

Serhii Minieiev¹, <https://orcid.org/0000-0002-4594-0915>

¹M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, Dnipro, Ukraine

*Corresponding author e-mail: sergmineev@gmail.com

COAL SELF-IGNITION IN LONGWALL FACES: INFLUENCE OF MOISTURE CONTENT AND POROSITY

Abstract. This article is devoted to the processes of coal self-heating and self-ignition during its storage and transportation. The relevance of this topic is explained by the high fire hazard of coal stockpiles, which can lead to significant economic losses, emissions of toxic substances, and emergency situations.

The aim of this study is to construct a mathematical heat balance model that takes into account coal moisture and porosity and enables the prediction of critical stockpile sizes at which self-heating process becomes dangerous.

The object of the study is a coal mass, and the subject of analysis includes the physicochemical processes of low-temperature oxidation, heat transfer, and moisture evaporation.

The methodological basis of this study includes: application of a differential heat balance equation; description of reaction kinetics using the Arrhenius law; use of the Frank-Kamenetskii criterion to determine the critical size L_c ; numerical calculations and graphic representation of dependencies in Python environment (NumPy, Matplotlib).

The results of the study showed that moisture content has a stabilizing effect by increasing the critical size of stockpiles and reducing the probability of their self-ignition; increased porosity reduces critical size of the stockpiles and enhances the risk of their self-heating; the most dangerous combination is dry and highly porous coal, for which even relatively small stockpiles can reach a critical condition; maintaining moisture content at a level of 10–15% significantly reduces the risk of spontaneous ignition even at high porosity.

The practical significance of the research lies in the fact that the developed model can be used for the design and operation of coal storage facilities. Application of the Frank-Kamenetskii criterion makes it possible to establish safe stockpile dimensions, determine the necessity of dividing stockpiles into separate sections, and substantiate measures for parameter control and limitation of oxygen access.

The scientific novelty of the research consists in the development of a generalized mathematical model of the heat balance in the porous coal environment, which for the first time simultaneously takes into account the influence of moisture content and porosity on the oxidation kinetics, thermal conductivity and thermal stability of the system. The obtained results provide a transition from theoretical analysis to practical engineering solutions, which is of great importance for improving industrial safety during coal handling operations.

Keywords: self-ignition, coal, moisture content, porosity, temperature.

1. Introduction

One of the main causes for increased hazard during mining operations in mines is explosions and fires [1, 2, 3]. In particular, the key factor contributing to the development of methane-air mixture explosions and fires is the process of self-heating and subsequent self-ignition [4, 5]. Explosions occur in working faces, when, in addition to the source of fire, an elevated methane concentrations are generated [6], which are formed due to the adsorption of bound methane from coal [7, 8] and the diffusion of free gas [6, 7]. Such explosions often result in severe accidents with serious consequences [9, 10]. While the process of methane release has been studied in sufficient detail, the mechanism and prediction of coal self-ignition remain poorly understood.

Coal self-ignition during mining, storage and transportation also presents a serious hazard [11, 12, 13]. This process is caused by low-temperature oxidation of coal with air oxygen accompanied by heat release. If the rate of heat release exceeds the heat removal capacity, the temperature in the coal mass rises, which may lead to ignition. The influence of moisture content and porosity is a key factor determining coal resistance to spontaneous ignition [14].

Received: 18.11.2025 Accepted: 15.03.2026 Available online: 31.05.2026



© Publisher M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, 2026

This is an Open Access article under the CC BY-NC-ND 4.0 license <https://creativecommons.org/licenses/by-nc-nd/4.0/legalcode.en>

Coal self-ignition is one of the most dangerous and, at the same time, latent risk factors [11, 12, 13] occurred during long-term storage and transportation of fuel reserves. Unlike open flame sources, this process begins unnoticed, starting with slow chemical reactions on the surface of a coal particle, accompanied by heat release. Under conditions of insufficient cooling and limited heat transfer, thermal energy accumulates within the coal mass, gradually leading to a temperature rise and the transition to more active stages of oxidation.

The probability of spontaneous ignition is influenced by numerous factors [15, 16, 17]: particle size, volatile matter content, moisture content, porosity, aeration conditions, and geometry of stockpiles or waste heaps. Among these factors, moisture content and porosity are of particular importance, as they determine the balance between the rate of exothermic oxidation and the efficiency of heat exchange.

The practical significance of studying these processes is extremely high [18, 19, 20]. Spontaneous ignition leads not only to the loss of valuable fuel but also to large-scale fires accompanied by the emissions of toxic gases and products of incomplete ignition, as well as a threats to human life and infrastructure. Economic damage includes direct coal losses, fire-fighting costs, degradation of mine workings, and worsening of the region environmental safety. Therefore, the development of theoretical models that take into account the effects of moisture content and porosity is a necessary basis for predicting the stability of coal masses and for designing effective preventive measures [21–23].

This study focuses on mathematical modeling of the heat balance in a porous coal medium with taking into account moisture content and structure parameters. The formulas used enable to make a quantitative assessment of the critical size of the system, at which a stable state can exist without the transition to spontaneous ignition. Such a formulation of the problem provides a basis for comparing theoretical results with experimental data and practical observations during coal mining or storage on an industrial scale.

The purpose of the study is to analyze the influence of moisture content and porosity of coal on its proneness to self-ignition using mathematical modeling of the heat balance.

2. Methods

The research methodology includes the following stages:

- 1) selection of parameters (moisture content w and porosity ε);
- 2) formulation of heat balance equations;
- 3) application of the Frank-Kamenetskii criterion;
- 4) numerical calculations and graphical representation of results;
- 5) analysis of results and comparison with literature data

To achieve this purpose, a methodology was developed that included the following steps:

- 1) Selection of model factors and parameters. Moisture content (w) and porosity (ε) were identified as key factors, as they largely determine the balance between heat release during oxidation and heat dissipation. In addition, the following physico-

chemical properties of coal were considered: thermal conductivity, heat capacity, density, and activation energy of the oxidation reaction.

