An Experimental and Theoretical Study of the Thermal Treatment Stage during Semi-Coke Briquetting from Weakly Caking Coal

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***Abstract* — The paper proposes a method for assessing the state of coal particle packing before pressing. The method is based on a numerical calculation of internal temperature and component composition heterogeneities. The mathematical model developed for this purpose is validated using experimental data. The calculation results are used to predict the quality of briquettes based on the distribution of the coal conversion degree. The obtained dependencies show that the low mechanical strength of briquettes corresponds to conditions where the conversion degree exhibits high heterogeneity. Using the model, a numerical study is conducted to find suitable briquetting conditions (lower temperature, longer heating).**

***Index Terms* — Coal briquettes, semi-coking, pyrolysis, mechanical strength, mathematical modelling.**

I. Introduction

Among coal technologies, those designed for the production of high-carbon materials are the most challenging for reducing emissions. This is due to both the inevitable high energy consumption in the target processes and the continuous deterioration of the quality of fossil fuels [1]. In this context, studies aimed at developing new methods for extracting solid carbon (semi-cokes and cokes) from a wide range of coals, including those lower-grade ones, are highly relevant. It is worth noting that in addition to carbonaceous materials, coal pyrolysis yields a variety of valuable chemical products, including calorific gas, pyro-liquids, and others [2].

Coal matter is a natural porous composite characterized by highly variable physical and chemical properties. In this regard, the main role in the study of coal pyrolysis processes is played by the statistical approach, which requires a large number of experiments to develop prognostic tools. As of now, no universal models exist for describing the set of processes of chemical transformations with heat and mass transfer during heating and decomposition of coals, although over fifty years of research have produced a number of methodological approaches relying on basic models of chemical kinetics, some approximations of the coal macromolecule structure, representation of functional groups in the form of networks, and others [3–7]. The disadvantages of such approaches are the large volume of initial information required for calculations and the empirical nature of the patterns they are based on [8].

The main tool for controlling the pyrolysis process is temperature [9]. The structure of carbon materials depends significantly on the conditions of raw material pyrolysis [10]. Even for coals that are weakly caking at low heating rates, it is possible to select conditions (thermal shock, pressure, particle size) that allow the production of good-quality semi-coke [11]. However, this requires fine (and often completely empirical) adjustment of the apparatus [12]. The temperature at which the plastic state is reached for coals usually ranges from 350 to 550 °C [13], but with

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slow heating, secondary reactions (crosslinking of aromatic structures [14], interaction with volatile components [15], and formation of new phases [16]) lead to deterioration in the quality of the carbonaceous material. Controlled heating allows separating the time scales of thermal processes and chemical transformations to control semi-coking processes. For this purpose, both traditional transport devices for dispersed flows and other methods of controlling thermal processes (for example, high-frequency heating [17]) can be used.

Another important factor is the composition of the raw material. Instead of raw coal, individual fractions [18], mixtures of different types of coal or even different types of fuel, such as coal and biomass [19], coal and waste [20–22], can be processed through pyrolysis. The choice of binding additives and the method of mechanical processing of the plasticized mass are also of great significance.

In addition, thermal schemes of semi-coking processes are constantly improved, primarily to enhance their thermodynamic efficiency [23]. To this end, studies are conducted on the interaction of heat transfer and thermal decomposition of coals in pyrolysis apparatuses [24–26], (which often requires at least crude estimates of the chemical reaction rates). Another important area is the use of staged schemes (for example, with the combustion of pyrolysis gas in process furnaces [27, 28] or with partial gasification [29, 30]).

Numerical modeling is usually based on simplified concepts of the pyrolysis mechanism, heat and mass transfer of decomposing particles with the environment and with other decomposing particles, which is associated with high computational costs of detailed mathematical models. The most widely used approaches are the selection of a reference particle [7, 31], spatial averaging [32], and the reduction of kinetic models to one- and two-stage lumped schemes [33]. It is important to note that many of the data required for thermochemical calculations (primarily the thermophysical properties of intermediate compounds) are often unknown due to the complexity involved in experimentally measuring the characteristics of the reacting phases. Selecting methods for assessing such characteristics poses a significant challenge in numerical modeling, which is usually approached only by comparing the calculation results and experimental measurements. In this context, empirical research holds immense value [34].

