ar-C}}$	$\text{C}_{\text{Ar-O}}$	COOH	
DF AF	3.8	1.9	0.4	70.0	22.5	1.2	0.2	0.94
DF CT	6.0	4.1	0.2	62.0	26.0	1.5	0.2	0.89

DF HCO/CT	10.2	14.1	0.1	49.3	25.0	1.3	-	0.75
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The results of the ^{13}C NMR spectra analysis conclusively demonstrate the predominance of aromatic hydrocarbons in all obtained fractions. Depending on the coal extraction conditions, their aromaticity factor ranges from 0.75 to 0.94. The content of aliphatic carbon, including that bound in methoxyl and carboxyl groups, is comparatively lower in distillate fractions derived from coal extracts obtained using coal tar and anthracene fraction as solvents.

The use of the mixed solvent for coal thermal dissolution leads to a significant decrease in fa value. Based on the boiling points of substituted and unsubstituted individual hydrocarbons (naphthalene, anthracene, phenanthrene, pyrene, and chrysene series), we can assume that the aromatic molecules in the studied fractions typically contain 2–4 condensed aromatic rings.

The relative abundance of aliphatic substituents on aromatic cores increases in the following order: DF HCO/CT > DF CT > DF AF. Considering the fa value and $\text{C}_{\text{Ar-H}}$ content, the aromatic hydrocarbons in DF AF contain virtually no ring substituents. Conversely, the fraction obtained from HCO/CT coal extract shows maximum aromatic rings substitution, as evidenced by comparative analysis of $\text{C}_{\text{Ar-H}}$ and $\text{C}_{\text{Ar-C}}$ values across all DF samples. This sample also exhibits the highest concentration of methylene groups, which may constitute either long aliphatic substituents on aromatic rings or naphthenic ring structures.

Data of ^{13}C NMR spectroscopy revealed the presence of methoxyl, carboxyl, ether, and phenolic groups in the samples. The addition of 50 wt.% HCO to coal tar during coal thermal dissolution reduces the proportion of ether and phenolic functional groups in the 230–450°C fraction components.

The carbonization of distillate fractions was performed in two strictly identical conditions. First, green coke was produced, which was subsequently calcined in the same apparatus. The yields of calcined cokes from AF-, CT-, and HCO/CT-derived coal extract fractions were 57.3%, 30.1%, and 52.6%, respectively.

X-ray diffraction analysis of the calcined cokes revealed characteristic diffraction patterns of carbon materials with significant intensity variations. The dominant intense peak at $2\theta \approx 26^\circ$ corresponds to the (002) Bragg reflection from the basal plane of graphite-like structures. The observed peak broadening combined with pronounced low-angle asymmetry indicates the presence of domains with varying degrees of structural ordering and different interlayer spacing. These features are typical for partially graphitized carbon matrices containing both ordered layered fragments and amorphous carbon phases.

The structural analysis of carbonization products focused on the most intense (002) reflection, which evidences the presence of stacked layers formed by parallel-oriented polyaromatic graphite-like lamellae in the samples.

The broad asymmetric reflection was subjected to mathematical deconvolution. The peak profile was optimally approximated by a superposition of three to four Gaussian components (Figure 3).

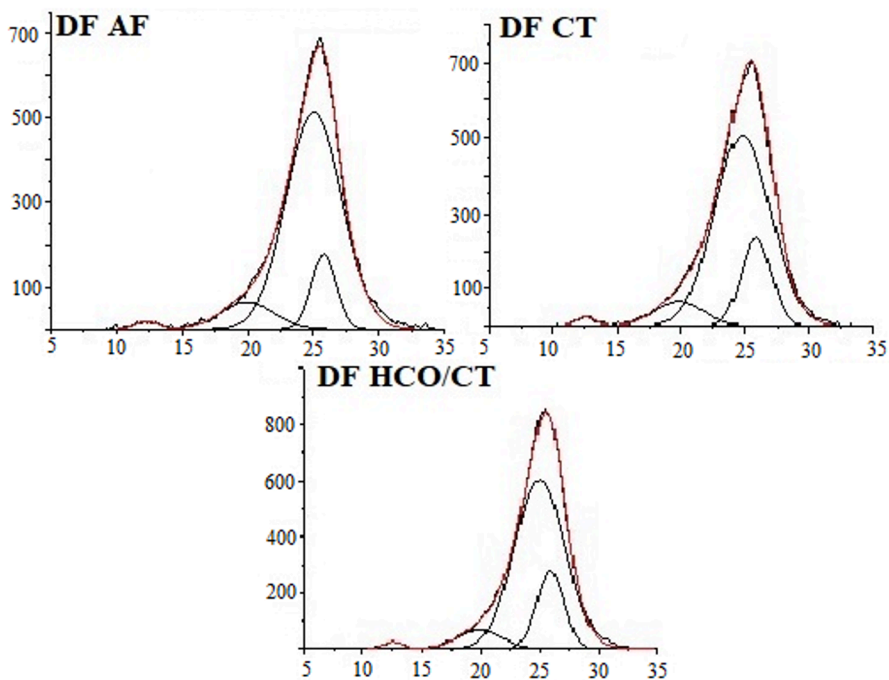


Fig. 3. Deconvolution of the main asymmetric diffraction reflections for coke X-ray diffraction patterns

The analysis revealed the following structural components.