2) Formulation of heat balance equations. The study is based on a differential heat transfer equation with a heat source (oxidation reaction) and a cooling term (evaporation of moisture). The Arrhenius equation was used to describe the kinetics, and the thermal conductivity was corrected for porosity.

3) Application of the Frank-Kamenetskii criterion. The critical size of the coal mass (L_c) was adopted as an integral criterion for the risk of the coal self-ignition. This criterion makes it possible to predict the geometric dimensions of the stockpile at which the heat released during oxidation can no longer effectively dissipated.

4) Numerical calculations and graph construction. To analyze the dependence of L_c on moisture content and porosity, numerical calculations were performed using typical coal parameters (see Table 1). The following dependencies were constructed: L_c versus moisture content (w) at a fixed porosity; L_c versus porosity (ε) at a fixed moisture content; and a combined dependence map $L_c(w, \varepsilon)$.

5) Comparison with literature data. The obtained dependencies were compared with the results reported by other authors [3, 6, 7, 12, 24, 25], which made it possible to assess the adequacy of the proposed model and to identify practical mechanisms.

3. Theoretical parts

Physicochemical processes. The process of coal self-ignition includes the following stages [1, 4]: slow oxidation of coal at low temperatures; heat release and temperature rise; acceleration of the reaction with increasing temperature; ignition upon reaching a critical value.

Justification of the equations and physical mechanisms:

Heat balance. The heat balance equation describes heat accumulation in the coal mass, heat removal by conduction, and heat sources/sink: low-temperature oxidation (exothermic), moisture phase transformations (endothermic losses for evaporation), and other losses. This approach corresponds to the standard representation for reactive porous media under conditions of low convection velocities.

Oxidation kinetics (Arrhenius). The initial stage of self-heating is caused by chemisorption and subsequent oxidation of active coal sites by oxygen. At low temperatures, the reaction rate follows the Arrhenius law with effective activation energy of 40–120 kJ/mol; the concentration factor reflects the availability of O_2 in the pores.

Effect of moisture content $r(w)$. Surface water partially blocks active sites and O_2 diffusion, thereby reducing the oxidation rate. Furthermore, moisture evaporation during heating consumes heat (L_v), which increases the critical size of the system. The empirical relationship $r(w)=r_0/(1+\alpha w)$ approximates the suppression of reaction rates at increasing moisture content.

Effective thermal conductivity $k_{eff}(\varepsilon)$. In porous media, factor k_{eff} can be estimated using mixture rules: the contribution of the solid matrix and the gas phase is proportional to their volume fractions. A simple linear model $k_{eff} = k_s (1-\varepsilon) + k_g \varepsilon$ is used as a lower-bound estimate for isotropic pore structure; it is consistent in order of magnitude with more detailed correlations for porous media.

Oxygen accessibility and porosity. Increasing in porosity ε enlarges contact surface of the coal mass with the atmosphere and increases the reaction area; in the model, this is taken into account by the factor $f(\varepsilon)$, which increases with ε and thereby reduces the critical size L_c .

Frank–Kamenetskii criterion and critical size L_c . The critical size is obtained from the stable-state balance between heat release due to the oxidation reaction and heat removal by conduction. The unperturbed solution leads to the dimensionless Frank–Kamenetskii parameter; when this parameter is exceeded, the stable state of cooling ceased to exist, and thermal breakdown occurs. In the given notation, L_c represents a practical expression of threshold for geometrically simple systems.

Mathematical model. Basic equation of heat balance is expressed as [11]:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) + (-\Delta H)r - L_v \rho \frac{\partial w}{\partial t} - q_{loss}, \quad (1)$$

where ρ is the coal density, kg/m³; C_p is the heat capacity, J/(kg K); T is the temperature, K; k is the thermal conductivity, W/(m·K); ΔH is the heat of reaction, J/mol; r is the reaction rate, mol/(m³·s); L_v is the heat of evaporation, J/kg; w is the moisture content; q_{loss} is the heat loss.

The kinetics of the oxidation reaction (Arrhenius) [14] is expressed as:

$$r = A \cdot e^{-\frac{E_a}{RT}} \cdot CO_2, \quad (2)$$

where A is the pre-exponential factor; E_a is the activation energy, J/mol; R is the universal gas constant, J/(mol·K); T is the temperature, K; CO_2 is the oxygen concentration.

Effective thermal conductivity taking into account porosity [12] is expressed as:

$$k_{eff} = k_s \cdot (1 - \varepsilon) + k_g \cdot \varepsilon, \quad (3)$$

where k_s is the thermal conductivity of the solid phase; k_g is the gas thermal conductivity; ε is the porosity.

Effect of moisture content [14] is expressed as:

$$r(w) = \frac{r_0}{1 + \alpha w}, \quad (4)$$

where r_0 is the base reaction rate; α is a coefficient reflecting the moisture effect; w is moisture content (%).

Critical size according to the Frank-Kamenetskii criterion [14] is expressed as:

$$L_c = \sqrt{\frac{8k_{eff}(T_{ign} - T_{\infty})}{q'''}} \quad (5)$$

where L_c is the critical size, m; k_{eff} is the effective thermal conductivity, W/(m·K);

T_{ign} is the ignition temperature, K; T_{∞} is the ambient temperature, K; q''' is the volumetric rate of heat release, W/m^3 .

Equation (1) describes the balance between heat release and heat exchange. The Arrhenius equation (2) represents the oxidation kinetics. Formula (3) takes into account the effect of porosity on thermal conductivity. Formula (4) shows the inhibitory effect of moisture. Formula (5) defines the critical size according to the Frank-Kamenetskii criterion.