This paper considers the pyrolysis process of a small coal bed (with a height of several centimeters) in a muffle furnace. Typical heating times are tens of minutes. The study aims to find conditions for producing mechanically strong briquettes. This is achieved using experimental methods and mathematical modeling. The novelty of the study lies in the method proposed for producing semi-coke briquettes from weakly caking coal and in a new mathematical model developed for the pyrolysis process of the coal packing, which determines the degree of heterogeneity of temperature and conversion of coal. The resulting briquettes are semi-products; a higher-quality product is yielded through further high-temperature processing, which ensures complete devolatilization, hardening of the material, and high reactivity. These issues will be considered in subsequent studies.

The paper is organized as follows: Section 2 describes experimental techniques; Section 3 presents the mathematical model; Section 4 compares the measurements and calculated results; and Section 5 focuses on the mathematical model used to identify the optimal conditions for coal pyrolysis for the purpose of briquetting.

II. Experimental Methods

Cheremkhovo coal, characterized by fractions with an average particle size of 6 mm, was used to obtain semi-coke samples. The problems of Siberian coal use are partially covered in the review presented in [35].

The physicochemical properties of coals were determined using macrothermogravimetry, calorimetry, and fuel elemental composition analyzers. A TGA 801 macrothermogravimetric analyzer (LECO, USA) was used to determine moisture (W), ash content (A), volatile matter yield (VM), and the proportion of fixed carbon (FX). The net calorific value (Q) was determined using an AC 500 calorimeter (LECO, USA). The carbon (C) and sulfur (S) content was determined using a Metavac CS20 elemental analyzer (Russia). The equipment employed is part of the High-Temperature Circuit Multi-Access Research Center (MESI SB RAS). The physicochemical properties determined are given in Table 1.

Table 1 also shows the reactivity index (RI). The reactivity of fuels is understood as their chemical activity in the oxidation process. Most often, the reactivity of fuels is expressed through the volatile matter yield index, which characterizes the process of ignition and combustion of the fuel. The reactivity of the fuel (RI) is calculated using the following equation:

$$RI = \frac{FX}{VM} = \frac{100}{VM} - 1\,.$$

The higher the value, the lower the reactivity. According to the reactivity value, coals can be divided into several

TABLE 1. Physicochemical Properties of Cheremkhovo Coal (*r* is for Raw Matter)

Property	*W*, %	*VM*, %	*A*, %	*FX*, %	Q^r, MJ/kg	*RI*	C^r, %	S^r, %
Value	10	38.7	30.2	31.2	19.2	1.6	43.4	0.8

TABLE 2. Results of a Semi-Quantitative XRF Analysis of Mineral Matter

Component	Mass fraction, %
Na_2O	<d.t.*
MgO	1.4
Al_2O_3	16.5
SiO_2	74.8
P_2O_5	<d.t.
SO_3	0.57
K_2O	1.87
CaO	1.24
TiO_2	0.30
Cr_2O_3	<d.t.
MnO	<d.t.
Fe_2O_3	2.70
SrO	0.025
ZrO_2	0.015
BaO	0.339

*<d.t. is for "less than detection threshold"

groups: those with a value of *RI* = 0.8 – 1.0 can be classified as subbituminous brown coals, when RI falls between 1.1 and 1.2, they are identified as highly reactive bituminous brown coals. An *RI* of 1.3 indicates medium-reactive bituminous brown coals. An *RI* between 1.4 and 1.5 represents low-reactive bituminous brown coals. For low-reactive hard coals, *RI* = 1.6 – 2.3. Thus, the coal under study is classified as low-reactive hard coal.

To determine the composition of the mineral part of coal, the X-ray fluorescence analysis (XRF) method was used. The coal ash samples were analyzed using an S4 Pioneer wave-dispersive X-ray spectrometer from Bruker AXS, featuring a Soller-type X-ray optical scheme, equipped with an Rh-anode X-ray tube operating at 4 kW.

