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DEPENDENCE OF THE IGNITION TEMPERATURE OF COALS ON THEIR PROPERTIES

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Abstract. The reactions of coal with the materials used in determining the ignition temperature of unoxidized coal were analyzed. The ignition temperatures of various types of coal from Ukraine, Russia, Canada, Australia, the Czech Republic, Poland, and Indonesia were determined. The influence of the composition, structure, and properties of the coal on its ignition temperature was assessed. The ignition temperature of the unoxidized coal was found to be closely related to the content of organic and aromatic carbon, the structural parameter characterizing the degree of saturation of the coal organic mass, and also the mean vitrinite reflectance coefficient and the volatile matter.

Keywords: coal, ignition temperature, coal properties, mathematical equations.

1. Introduction

The lowest temperature at which coal can be ignited is referred to as the ignition temperature. The ignition temperature for a certain coal is variable under different conditions because of the complexity of the ignition process. For the convenience of comparison, the ignition temperature is specified in terms of specific conditions. Table 1 shows the ignition temperatures of different types of coal, and Table 2 presents the range of ignition temperatures $t_{ig.un}$ of unoxidized coking coal according to [1].

Note that the several intervals were not found to include the ignition temperatures of any unoxidized coal in [1]: in particular, 613–623; 633–638, and 643–648 K. In our opinion, these gaps would be filled if further tests were conducted. In addition, the classification adopted by the authors included no information regarding the quality of the coal ranks. For example, for coal of each specific rank, no information was provided regarding the range of the mean vitrinite reflectance coefficient, the volatile matter, or the plastic-layer thickness.

The aim of the present work is to study the factors that affect the ignition temperature of unoxidized coal, for a wide range of coal samples. It should be noted that the effect of the mineral part of the coal on its ignition temperature in this work has not been investigated.

2. Experimental

The State Standard of Ukraine regarding the quality control of coal deliveries at coke plants permits characterization of the coal in terms of its ignition temperature.

The laboratory setup (Fig. 1) consists of electric furnace 1, copper block 2, thermocouples 3 and 4, furnace temperature regulator 5, four sets of test tubes 6, burettes 7, glasses 8 and two laboratory supports 9.

The main component of the setup is an electric furnace with a copper block where the coal sample is heated in order to determine its ignition temperature.

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Table 1

Ignition temperatures of different types of coal

Coal type	Ignition temperature, K
Lignite	523–723
Bituminous	673–723
Anthracite	973–1073

Table 2

Ignition temperature of unoxidized coal samples

Coal rank	Ignition temperature, K
G	593–613
Zn	623–633
K	638–643
OS	648–653

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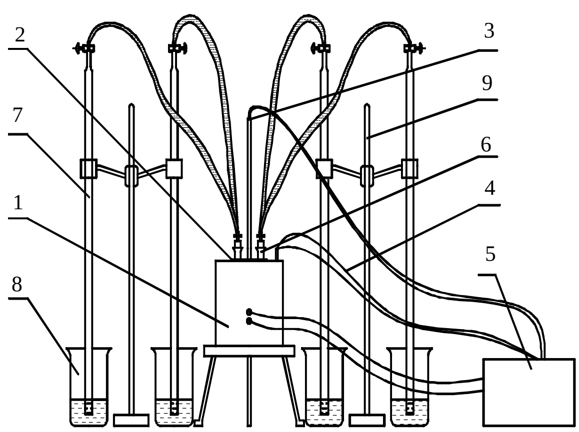

Fig. 1. Laboratory setup to determine coal inflammation temperature: electric furnace (1); copper block (2); thermocouples (3, 4); furnace temperature regulator (5); test tubes (6); burettes (7); glasses (8); laboratory supports (9)

To determine the ignition temperature $t_{ig.un}$ of reduced (unoxidized) coal, we mix 0.5 g of coal with 0.25 g of sodium nitrite ($NaNO_2$) and 0.0125 g of benzidine (4.4-diaminodiphenyl).

We know that, on heating in the absence of air, coal will undergo thermal destruction; this complex process will depend on the composition and structure of the coal organic mass and the heating conditions. At the initial stage of heating (up to 623–673 K), we primarily observe decomposition of their organic mass, accompanied by the formation of water, various oxidebearing gases, and low-molecular hydrocarbons [2]. The use of sodium nitrite as an oxidant is based on its ability to melt at 544 K, with subsequent decomposition [3, 4]:

$$2NaNO_2 \xrightarrow{t} Na_2O + NO + NO_2 \qquad (1)$$

In our opinion, the appearance of NO and NO_2 free radicals (as decomposition products of sodium nitrite) in a mixture with coal causes an oxidation of the coal thermal destruction products in a free-radical chain [2, 5]. Consequently, in the presence of sodium nitrite, the usual thermal destruction of coal is converted to thermooxidative destruction [5, 6]. The process becomes autocatalytic.