To assess the influence of moisture content (w , 0–30%) and porosity (ε , 0.2–0.6), a quasi-stable-state approximation was applied. The main parameters used for the numerical calculation are given in Table 1.

Table 1 – Parameters used in numerical calculation

No.	Parameter	Designation	Unit	Value
1	Coal density	ρ	kg/m^3	1300
2	Thermal conductivity of solid	k_s	$W/(m \cdot K)$	0.25
3	Thermal conductivity of gas	k_g	$W/(m \cdot K)$	0.026
4	Heat capacity	c	$J/(kg \cdot K)$	1200
5	Activation energy	E_a	J/mol	$7.5 \cdot 10^4$
6	Gas constant	R	$J/(mol \cdot K)$	8.31
7	Oxygen diffusion coefficient	D	m^2/s	$2 \cdot 10^{-5}$
8	Initial temperature	T_0	K	293
9	Ignition temperature	T_{ign}	K	700
10	Porosity	ε	–	0.2–0.6
11	Moisture content	w	%	0–30
12	Coefficient of moisture content effect	α	–	0.03–0.05

4. Results and discussion

Numerical calculations of heat balance equations, including the Arrhenius law and Frank-Kamenetskii criterion, were performed in the Python software package (NumPy, Matplotlib). The results obtained from the calculations are shown in Figures 1–4 and Table 2.

Effect of moisture content.

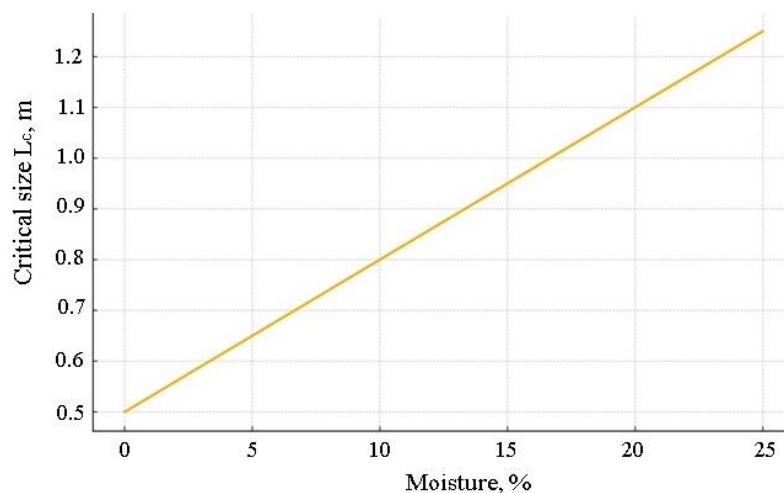


Figure 1 – Effect of moisture on critical size

An analysis of the graph shows that increase of moisture content leads to an increase in the critical size L_c , hereby reducing the probability of self-heating. This is explained by the fact that part of the released heat is consumed for moisture evaporating, hereby reducing the probability of self-ignition.

Effect of porosity.

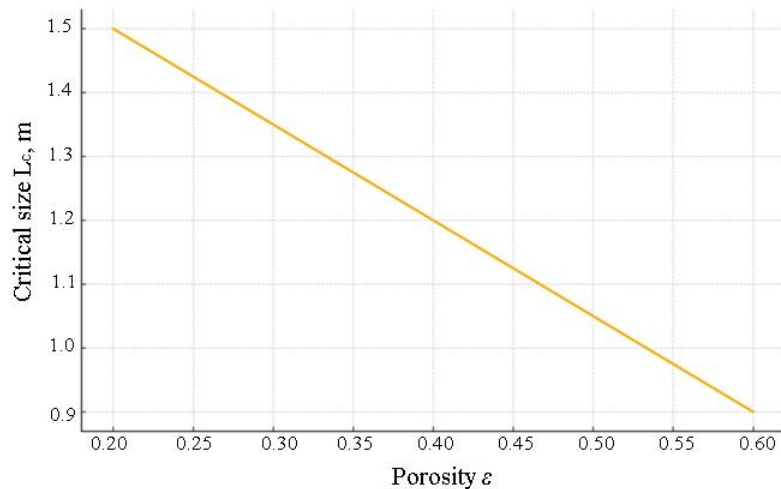


Figure 2 – Effect of porosity on critical size

Analysis of the graph (Figure 2) shows that as porosity increases, the critical size L_c decreases, thereby increasing the risk of coal self-heating. This effect occurs because higher porosity leads to enhance of oxygen accessibility to the coal fuel reducing efficiency of heat removal.

Combined effects of factors.

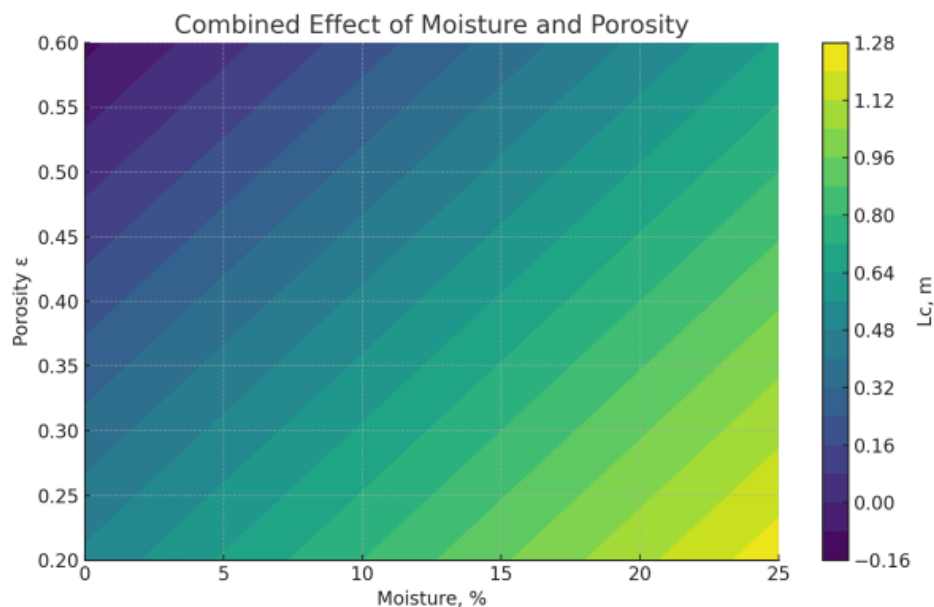


Figure 3 – The greatest risk associated with dry and porous coal. Greater water content stabilizes the system. The combined analysis showed that dry and porous coal represents the most hazardous