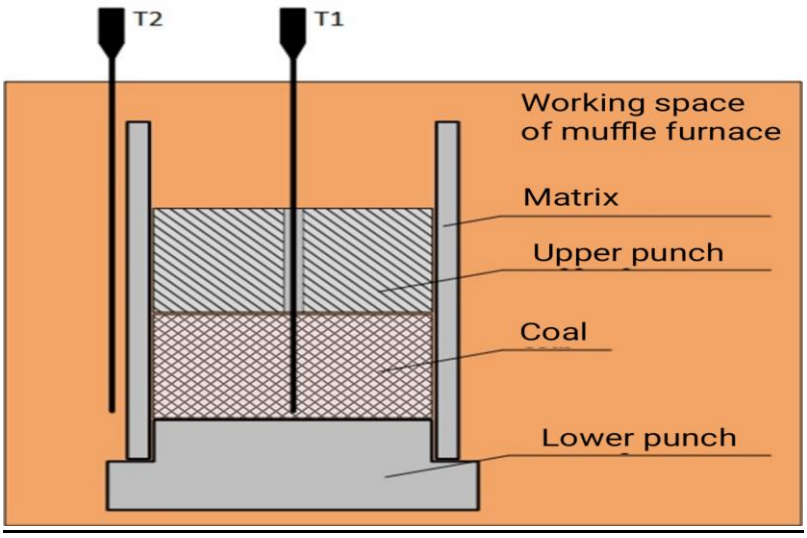

Fig. 1. The scheme of the mold used in experiments.

TABLE 3. Experimental Conditions

	Target temperature, °C	Residence time, min	Coal weight, g	Produced briquette mass, g
1	300	0		67.1
2	300	5		68.7
3	300	10		67.3
4	320	10	80.0	63.9
5	350	10		59.7
6	400	0		55.0
7	375	0		57.1

Table 2 shows the results of the approximate quantitative X-ray fluorescence analysis for the ash of the coal under study.

The packing density of particles was 759 kg/m^3, the swelling index stood at 1.5, and the coking residue type by Gray-King was G1 (sintered, non-melted).

The technique of coal briquette production under laboratory conditions can be represented by the following algorithm:

1) Prepare the coal packing (mass is 80 g);

2) Fill the mold;

3) Install the upper punch with a hole for the thermocouple on the hanger.

4) Place the assembled mold in a muffle furnace. Install a thermocouple (T1) through the hole in the upper punch so that it touches the lower punch.

5) Place the second thermocouple (T2) in the volume of the muffle furnace near the wall of the mold.

6) Turn on the muffle furnace and set the heating temperature to 500–600°C.

7) After reaching the target temperature inside the mold, remove the thermocouple, transfer the mold from the muffle to the platform, and press it with a 5-ton force.

8) Keep the mold under pressure until it cools to room temperature.

9) Remove the lower punch and take out the produced coal briquette.

The influence of residence time (up to 10 min) and temperature (300-400°C) was studied according to the experimental plan presented in Table 3. The obtained briquettes are shown in Fig. 2. The obtained coal briquettes were non-uniform (coal grains are clearly visible on the upper and lower parts) and crumbled. This was especially pronounced for samples 6 and 7 (see Appendix, Fig. 1A), which were processed at higher temperatures relative to the other samples. The non-uniformity of the briquettes and cracks were present across all samples, both on their upper and lower sides.

These phenomena likely result from the non-uniformity of the coal conversion degree along the height of the briquette. To assess the non-uniformity quantitatively, we developed a mathematical model of the physical and chemical processes that occur during the heating of the workpiece. This model is detailed in the next Section.

III. MATHEMATICAL MODEL OF COAL PACKING PYROLYSIS

We consider a quasi-one-dimensional coal packing with an initially uniform distribution of temperature, moisture content, and conversion degree. The packing is placed in a muffle furnace and heated at a given temperature of the furnace walls. Since the shell of the mold is metallic, it can be assumed that the main thermal resistance is related to the convective and radiative heat transfer between the shell surface and the environment. During heating, the organic mass undergoes drying and a two-stage decomposition.