Graphite-like domains ($2\theta=26.3\pm 0.3^\circ$) exhibiting ordered stacking of planar polyaromatic layers with distinct three-dimensional periodicity.

Turbostratic domains ($2\theta=24.4\pm 0.4^\circ$) which maintaining parallel alignment of basal graphene planes while displaying random angular displacement of adjacent layers relative to the stacking plane normal.

Amorphous components comprising two distinct phases:

γ_1 -phase ($2\theta=20.7\pm 0.9^\circ$) corresponding to weakly ordered carbon clusters localized at the boundaries of layered stacks;

γ_2 -phase ($2\theta\approx 13^\circ$) associated with completely disordered carbon formations lacking pronounced spatial periodicity.

The obtained data (Table 5) demonstrate the heterogeneous nature of the studied carbonization products, where regions with varying degrees of structural order coexist. The structures rang from crystallite-like graphite domains to completely amorphous carbon phases.

In the samples carbonized at 1100°C , the dominant carbon ordering form consists of turbostratic domains with rotationally disordered layer stacking, accounting for 73–78% of the structure (Table 6). Well-ordered graphite-like domains constitute 12–18%, while weakly ordered carbon (γ_1 -component) represents no more than 9%. Amorphous carbon content is minimal at approximately 1%.

Table 6. Parameters of carbon structures in cokes calculated on the basis of X-ray diffraction patterns

Sample	Phase	Phase Content, %	d_{002}	L_c	N	L_a	L_a/L_c
DF AF	γ_2	1	7,18	39,7	6,5	47,3	1,33
	γ_1	9	4,44	16,6	4,7		
	Turbostratic	78	3,55	15,9	5,5		
	Graphite	12	3,45	35,5	11,3		
DF CT	γ_2	1	7,06	39,7	6,6	39,7	1,40
	γ_1	8	4,47	17,9	5,0		
	Turbostratic	72	3,58	15,3	5,3		
	Graphite	18	3,44	28,4	9,3		
DF HCO/CT	γ_2	1	7,04	42,8	7,1	45,0	1,55
	γ_1	7	4,46	18,1	5,1		
	Turbostratic	73	3,56	15,8	5,5		
	Graphite	18	3,44	29,2	9,5		

The spatial structure of these cokes shows remarkable similarity to industrial needle coke samples. For reference needle cokes, the (002) reflection-derived domain width typically ranges 38–44 Å with an average interlayer spacing of 3.46 Å [16].

The coke derived from DF AF exhibits the largest L_a value. However, compared to other samples, its structure contains higher proportions of disordered carbon clusters and lower graphite-like domain content. As demonstrated in [16], increased amorphous phase content reduces anisotropic coke quality by elevating its coefficient of thermal expansion.

Carbonization of the 230–450°C fraction from CT coal extract yields coke with the smallest domain width, likely due to high heteroatom concentration in the feedstock (Table 3). Oxygen-, nitrogen-, and sulfur-containing compounds are known to adversely affect petroleum coke microstructure and performance characteristics [17].

Partial replacement of CT with HCO during coal thermal dissolution significantly improves resultant coke structure. The L_a/L_c ratio suggests this coke most closely resembles needle coke which characterized by extensive graphite-like domains with minimal thickness.

The positive effect of the petroleum solvent adding on the quality of coke can be associated with a decrease in the number of S, N and O atoms in the composition of the feedstock. Also, hydrocarbons included in the fraction 230–450°C from the coal extract in HCO/CT are distinguished by a large number of aliphatic substituents at aromatic nuclei, which has a positive effect on the structure of coke, increasing the degree of its anisotropy.

4 CONCLUSIONS

Coal extracts were obtained through thermal solvolysis using various technical solvents. These extracts can be used as carbon binder materials. Their main advantage compared to traditional pitches is their significantly lower benzo(a)pyrene content.

Yield and composition of distillate fractions (i.b.p.–450°C) depend on the type of solvent used for coal thermal dissolution. The highest content of components boiling in this range was observed in the extract obtained with anthracene fraction. Replacing 50% of coal tar with HCO during thermal solvolysis increases the yield of the 230–450°C fraction by 9.4 wt.%. The distillates consist predominantly of aromatic hydrocarbons. Using a mixture of CT and HCO as the coal solvent reduces the aromaticity factor due to an increased proportion of aliphatic carbon.

Cokes derived from distillate fractions primarily consist of turbostratic domains (72–78%), with graphite-like domains accounting for no more than 18%. During carbonization, extended domains characteristic of needle coke with a lamellar structure are formed. Comparison with literature data showed that the coke based on the distillate from the HCO/CT coal extract has the closest structural similarity to needle coke.