According to handbook data, benzidine (4,4'-diaminodiphenyl), with the chemical formula $C_{12}H_{12}N_2$, takes the form of white or pale yellow crystalline needles that darken in the light and in air, are poorly soluble in water, and dissolve readily in alcohol and ether. Its molar mass is 184.24 g/mol, and its melting point is 395–398 K. Concerning its chemical properties, benzidine is a typical aromatic amine [7].

By mixing the coal sample with the oxidant (sodium nitrite) and heating the mixture, we ensure vigorous coal oxidation with the appearance of a flame on reaching a certain temperature. The addition of benzidine, which is known to be a reducing agent, neutralizes the excess free radicals in the reaction mixture. Ultimately, this results in an ignition temperature close to that for fresh unoxidized coal.

The resulting mixture is transferred into a dry test-tube. The test-tubes are closed up with rubber stoppers with inserted glass tubes, which are connected to burettes with rubber (silicone) tubes; burettes are filled with water and then the open end is immersed into a glass of water to a depth of 20–30 mm. The system is checked for leaks. The burette is connected to a test-tube.

The test-tubes are dropped into a block which enables simultaneous heating of the four test-tubes. In the center of the block a recording unit of a thermocouple is set which provides heating rate of 5 K/min. At the moment of explosion (ignition of the coal sample), which is accompanied by a sharp decrease of the water level in the burette as a result of the pressure of gases evolved, the temperature is registered.

We studied 170 coal samples: 50 from Ukraine; 78 from Russia; and 42 from other countries (the United States, Canada, Australia, the Czech Republic, Poland, and Indonesia).

Table 3 presents the minimum, maximum and mean values of the technological properties of the coal samples [8-10]. The samples are characterized by low analytical moisture (which indirectly indicates the lack of oxidation) and ash content. The ignition temperature increases with the increase in the metamorphic development of the coal.

Table 3

The minimum, maximum and mean values of properties of the coal samples

Values	Minimum	Maximum	Mean
Proximate analysis, %			
W^a	0.2	3.8	1.4
A^d	3.7	12.4	8.4
S_t^d	0.13	3.26	0.83
V^{daf}	16.7	43.4	30.0
Mean vitrinite reflectance coefficient, %			
R_0	0.53	1.60	1.04
Maceral composition, %			
Vt	20	99	71
Sv	0	4	0.8
I	1	77	26
L	0	10	1.6
ΣFC	1	79	26.5
Ultimate analysis, %			
C^{daf}	80.79	91.19	86.81
H^{daf}	4.64	6.42	5.43
N^{daf}	0.85	2.99	1.95
O_d^{daf}	1.31	10.75	4.96
The degree of incomplete saturation of unit mass of the coal organic mass with hydrogen			
δ	7.62	10.42	9.18
The content of aromatic carbon in the coal organic mass, %			
C_{ar}	14.30	35.19	23.03
Ignition temperature of unoxidized coal, K			
$t_{ig.un}$	614	691	657

Table 4

The values of *r* and $|r|\sqrt{n-1}$ for correlations between individual properties of the coal and the ignition temperature $t_{ig.un}$

Statistical correlation	V^{daf}	*Vt*	ΣFC	R_0	C^{daf}	H^{daf}	O_d^{daf}	δ	C_{ar}
r	–0.915	–0.389	0.410	0.891	0.914	–0.637	–0.113	0.880	0.910
$\lvert r\rvert\sqrt{n-1}$	10.763	3.827	4.051	7.878	10.901	6.106	1.218	9.949	7.974

The degree δ of incomplete saturation of unit mass of the coal organic mass with hydrogen was calculated as:

$$d = C^{daf}/6 - H^{daf} + N^{daf}/14 \quad (2)$$

where C^{daf}, H^{daf} and N^{daf} are the concentrations of the corresponding elements in the coal organic mass, %.