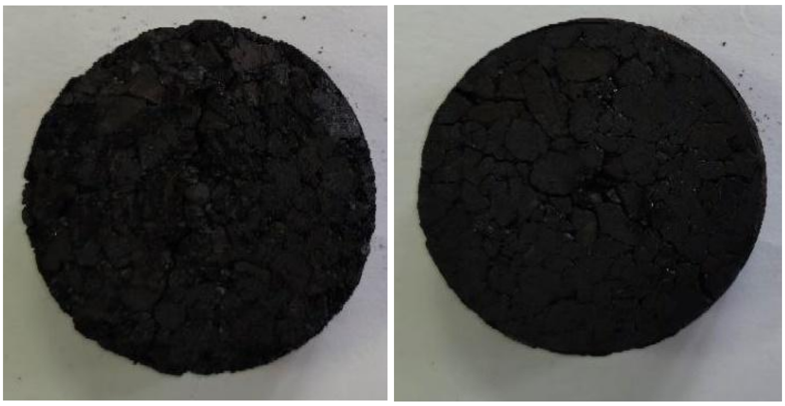

Fig. 2. The appearance of coal briquettes for experiment No. 1 (with the upper view on the left and the bottom view on the right). Other appearances can be found in the Appendix.

The presented model is grounded in the findings of [5, 36–39], which reveal the main physical and chemical features of the processes of thermal decomposition and softening of the coal matter, particularly when subjected to mechanical loading. Chemical transformations of the coal mass involve thousands of organic substances formed during the decomposition of macromolecules. Practical experience, however, demonstrates that despite this diversity, the overall behavior of the coal mass can be described with a small number of variables. These variables do not always correspond to specific organic compounds, but instead represent broader "classes" of decomposition products characterized by their properties such as stages of appearance, phase state, hydrophobicity, and others. In this context, excessive detailing can be an unfavorable factor for the computational model, especially at the stage of the reactor concept testing where identifying qualitative patterns is more crucial than accurate quantitative results.

The propagation of heat is described by a one-dimensional heat conduction equation with the coordinate representing the height of the packing:

$$c\rho \frac{\partial T}{\partial t} = \lambda \frac{\partial^2 T}{\partial x^2} + q ,$$

where c is the heat capacity, ρ is the density, T is the temperature, t is the heating time, x is the sample height, λ is the thermal conductivity, and q is the heat sink, related to phase transitions and chemical reactions. Thermophysical properties depend on temperature and coal conversion:

$$c\rho = c_W\rho_W + c_C\rho_C + c_A\rho_A ,$$

$$\lambda = \frac{\lambda_W\rho_W + \lambda_C\rho_C + \lambda_A\rho_A}{\rho} + \lambda_{rad} ,$$

where c_i is the heat capacity of components (moisture, organic mass, mineral matter), ρ_i is the mass concentration of components (given porosity); λ_i is the thermal conductivity of components, and λ_{rad} is the radiative thermal conductivity (calculated by a formula proposed by Kovenskii and Teplitskii [40]). The thermal conductivity of coal matter (W/(m·K)) linearly increases with temperature [41]:

$$\lambda_C = 0.12 + 0.12\frac{T-273}{1000} .$$

The drying rate is determined by a heat balance:

$$\frac{\partial \rho_W}{\partial t} = \begin{cases} 0, & T < T_b, \\ -\dfrac{c\rho}{|Q_b|}\dfrac{\partial T}{\partial t}, & T \ge T_b, \end{cases}$$

where, T_b is the water phase transition temperature (373 K) and Q_b is the water phase transition latent heat.