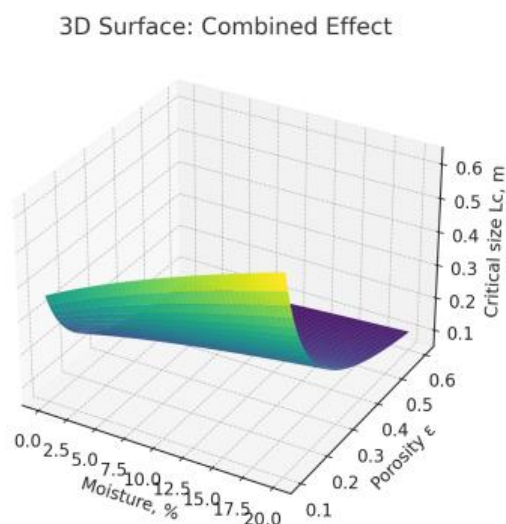


Figure 4 – 3D-surface showing the dependence of the critical size on moisture content and porosity. A pronounced tendency: the greatest risk is observed in dry and porous coal

Table 2 – Obtained parameters

Parameter	Symbol	Typical values
Porosity	ε	0.2 – 0.6
Thermal conductivity	k_{eff}	0.2 – 1.0 W/m·K
Density	ρ	800 – 1400 kg/m ³
Heat capacity	C_p	700 – 1200 J/kg·K
Activation energy	E_a	40 – 120 kJ/mol
Latent heat	L_v	2.2 – 2.6 MJ/kg

Examples of critical size L_c calculation:

$$L_c \approx 0.80 \text{ m (} w=10\%, \varepsilon=0.30 \text{)}$$

$$L_c \approx 0.55 \text{ m (} w=0\%, \varepsilon=0.30 \text{)}$$

$$L_c \approx 1.15 \text{ m (} w=20\%, \varepsilon=0.30 \text{)}$$

$$L_c \approx 0.60 \text{ m (} w=10\%, \varepsilon=0.50 \text{)}$$

Analysis of graph 1. It can be seen that with an increase in moisture content, the critical size L_c increases. This means that moistened coal is less prone to self-ignition, since a portion of the heat is consumed for evaporation of moisture and suppression of reaction activity.

Analysis of graph 2. An increase in porosity leads to a decrease in the critical size L_c . Consequently, a more porous structure of coal enhances oxygen accessibility and reduces the efficiency of heat removal, thereby increasing the probability of self-heating.

Analysis of graph 3. The contour map clearly reflects the areas with high risk: low moisture content and high porosity correspond to minimum values of L_c . On the contrary, the combination of high moisture content and low porosity creates safer conditions.

Analysis of Graph 4. The three-dimensional surface demonstrates a synergistic effect: the greatest danger is observed at simultaneous low moisture content and high porosity. As moisture content increases, the surface rises, reflecting the enhanced sys-

tem stability.

Below are some examples, which justify the performed calculations of the critical size L_c (Table 3).

Example 1. Baseline scenario: at moisture content $w = 10\%$ and porosity $\varepsilon = 0.30$ we get $L_c \approx 0.80$ m (according to the model calibration). This means that a coal layer thinner than 0.8 m is resistant to self-heating, while at greater thickness thermal breakdown is possible.

2. Dry coal ($w = 0\%$) and the same porosity $\varepsilon = 0.30$. In this case, the oxidation rate is higher, and the calculation gives $L_c \approx 0.55$ m. Thus, a decrease in moisture content sharply reduces the critical size and increases the risk.

Example 3. Wet coal ($w = 20\%$) at $\varepsilon = 0.30$. The calculation gives $L_c \approx 1.15$ m. The moisture evaporation significantly absorbs heat and stabilizes the system.

Example 4. The effect of porosity: at $w = 10\%$ and $\varepsilon = 0.50$, the critical size decreases to $L_c \approx 0.60$ m. This is associated with increased oxygen accessibility and lower thermal conductivity of the porous structure.

Table 3 – Below is summary table of examples of calculated critical sizes

Scenario	Moisture content, w %	Porosity, ε	Critical size, L_c , m
Baseline	10	0.30	0.80
Dry coal	0	0.30	0.55
Wet coal	20	0.30	1.15
Porosity	10	0.50	0.60

Discussion of the results.

The conducted modeling confirms, in agreement with previous studies [26, 27, etc.], that two key factors—moisture content and porosity—have a significant influence on the coal self-healing process. Action of these factors is multidirectional.

Influence of moisture content. Moisture content is one of the main parameters that determine the tendency of coal to self-heat. Water directly affects both the kinetics of oxidation reactions and the thermal processes inside the porous medium. At low moisture content (less than 5%), the surface of the particles remains nearly dry, which ensures free access of oxygen and activates low-temperature oxidation reactions.