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References

1. Predel, H: Petroleum Coke. In: Ullmann's Encycl. Ind. Chem, pp. 1–21. Wiley-VCH Verlag GmbH & Co. KGaA, Germany (2014)
2. Zhichen, Z., Kun, Ch., Dong, L., Bin, L., Min, L., Shuhai, G., Ran, Yu, Bo, W., Xin, G., Gang, L.: Comparative study of the carbonization process and structural evolution during needle coke preparation from petroleum and coal feedstock. *Journal of Analytical and Applied Pyrolysis* **156**(6), 105097 (2021)
3. Gabdulkhakov, R.R., Rudko, V.A., Pyagay, I.N.: Methods for modifying needle coke raw materials by introducing additives of various origin (review). *Fuel* **310**(part A), 1–13 (2022)
4. Zhang, Z., Lou, B., Zhao, N., Yu, E., Wang, Z., Du, H., Chen, Z., Liu, D.: Co-carbonization behavior of the blended heavy oil and low temperature coal tar for the preparation of needle coke. *Fuel* **302**, 121139 (2021)
5. Xian, X., Louwei, C., Junhe, S., Jiaojiao, L., Yonghong, Z., Yafei, T., Mingming, Ma, Tao, L., Huaan, Z., Dong, L.: Effects of co-carbonization of medium and low temperature refined pitch and high temperature refined pitch on the structure and properties of needle coke. *Journal of Analytical and Applied Pyrolysis* **169**, 105783 (2023)
6. Craddock, J. D., Rantell, T. D., Hower, J. C., Whitlow, D. T., Wiseman, J., Weisenberger, M. C.: Anode coke from coal – A low cost approach. *Fuel* **187**, 229–241 (2017)
7. Thompson C., Frank G., Edwards V., Martinelli M., Vego A.: Mesophase pitch-based high performance carbon fiber production using coal extracts from mild direct coal liquefaction. *Carbon* **226**, 119212, (2024)

8. Kuznetsov, P.N., Kamenskiy, E.S., Kuznetsova, L.I.: Solvolysis of bituminous coal in coal- and petroleum-derived commercial solvents. *ACS OMEGA* **5**, 14384–14393 (2020)
9. Jiaxing, Y., Huimei, L., Yaming, Z., Yunliang, X., Chaoshuai, H., Junxia, Ch., Yonghui, B., Xuefei, Z.: Study on the characterization and thermal conversion behavior of sequential extraction products from medium temperature coal pitch. *Fuel* **367**, 131571 (2024)
10. Moriyama, R., Hayashi, J.-i., Chiba, T.: Effects of quinoline-insoluble particles on the elemental processes of mesophase sphere formation. *Carbon* **42** (12–13), 2443–2449 (2004)
11. Panaitescu, C., Predeanu, G.: Microstructural characteristics of toluene and quinoline-insolubles from coal–tar pitch and their cokes. *International Journal of Coal Geology* **71** (4), 448–454 (2007)
12. Jie, L., Xue-mei, S., Lou-wei, C., Xiao-yong, F., Jun-he, S., Xian, X., Jia-yong, T., Yu-cheng, T., Jin-xin, Z., Dong, L.: Effect of raw material composition on the structure of needle coke. *Journal of Fuel Chemistry and Technology* **49** (4), 546–553 (2021)
13. Long, G., Yonggang, W., Yiting, Z., Jingdong, Y., Haiyong, Z., Xiongchao, L.: The effect of n-heptane soluble content on the composition and structure of coal tar pitch and the preparation of needle coke. *Journal of Analytical and Applied Pyrolysis* **175**, 106201, (2023)
14. Kuznetsov, P.N., Perminov, N.V., Kuznetsova, L.I., Buryukin, F.A., Kolesnikova, S.M., Kamenskii, E.S., Pavlenko, N.I.: Thermal Dissolution of Different-Ranked Coals in Tetralin and the Anthracene Fraction of Coking Tar. *Solid Fuel Chemistry* **54** (2), 61–68 (2020)
15. Kuznetsov, P., Avid, B., Kuznetsova, L., Fan, X., Xu, J.-F., Kamenskiy, E., Lyrschikov, S.: Comprehensive Characterization of the Molecular Structure and Properties of Pitch-like Products from Coal Dissolution at Mild Temperature Using Heavy Solvents of Coal and Petroleum Origin. *Materials* **18**, 1660, (2025)
16. Gabdulkhakov, R.R., Rudko, V.A., Efimov, I.I., Spektoruk, A.A.: Quality assessment of needle coke used in the production of graphite electrodes for metallurgical furnaces. *Tsvetnye Metally* **7**, 46–56 (2022)
17. Guo, A., Lin, X., Liu, D., Zhang, X., Wang, Z.: Investigation on shot- coke- forming propensity and controlling of coke morphology during heavy oil coking. *Fuel Processing Technology* **104**, 332–342 (2012)

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