The thermal conductivity of coals ranges from 0.1 to 0.5 W/(m·K) depending on the carbon content (for coals with a carbon content exceeding 80%, the thermal conductivity is higher due to graphitization) [42]. Then, with a heat transfer coefficient of about tens of W/(m^2·K) and a particle size of about a centimeter, the Biot number will be in the range of hundredths to tenths. It can be confidently assumed that the temperature inside the particle relaxes quickly enough to neglect internal gradients [43]. In some cases, intense gas evolution or mechanical abrasion can lead to cracking of particles, additionally intensifying heat transfer.

To describe the lumped kinetics of coal decomposition, we adopt a two-stage model, which is often used to describe coal semi-coking processes. The first stage involves the formation of a multiphase set of products, including organic matter in a plastic state termed metaplast. The second stage corresponds to the degradation of the plastic state, its transformation into a solid product and residual volatile substances. For modeling purposes, it suffices to consider only the phase state of the products and their mass fractions. Therefore, for example, volatile substances are not separated by composition but are included in one macrocomponent.

Gross reaction kinetic equations can be written as follows [39]:

$$\frac{dC}{dt} = -k_1 C ,$$

$$\frac{dM}{dt} = k_1 C - k_2 M ,$$

$$\frac{dR}{dt} = k_2 M ,$$

where C is the raw coal organic mass, M is the coal organic mass in its plastic state, R is the solid residue mass (semicoke and ash); k_1 and k_2 are kinetic coefficients for gross reactions. The sum of the components $C + M + R$ is the packing mass. The kinetic coefficients exhibit temperature dependence in accordance with Arrhenius's law:

$$k_i = k_i^0 e^{-\frac{E_i}{R_g T}} ,$$

where E is the activation energy, k^0 is the pre-exponential factor, and R_g is the gas constant. The mass of the particle at each moment is equal to the sum of masses of the condensed macrocomponents. The kinetic coefficients, holding the highest degree of uncertainty of all the coefficients in the model, are sourced from the

TABLE 4. Numerical Values of the Coefficients Used in the Mathematical Model

Parameter	Dimensions	Value
Specific heat of coal, c_C	J/(kg·K)	1 400
Specific heat of moisture, c_W	J/(kg·K)	4 200
Specific heat of ash, c_A	J/(kg·K)	2 000
Raw coal density, ρ	kg/m^3	1 300
Universal gas constant, R_g	J/(mol·K)	8.314
Preexponent of the first reaction, k_1^0	1/s	245
Activation energy of the first reaction, E_1	kJ/mol	40.7
Preexponent of the second reaction, k_2^0	1/s	2×10^8
Activation energy of the second reaction, E_2	kJ/mol	133
Pyrolysis heat, Q_p	kJ/kg	–300
Water evaporation heat, Q_{ev}	kJ/kg	-2.27×10^3
Heat transfer coefficient, α	W/(m^2·K)	20
Stefan-Boltzmann constant, σ	W/(m^2·K^4)	5.67×10^{-8}
Emissivity, ε	–	0.99
Packing height, H	м	0.044
Packing porosity, Π	–	0.3
Coke-ash residue thermal conductivity, λ_A	W/(m·K)	1

aforementioned literature. The coefficients factoring in the distribution of the products across phases are chosen so that the solid residue is equal to that measured in the laboratory.

With the total yield of volatiles assumed at 42%, we can assume that the yield of condensed organic residue in the first reaction stands at 95%, while in the second reaction, it is 61%. Both reactions are irreversible and have formal first order with respect to the reagent. The integral thermal effect of decomposition Q_p is –300 kJ/kg (in some cases the thermal effect depends on the degree of conversion [8], but we neglect this dependence). Then the term q on the right-hand side of the heat balance equation can be written as follows:

$$q = -Q_b \frac{\partial \rho_W}{\partial t} - Q_p \frac{\partial \rho_C}{\partial t} .$$

The boundary conditions are as follows:

$$-\lambda \frac{\partial T}{\partial x}\left(x \in \Omega\right) = \alpha\left(T - T_g\right) + u\left(t\right)\varepsilon\sigma\left(T^4 - T_w^4\right),$$

where, α is the heat transfer coefficient (mainly due to free convection in the muffle furnace space), Ω is the outer surface of the sample, ε is the emissivity of the surface (0.99), and σ is the Stefan-Boltzmann constant. Note that the temperatures of heating through the convective and radiant heating differ. The gas temperature near the surface of the samples is measured by a thermocouple and the wall temperature is set constant. When the gas temperature reaches a given temperature, the experimental technique disables radiant heat exchange. As a result, the second term on the right-hand side contains the control $u(t)$, which equals one during the heating phase and switches to zero when the target temperature is achieved. This condition underlies the control of the thermal state of the muffle furnace. We take these values from the measurements. Table 4 shows the coefficients used in the calculations.