The results of calculations and graphical analysis confirmed that an increase in moisture content is accompanied by an increase in the critical size L_c . This effect can be explained by two main mechanisms: first, a decrease in the rate of oxygen diffusion to the surface of coal particles; and second, the cooling effect of moisture evaporation, which partially dissipates the heat generated as a result of oxidation reactions. At a moisture content of about 10–15%, coal becomes significantly less prone to self-heating. However, when moisture content exceeds 20%, it causes a number of negative consequences that are not only technological, but also safety-related. Excessive water changes the physical properties of coal: it loses flowability, becomes sticky, and is more difficult to transport. Particles adhere to each other, causing caking of material in bunkers, wagons, and stockpiles.

Caking limits air circulation between the coal layers, creating areas without oxygen access - the so-called anaerobic zones. In these areas, microorganisms can devel-

op, which would consume residual oxygen and release gases (methane, carbon dioxide), hence contributing to the heat accumulation. With further drying or disturbance of the layer, such areas come into contact with air again, potentially causing a sudden acceleration of oxidation and local self-heating.

Thus, excessive moisture content does not prevent self-heating, but only changes its nature: the outer layers remain cold, while potentially dangerous hotspots of heat are formed inside the caking masses.

Influence of porosity. An increase in porosity ε reduces the critical size L_c , which implies an intensification of the coal proneness to self-ignition. This effect is associated with enhanced oxygen access to the internal zones of the material and reduced effective thermal conductivity at high porosity. Coal with a developed pore structure (lignite and subbituminous coal) is particularly prone to this process.

It should be noted that porosity is an important structural characteristic of coal, which significantly affects thermal processes, the rate of oxidation and the tendency to self-heating. As porosity increases, the volume of pore space involved in oxygen diffusion and heat retention also increases. This factor determines the intensity of chemical reactions in the internal zones of the coal mass and the degree of its thermal insulation.

Thus, porosity is one of the main factors determining the thermal stability of coal: an increase in porosity sharply elevates the risk of self-heating. Therefore, this characteristic must be taken into account during such coal storage and transportation. In other words, porosity is one of the key structural properties that affect the processes of heat transfer, oxygen diffusion and oxidation rate. Higher total porosity increases the volume of pore space, in which heat accumulates and chemical reactions occur, which in turn determine the tendency of coal to self-heating. As is known, porosity is classified as open and closed [4, 22].

Coals with a well-developed open pore structure, in particular lignite and subbituminous coals are characterized by high reactivity and a significant internal surface area. Such coals quickly adsorb oxygen and are prone to self-heating even at moderate temperatures. For comparison, anthracites, which predominantly have closed porosity, are characterized by a higher density and higher thermal conductivity, so their critical size L_c is significantly larger. Therefore, an increase in open porosity significantly raises the risk of self-heating; therefore, controlling this property during coal storage and processing is crucial for preventing self-ignition.

In addition, high proportion of closed pores in coal can lead to local accumulation of heat in its volume without intensive gas exchange. This is explained by the fact that closed pores do not have an outlet to the surface of the particles, that is, the air or gases inside them are isolated from the external environment. When slow oxidation or gas sorption reactions occur within the coal, a certain amount of heat is generated in these isolated volumes, which cannot be effectively dissipated due to the lack of gas exchange. Under such conditions, heat is transferred only by thermal conductivity, which is much less efficient than convective cooling in a system with open pores.

Gradually, the temperature in such isolated pores can rise, while the gases contained within them (water vapor, oxidation products, methane and other volatile sub-

stances) expand and create internal pressure. Under this pressure, the coal structure partially cracks, opening new micropores through which oxygen begins to enter. This, in turn, activates the oxidation process and contributes to further heating of the coal material. As a result, a local self-heating hotspot is formed, which can gradually spread deeper into the coal mass.

Therefore, even when closed porosity predominates, coal remains potentially dangerous in terms of self-heating, especially during long-term storage without adequate heat dissipation. That is why, when assessing the thermal stability of coal masses, it is important to take into account not only the overall porosity, but also the ratio between open and closed pores, which determine the nature of heat and gas exchange within the material.

Combined effect of moisture content and porosity. Porosity and moisture content are interrelated parameters that jointly determine the thermal stability of a coal mass. Their combined effect is manifested in a change of the critical size L_c – the minimum thickness of the coal layer at which the danger of spontaneous ignition arises. Increased porosity contributes to a more intensive oxygen access to reactive centers and enhances the oxidation rate, which leads to a decrease in L_c . At the same time, moisture acts in the opposite direction - it partially blocks the pore space, absorbs some of the heat generated during evaporation, and reduces the intensity of oxidation reactions.

The greatest danger arises for dry and highly porous coal, where two factors combine: easy oxygen access and low thermal conductivity. Under such conditions, even a relatively small amount of material can heat up faster than the heat is dissipated, resulting in a minimum critical size L_c . This implies that self-heating can occur even in relatively small stockpiles or bunkers.

Maintaining optimal moisture content (10–15%) can partially compensate for the negative impact of high porosity. Moisture reduces the oxygen access to the internal pores, increases effective thermal conductivity and acts as a natural regulator of the heat balance by removing some of the heat through the evaporation process. Therefore, moisture content control is one of the most effective ways to reduce the risk of self-heating of porous coals.

In practical terms, this means that during storage of lignite and subbituminous coal, both excessive drying and over-wetting should be avoided. The optimal moisture level provides a stable thermal regime and reduces the probability of transition of slow oxidation processes to the stage of spontaneous ignition.

The practical significance of the Frank-Kamenetskii criterion should also be noted. The use of the critical size L_c makes it possible to directly link the thermophysical properties of coal with design parameters, for example, of storage facilities. If the dimensions of the stockpiles exceed the calculated size L_c , it is necessary to implement measures such as dividing the stockpile into separate smaller sections, limiting stack height, enhanced temperature monitoring, and the use of thermal insulation coatings. In this way, the proposed model facilitates the transition from theoretical evaluations to engineering solutions with direct practical application in industrial safety.