The content of aromatic carbon (C_{ar}) in the coal organic mass with respect to the total carbon content was calculated as:

$$C_{ar} = \frac{3.4C^{daf}}{100 - C^{daf}} \quad (3)$$

3. Results and Discussion

The petrographic characteristics of the investigated coals indicate that they are not identical regarding their maceral composition. Some coals are characterized by elevated total content (79 %) of fusinized components (ΣFC).

It is evident that the carbon content (C^{daf}) increases uniformly from 80.79 to 91.19 % with the increase in the mean vitrinite reflectance coefficient R_0.

The hydrogen content varies from 4.64 to 6.42 %. As a rule, the oxygen content declines at later metamorphic stages.

The structural characteristics indicate the increase in the content of cyclic polymerized carbon in the coal macromolecules as a result of polycondensation in the course of metamorphism.

Thus, the structural parameter δ increases from 7.62 to 10.42. An analogous situation is observed for the content of aromatic carbon in the coal organic mass.

The analysis shows that the coal samples significantly differ in their technological properties, petrographic and structural characteristics. This is associated with different ignition temperature of coals.

Table 4 presents pair correlations between individual properties of the coal and the ignition temperature $t_{ig.un}$. The significance of the correlation coefficients r is verified by comparison of the product $|r|\sqrt{n-1}$ with its critical value H at the specified confidence level P [11]. For P = 0.999, in the case of 170 samples, H = 3.291. Table 4 presents the values of r and $|r|\sqrt{n-1}$ for each correlation.

The highest r values (0.88–0.915) are observed for the correlation of $t_{ig.un}$ with V^{daf}, R_0, C^{daf}, C_{ar}, and δ which characterize the composition, structure, and properties of the coal organic mass. These correlations also correspond to the highest values of $|r|\sqrt{n-1}$, which indicate their high reliability.

In Figs. 2-6, we plot the ignition temperature $t_{ig.un}$ *versus* the most significant characteristics of the coal. It is a linear dependence.

So, we may conclude that $t_{ig.un}$ depends on the carbon content and the structural ordering of the coal organic mass. The increase in $t_{ig.un}$ is associated with the increase in the total coal content (C^{daf}) and the content of aromatic carbon (C_{ar}), as well as the degree of its structure saturation (δ).

The ignition temperature also increases with the increase in the mean vitrinite reflectance coefficient R_0 and decrease in the volatile matter V^{daf}. Note that these characteristics also indirectly reflect the structure of the coal organic mass. The mean vitrinite reflectance coefficient is associated with the presence of cyclically polymerized carbon in the coal organic mass. The volatile matter reflects the thermal stability of the coal organic mass, which depends on the proportions of aliphatic and aromatic components in the macromolecules of the coal organic mass.

The increase in the ignition temperature with the coal rank was clearly observed by other authors [12-14].

Table 5 describes the dependence of $t_{ig.un}$ on the selected characteristics in Eqs. (4)-(8), with corresponding statistical estimates. Analysis shows high values of the correlation coefficient (0.88–0.92) and the determination coefficient (77.4–84.2 %) for these formulas.