The heat transfer equations with chemical reactions are numerically solved utilizing a combined scheme with splitting by physical process. The drying and pyrolysis processes are considered to occur under a fixed temperature distribution, independently in each grid element. Calculations rely on analytical and balance expressions, which include local temperature as a constant parameter. The process of heat conduction with heat sinks, whose intensity is determined in the previous stage, is considered to occur under fixed physical and chemical properties of the packing. For this purpose, a system of difference equations with implicit approximation is solved using the tridiagonal matrix algorithm. The resulting scheme has the first order of convergence in time and space grid steps [41].

As in the case of other similar systems, the choice of the spatial grid step cannot be based on any highly detailed characteristics of the sample. The coal particle packing is a heterogeneous system, therefore reducing the grid step to a size smaller than that of a single particle generally requires switching to other methods for its description, such as DEM, XDEM, and others [45]. In this paper, we assume that the interpenetrating phase model can still be applied (at least for calculations) even when the grid step is reduced to sizes that are smaller than single particles ($h = 0.4\times10^{-4}$ m). The time step was chosen in accordance with the constraints on the thermal relaxation time of both the grid element and the entire sample ($\tau = 5\times10^{-2}$ s). The calculation results presented below were obtained for these values of the difference scheme parameters.

IV. The Calculation Results and Their Comparison with Experimental Findings

For the experiments from Table 1, the conditions for heating the coal packings before pressing into briquettes were reproduced using the mathematical model. In all cases, the heating temperature varied from 300 to 400°C, the initial mass of the sample was 80 g, and the initial moisture content was about 10% (given the moisture content, the loss of organic mass during decomposition is quite small). At high temperatures, the briquettes are brittle, which may be associated, for example, with a change in the distribution of properties across the packing height.

Figure 3 (see also Fig. A2 in Appendix) shows the calculated temperature dynamics at different points (the