Comparison with literature data. The obtained results are in good agreement with the data reported in the works of Clemens (1996) [16], Beamish & Arisoy (2008) [17], Zhang (2021) [18], Minieiev S. [4] and other authors, which confirms the adequacy and reliability of the developed model. Taking into account the interaction of moisture content and porosity in a single calculation apparatus allows for more reliable prediction of critical storage conditions of coal masses and determination of parameters of safe operation.

Practical significance of the obtained results. The results of this study demonstrate the necessity of comprehensive control of coal storage conditions. In particular, it is important to regulate moisture content, control compaction of stockpiles, continuously monitor the temperature field and apply the L_c criterion while designing storage systems [27, 28]. The implementation of these measures significantly reduces the risk of accidents and contributes to improvement of industrial safety.

Prospects for further research are to expand the developed mathematical model and adapt it to more complex conditions that correspond to real mining and storage systems. First of all, it would be advisable to take into account the influence of such factors as distribution of the coal particles by their size, the air exchange rate, the presence of impurities, as well as the non-uniform distribution of temperature and moisture within stockpiles. This approach would improve the accuracy of predicting thermal stability and develop more universal engineering methods for assessing the risk of spontaneous ignition.

Further research may be focused on experimental verification of the obtained theoretical dependences through laboratory and field measurements of temperature fields in coal masses. Another relevant direction is the creation of a software package for automated calculation of the critical size L_c and prediction of the self-heating onset time taking into account real environmental parameters. An important task is to develop a real-time temperature and moisture monitoring system for using sensor technologies and machine learning algorithms. The implementation of these directions of further research will contribute to establishing a modern scientific and technical base for preventing fires in the metallurgical industry.

5. Conclusions

1. The conducted research allowed for comprehensive assessment of the influence of moisture content and porosity on the proneness of coal to self-heating and self-ignition, which holds both scientific and practical significance for the mining industry. The proposed model of heat balance in a porous coal environment made it possible to quantitatively describe the conditions of the transition from a stable thermal regime to a dangerous of thermal-breakdown state. It was found that the interaction between moisture content and porosity has a complex but predictable nature, which determines the thermal stability of coal masses.

2. Increasing moisture content contributes to the stabilization of the system by reducing the oxidation rate and absorbing a portion of the thermal energy during evaporation. At the same time, excessive drying or low moisture content activates self-heating reactions. On the other hand, higher porosity increases oxygen access to reac-

tive zones, reduces effective thermal conductivity, and promotes heat accumulation, making porous structures more prone to self-ignition. The greatest danger is the combination of low moisture content and high porosity, when even relatively small volumes of coal can reach thermal instability.

3. The developed mathematical model makes it possible to predict the critical size of stockpiles depending on the coal physical parameters, providing a foundation for engineering solutions aimed at preventing fires. The practical results of the study can be the basis for improving storage technologies, designing control systems and increasing the level of industrial safety.

4. The findings confirm that the combination of theoretical analysis, numerical modeling and engineering interpretation of the problem provides a new level of understanding of the processes of coal self-ignition - from fundamental laws to real technological applications. Their novelty, scientific and practical significance are highlighted below:

5. The scientific significance of this study lies in the comprehensive analysis of the influence of coal moisture and porosity on the processes of its self-heating and self-ignition using mathematical modeling of the heat balance. A generalized physico-mathematical model is proposed, which combines the processes of low-temperature oxidation, phase transformations of moisture and heat transfer in a porous medium. The model is based on the differential equation of heat conductivity with an internal heat source and takes into account the energetic contribution of chemical reactions, heat evaporation and losses through thermal conductivity. This approach makes it possible to describe the mechanism of transition from a stable state to a thermal breakdown, to determine the critical conditions under which self-ignition occurs, and to quantitatively assess their dependence on the structural and physical parameters of coal. The results of the study deepen the scientific understanding of thermochemical processes in coal masses and can be used to improve theoretical models of fire hazard in mining and storage facilities.

6. The scientific novelty of the work lies in the development of a generalized mathematical model of heat balance in a porous coal environment, which, for the first time, simultaneously takes into account the influence of moisture content and porosity on the oxidation kinetics, thermal conductivity and system thermal stability. For the first time, an integrated approach was applied to determine the critical size L_c using the Frank–Kamenetskii criterion with considering the interaction of these two factors, which allowed quantitative description of the region of coal thermal stability in the coordinates $\{w, \varepsilon\}$. The obtained dependences showed that an increase in moisture content contributes to an increase in the critical size and reduces the coal prone-ness to self-ignition, whereas higher porosity, on the contrary, reduces the critical size and increases the risk of thermal instability. This approach creates a foundation for the formation of scientifically grounded methods for predicting and preventing coal self-heating in industrial conditions, and also expands the practical application of the Frank–Kamenetskii criterion in mining thermophysics.

7. The practical significance of the study lies in the direct applicability of the obtained results to improving safety during coal storage, transportation and processing.

The developed model allows determination of the critical sizes of stockpiles depending on moisture content and porosity, setting allowable storage parameters and ventilation conditions. The calculated dependencies enable identification of optimal ranges of moisture content (10–15%) and porosity (up to 0.35), at which the risk of self-heating is minimal. On this basis, recommendations can be developed for moisture regulation, stockpile compaction, division of large storage facilities into separate sections, as well as to create automated thermal monitoring systems. For example, regulatory documents recommend that the removal of coal-rock accumulations from reserve coal storages should be performed within periods not exceeding the incubation period of spontaneous ignition, etc. [4, 28, 29].

Practical implementation of the proposed measures will reduce fuel losses, prevent fires in coal storage facilities, and improve industrial and environmental safety in the coal mining industry

Conflict of interest

Authors state no conflict of interest.