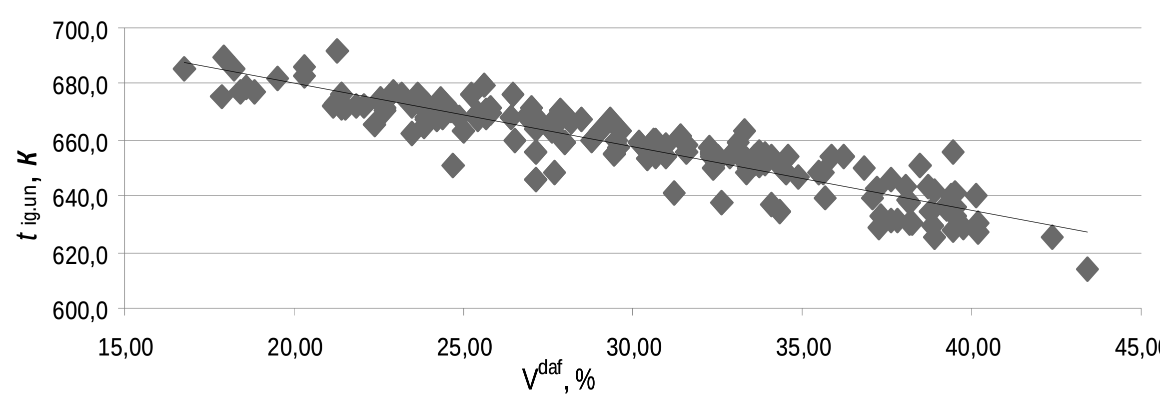

Fig. 2. Dependence of $t_{ig.un}$ on V^{daf}

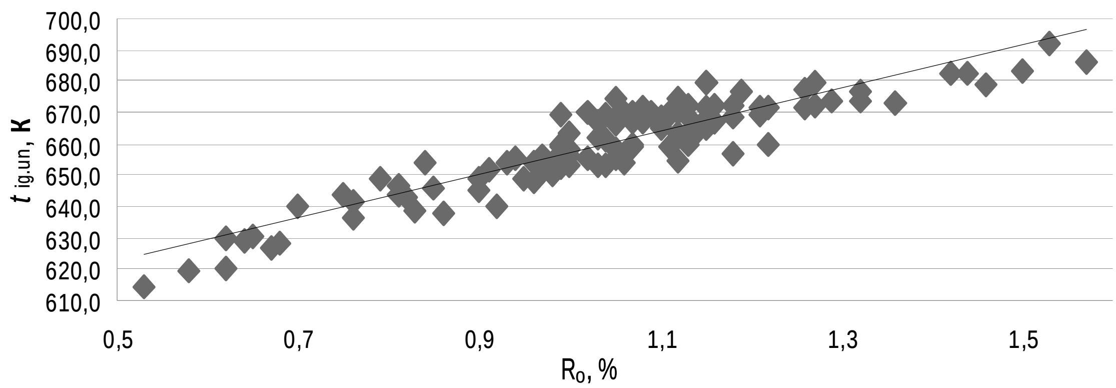

Fig. 3. Dependence of $t_{ig.un}$ on R_0

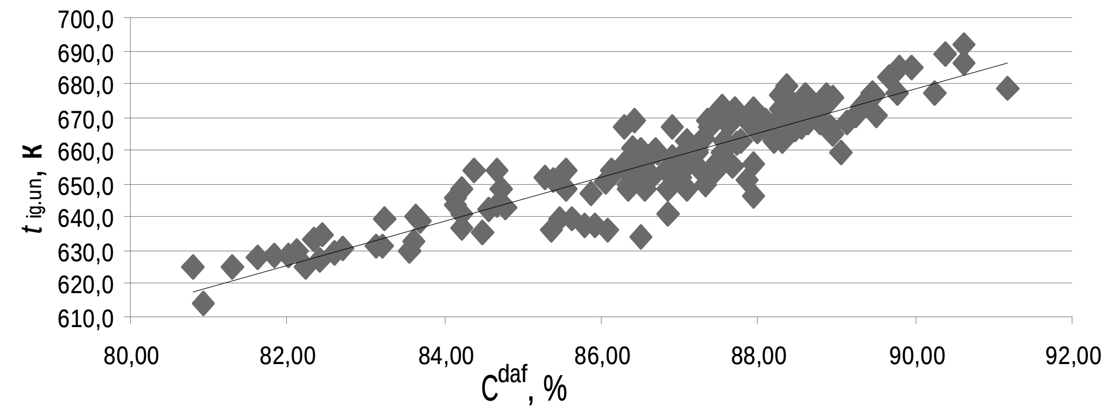

Fig. 4. Dependence of $t_{ig.un}$ on C^{daf}

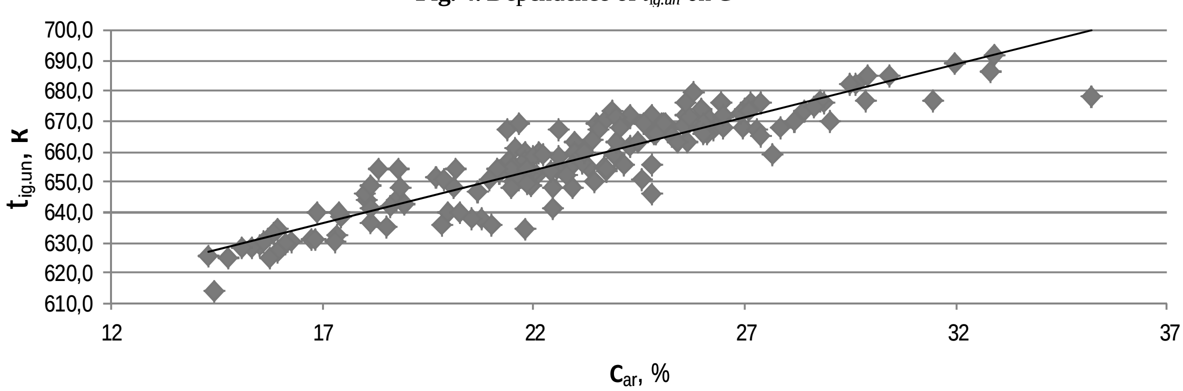

Fig. 5. Dependence of $t_{ig.un}$ on C_{ar}

Fig. 6. Dependence of $t_{ig.un}$ on δ

Table 5

Mathematical equations and corresponding statistical assessments

Eq.	Mathematical form	Statistical assessment	
		Multiple correlation coefficient *r*	Determination coefficient *D*, %
(4)	$t_{ig.un} = -2.2691 \cdot V^{daf} + 725.74$	0.91	83.7
(5)	$t_{ig.un} = 69.31 \cdot R_0 + 587.62$	0.92	84.2
(6)	$t_{ig.un} = 6.6134 \cdot C^{daf} + 83.521$	0.91	83.7
(7)	$t_{ig.un} = 3.4929 \cdot C_{ar} + 577.19$	0.91	82.7
(8)	$t_{ig.un} = 20.673 \cdot \delta + 468.31$	0.88	77.4

Table 6

Ignition temperature of coking coal (Ukrainian State Standard DSTU 3472:2015)

Coal	Designation		Mean vitrinite reflectance coefficient R_0, %	Volatile matter, V^{daf}, %	Ignition temperature, $t_{ig.un}$, K		
	rank	group			from Eq. (5)	from Eq. (4)	aggregate interval
Gas coal	G	G1	0.60–0.69	38–44	626–639	629–635	626–639
		G2	0.70–0.79	36–42	630–644	636–642	630–644
Lean bituminous gas coal	GZhO		0.80–0.89	33–39	637–651	643–649	637–651
Bituminous gas coal	GZh		0.80–0.89	33–38	639–651	643–649	639–651
Bituminous coal	Zh		0.90–1.19	28–36	644–662	650–670	644–670
Coke-grade coal	K	K1	1.04–1.19	28–30	658–662	660–670	658–670
		K2	1.20–1.49	18–28	662–685	671–691	662–691
Lean coking coal	OS		1.50–1.69	14–22	676–694	691–705	676–705

Table 6 presents the ignition temperatures calculated from Eqs. (5) and (4) for different coal ranks and groups in accordance with Ukrainian state standard. In Table 6, in contrast to Table 2, values of R_0 and V^{daf} are given for each coal rank or group, and there are no intervals within the range that do not contain ignition temperatures.