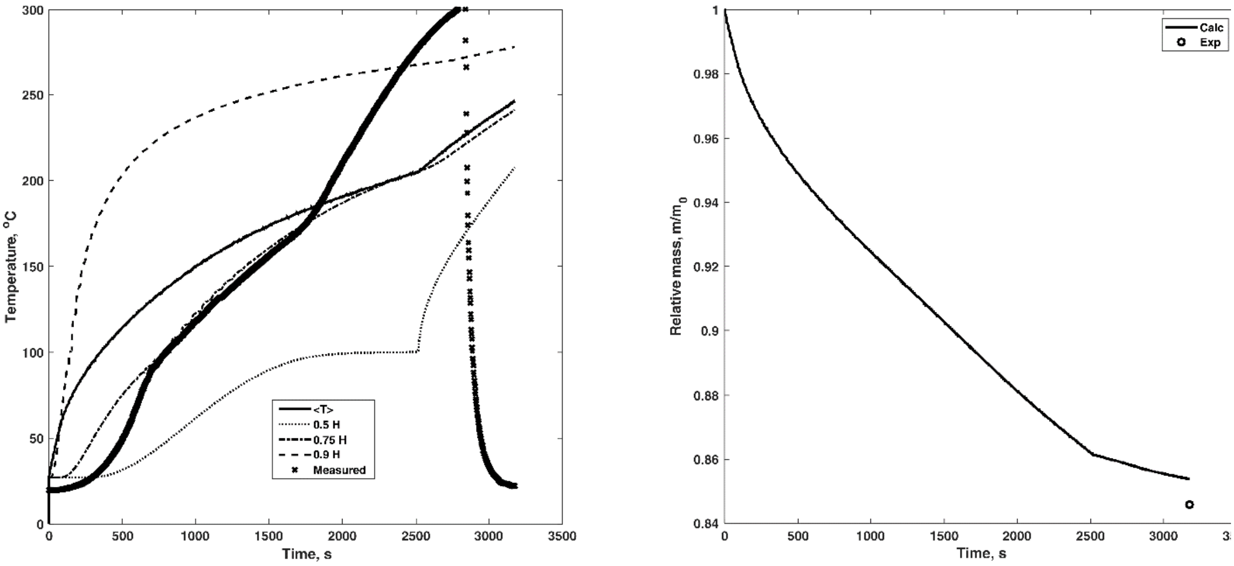

Fig. 3. The dynamics of temperature inside the samples (left) and their mass loss (right) for experiment No. 1 (300°C, no residence time). The markers indicate the measured values.

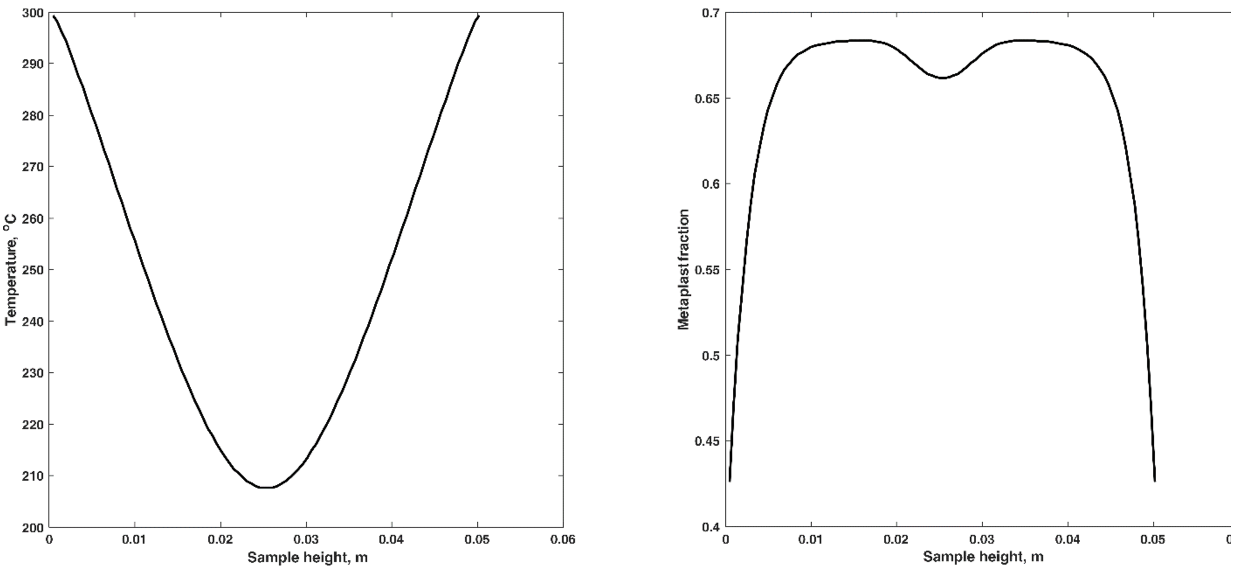

Fig. 4. The calculated distribution of the temperature (left) and softened coal mass fraction (right) along the sample height for experiment No. 1 (300°C).

center of the sample, a quarter of the height, and the near-surface layer) on the left side. The mass average temperature (<*T*>) is also presented. The temperature of the phase transition of water stands out on all the graphs: drying makes a significant contribution to the creation of high temperature gradients in the sample (as well as to the overall mass loss). The sharp decrease in temperature at the end of each experiment is caused by the removal of the thermocouple from the packing before pressing. Due to significant thermal inertia, the temperature distribution inside the packing is "preserved" for a significant time, sufficient to remove the samples from the muffle furnace and obtain briquettes.