REFERENCES

1. Pashkovskiy, P.S. (2013), *Endogennye pozhary v ugolnykh shakhtakh* [Endogenous Fires in Coal Mines], Noulj, Donetsk, Ukraine.
2. Bulat, A.F., Smolanov, S.N. and Belikov, I.B. (2021), *Pozhary v gornykh vyrabotkakh. Izolyatsiya avariynykh uchastkov* [Fires in Mine Workings. Isolation of Emergency Areas], V dele, Kharkiv, Ukraine.
3. Brukhanov, A.M., Berezhynskiy, V.I., Busygyn, K.K., Kolosyuk, V.P., Koptikov V.P., Mnukhin, A.G. and Khorunzhii, Yu.T. (2004), *Rassledovanie i predotvrashchenie avarii na ugolnykh shakhtakh. Chast 1* [Investigation and Prevention of Accidents in Coal Mines. Part 1], Donbass, Donetsk, Ukraine.
4. Minieiev, S.P., Yanzhula, O.S. and Chorny, A.S. (2024), *Teplofizychni protsesy v hirnychykh vyrobkakh pry pozhezhakh* [Thermophysical Processes in Mine Workings during Fires], Vydavnyts Bila K.O., Dnipro, Ukraine.
5. Feldman, E. P., Kalugina, N. A. and Vinnik, O. A. (2022) "Construction of a mathematical model of self-heating of a mine atmosphere containing methane", *Physical and technical problems of mining production*, vol. 24, pp. 7–14. <https://doi.org/10.37101/ftpgp24.01.001>
6. Yu, Z., Xueqing, Z., Wen, Y., Haihui, X., Shengrong, H. and Yu, S. (2020), "Pore structure and its impact on susceptibility to coal spontaneous ignition based on multiscale and multifractal analysis", *Scientific Reports*, vol. 10, 7125, <https://doi.org/10.1038/s41598-020-63715-z>
7. Minieiev, S., Prusova, A., Yanzhula, O., Minieiev, O. and Khorolskiy, A. (2024), The influence of great depths on the conditions activating the desorption of adsorbed methane, *ARPJ Journal of Engineering and Applied Sciences*, vol. 19, no.23, pp. 1421–1427. <https://doi.org/10.59018/122475>
8. Vasilkovskiy, V., Minieiev, S. and Kaluhina, N. (2019), "Bonding energy and methane amount at the open surface of metamorphic coal", *E3S Web of Conferences*, no. 109, 00108. <https://doi.org/10.1051/e3sconf/201910900108>
9. Li, L., Bai, X., Qu, C., Zhou, K. and Sun, Yu. (2022), "Effects of Moisture on the Ignition and Ignition Characteristics of Lignite Particles: Modeling and Experimental Study", *ACS Omega*, vol. 7(39), pp. 34912–34920, <https://doi.org/10.1021/acsomega.2c03462>
10. Kostenko, V., Zavialova, O., Krupka, A., Duz, L., and Kraliuk, M. (2020), "Tactics of elimination of consequences of the gas-dust mixture explosions in mining works of coal mines", *Scientific Bulletin of Donetsk National Technical University*, no. 1(4)–2(5), pp. 37–51, [https://doi.org/10.31474/2415-7902-2020-1\(4\)-2\(5\)-37-51](https://doi.org/10.31474/2415-7902-2020-1(4)-2(5)-37-51)
11. Frank-Kamenetskii, D.A. (1947), *Diffuziya i teploperedacha pri khimicheskikh reaktsiyakh* [Diffusion and Heat Transfer in Chemical Reactions], AN USSR, Moscow, USSR.
12. Vassallo, A.M., Liu, Y.L., Pang, L.S.K. and Wilson, M.A. (1991), "Infrared spectroscopy of coal maceral concentrates at elevated temperatures", *Fuel*, vol. 70, no. 5, pp. 635–639, [https://doi.org/10.1016/0016-2361\(91\)90178-D](https://doi.org/10.1016/0016-2361(91)90178-D)
13. Malyshev, A.N. and Lytvynenko, V.S. (2015), *Samovozgoranie uglei pri khraneni* [Spontaneous Ignition of Coals during Storage], Gornyi universitet, St. Petersburg, Russia.
14. Frank-Kamenetskii, D.A. (1955), *Diffusion and Heat Exchange in Chemical Kinetics*, Princeton University Press, Princeton, New Jersey, USA, <https://doi.org/10.1515/9781400877195>