4. Conclusions

The reactions of coal with the materials used in determining the ignition temperature of coal were analyzed. The influence of the composition, structure, and properties of various types of 170 coal samples from Ukraine, Russia, Canada, Australia, the Czech Republic, Poland, and Indonesia on its ignition temperature was assessed.

The influence of the carbon content and the structural ordering of the coal organic mass on the ignition temperature of coal were determined. The increase in $t_{ig.un}$ from 614 to 691 K with the increase in total coal content of carbon (from 80.79 to 91.19 %) and the content of aromatic carbon (from 14.30 to 35.19 %), as well as the degree of its structure saturation (from 7.62 to 10.42) were defined. Correspondingly, the increase of the volatile matter (from 16.7 to 43.4 %) and the decrease in the mean vitrinite reflectance coefficient (from 1.60 to 0.53 %) with the decrease in the ignition temperature were associated. The ignition temperatures for different coal ranks and groups in accordance with Ukrainian state standards were calculated.

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ЗАЛЕЖНІСТЬ ТЕМПЕРАТУРИ ЗАЙМАННЯ ВУГІЛЛЯ ВІД ЙОГО ВЛАСТИВОСТЕЙ

Анотація. *Проаналізовані реакції вугілля з реагентами, які використовуються для визначення температури займання неокисненого вугілля. Визначені величини температур займання вугілля України, Росії, Канади, Австралії, Чехії, Польщі та Індонезії. Оцінено вплив складу, структури та властивостей вугілля на температуру його займання. Встановлено, що температура займання неокисненого вугілля щільно пов'язана з вмістом органічного та ароматичного карбону, структурним параметром, що характеризує ступінь насичення органічної маси вугілля, а також показниками середнього коефіцієнту відбиття вітриніту та виходу летких речовин.*

Ключові слова: *вугілля, температура займання, властивості вугілля, математичні рівняння.*