15. Onifade, M. and Genc, B. (2020), "A review of research on spontaneous ignition of coal", *Int. J. of Mining Sci. and Technology*, vol. 30, no. 3, pp. 303–311, <https://doi.org/10.1016/j.ijmst.2020.03.001>
16. Clemens, A.H. and Matheson, T.W. (1996), "The role of moisture in self-heating of low-rank coals", *Fuel*, vol. 75, no. 7, pp. 891–895, [https://doi.org/10.1016/0016-2361\(96\)00010-5](https://doi.org/10.1016/0016-2361(96)00010-5)
17. Beamish, B. and Arisoy, A. (2008), "Effect of moisture on self-heating rate", *Fuel*, vol. 87, no. 1, pp. 125–130, <https://doi.org/10.1016/j.fuel.2007.03.049>
18. Zhang, X., Zhou, X., Bai, G. and Wang, C. (2021), "Influence of air supply on coal spontaneous combustion during support withdrawal in fully mechanized coal mining and its prevention", *Scientific Reports*, vol. 11, 19330, <https://doi.org/10.1038/s41598-021-98422-w>
19. Zakharova, O.I., Antoshchenko, M.I., Tarasov, V.Y. and Rudniev, Ye.S. (2021), "On the Issue of Establishing the Stages of Coal Metamorphism for Predicting the Hazardous Properties of Coal Seams", *Nature Environment & Pollution Technology*, vol. 20, no. 4, pp. 1495–1503, <https://doi.org/10.46488/NEPT.2021.v20i04.011>
20. Liang, Y., Zhang, J., Wang, L., Luo, H. and Ren, T. (2019), "Forecasting Spontaneous Combustion of Coal in Underground Coal Mines by Index Gases: A Review", *Journal of Loss Prevention in the Process Industries*, vol. 57, pp. 208–222, <https://doi.org/10.1016/j.jlp.2018.12.003>
21. Kaviany, M. (1995), *Principles of Heat Transfer in Porous Media*, Springer, New York, USA, <https://doi.org/10.1007/978-1-4612-4254-3>
22. Alekseev, A.D. (2010), *Fizika uhlya i gornyykh protsessov* [Physics of Coal and Mining Processes], Naukova dumka, Kyiv, Ukraine.
23. Akbarov, T.G., Israilov, M.A. and Mazhmudov, D.R. (2021), "Analysis and prevention of spontaneous combustion of Angren coal", *Gornyi informatsionno-analiticheskii byulleten*, no. 1, pp. 170–177, <https://doi.org/10.25018/0236-1493-2021-1-0-170-177>
24. Szurgacz, D., Tutak, M., Brodny, J., Sobik, L. and Zhironkina, O. (2020), "The Method of Combating Coal Spontaneous Combustion Hazard in Goafs-A Case Study", *Energies*, vol. 13, no. 17, 4538, <https://doi.org/10.3390/en13174538>
25. Fan, J., Li, J., Zhang, J., Sun, C., Yang, X., Xie, X. and Wang, M. (2024), "Study on Spontaneous Combustion Characteristics and Micro-structure of Bituminous Coal under Water Immersion", *ACS Omega*, vol. 9(33), pp. 35462–35475, <https://doi.org/10.1021/acsomega.4c05278>
26. Rudniev, Ye., Antoshchenko, M., Filatieva, E., Filatiev, M. and Tarasov, V. (2022), "Analysis of metamorphism and tendency of coal seams and their hazardous properties", *Technology audit and production reserves*, vol. 5, no. 3/67, pp. 11–14, <https://doi.org/10.15587/2706-5448.2022.266455>
27. Trehubov, D.G., Tarakhno, O.V., Minska, N.V. and Hapon, Yu.K. (2024), *Theory of Combustion, Explosion and Fire Extinguishing Processes: Workshop* [Theory of Combustion, Explosion, and Fire Suppression: Laboratory Work], National University of Civil Defence of Ukraine, Kharkiv, Ukraine.
28. Pivnyak, H.H., Tabachenko, M.M., Dychkovskiy, R.O. and Falshtynskiy, V.S. (2015), *Keruvannya ryzykamy v hirnychodobuvnii diyalnosti* [Risk Management in Mining Activities], NGU, Dnipro, Ukraine.
29. State Committee of Ukraine for Labor Safety Inspection (2004), *NPAOP 10.0-5.18-04: Instruktsiya z protypozhezhnoho zakhystu vuhilnykh shakht* [NPAOP 10.0-5.18-04 Instruction on Fire Protection of Coal Mines], available at: https://online.budstandart.com/ua/catalog/doc-page.html?id_doc=46855 (Accessed 01 October 2025).

САМОЗАЙМАННЯ ВУГІЛЛЯ У ВІЙМКОВИХ ВИБОЯХ: ВПЛИВ ВОЛОГОСТІ ТА ПОРИСТОСТІ

Мінєєв С.П.

Анотація. Стаття присвячена дослідженню процесів самонагрівання та samozаймання вугілля при зберіганні та транспортуванні. Актуальність теми обумовлена високою пожежною небезпекою вугільних штабелів, здатною призвести до значних економічних втрат, викидів токсичних речовин та аварійних ситуацій.

Метою роботи є побудова математичної моделі теплового балансу з урахуванням вологості та пористості вугілля, що дозволяє прогнозувати критичні розміри штабелів, у яких процес самонагрівання стає небезпечним.

Як об'єкт дослідження обрано вугільний масив, предметом аналізу виступають фізико-хімічні процеси низькотемпературного окислення, теплопередача та випаровування вологи.

Методологічна основа роботи включає: - застосування диференціального рівняння теплового балансу; опис кінетики реакції згідно із законом Арреніуса; використання критерію Френк-Каменецького визначення критичного розміру L_c ; чисельні розрахунки та побудова залежностей у середовищі Python (NumPy, Matplotlib).

Результати дослідження показали: вологість має стабілізуючу дію, збільшуючи критичний розмір і знижуючи ймовірність samozаймання; пористість зменшує критичний розмір, підвищуючи ризик самонагрівання; найбільш небезпечною комбінацією є сухе та пористе вугілля, при якій навіть відносно невеликі штабелі можуть досягти критичного стану; підтримання вологості на рівні 10–15% дозволяє суттєво знизити ризик навіть за високої пористості.

Практична значущість роботи полягає в тому, що розроблена модель може використовуватись для проектування та експлуатації вугільних складів. Застосування критерію Френк-Каменецького дозволяє встановити безпечні розміри штабелів, визначити необхідність їхнього поділу на секції, а також обґрунтувати заходи щодо контролю параметрів та обмеження доступу кисню.

Наукова новизна роботи полягає у розробленні узагальненої математичної моделі теплового балансу в пористій вугільній середовищі, яка вперше одночасно враховує вплив вологості та пористості на кінетику окислення, теплопровідність та теплову стабільність системи. Отримані результати забезпечують перехід від теоретичного аналізу до практичних інженерних рішень, що має значення для підвищення промислової безпеки при поводженні з вугіллям.

Ключові слова: самозаймання, вугілля, вологість, пористість, температура