Figure 3 shows that the mathematical model reproduces the mass loss of the samples quite accurately. Comparison of temperatures demonstrates a qualitative agreement (which can be attributed to various factors, ranging from neglected convective transfer processes inside the packing to a simplified mechanism of chemical transformations). A major source of error is the uncertainty of the thermophysical properties of the coal organic mass throughout the conversion process. With a rise in heating temperature, the differences between measurements and modeling results decrease.

Despite the differences between the measured and calculated curves, the model proves to be a reliable tool for estimating the thermal state of coal packing. The distribution of temperature and metaplast at the end of the experiment can be seen in Fig. 4 (also see Fig. A3 in Appendix). The general patterns of the packing heating are as follows. The temperature gradient is significant for all cases and ranges from 30 to 90°C per half-height of the

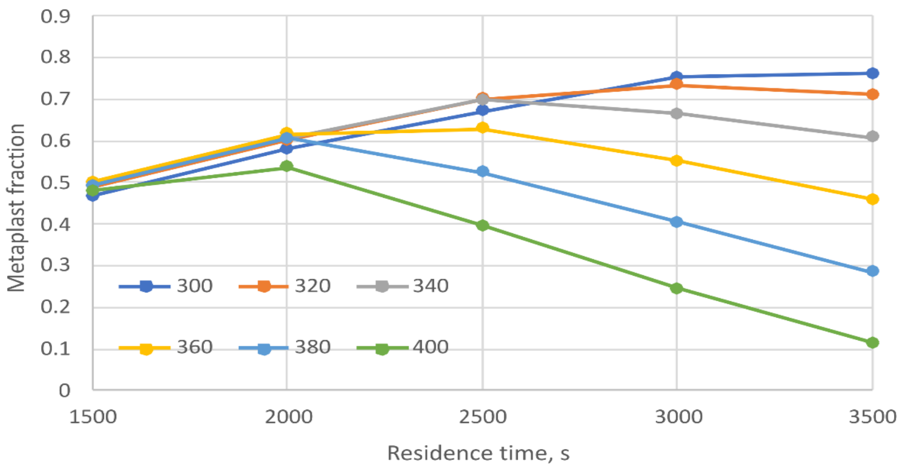

Fig. 5. The dependence of organic mass in plastic state mass fraction on residence time and maximum temperature (numbers in the Figure, °C)

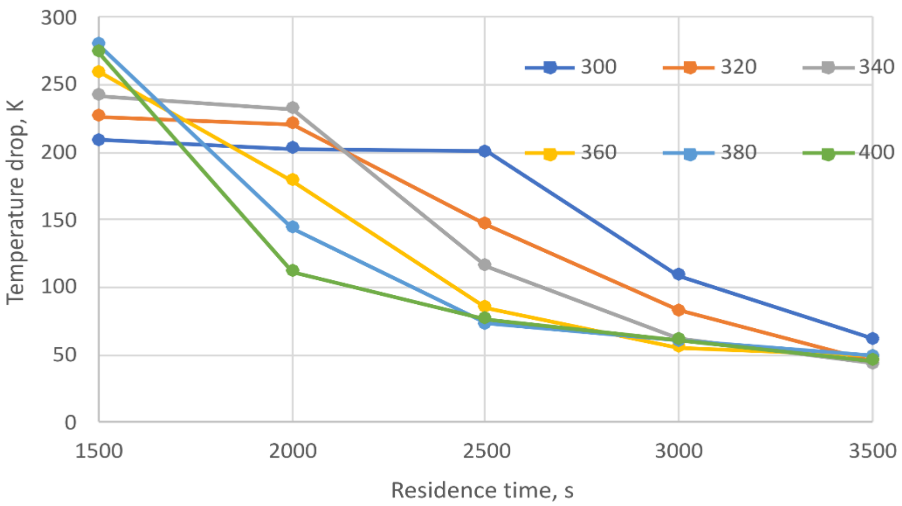

Fig. 6. The dependence of maximum temperature difference across the packing on residence time and maximum temperature (numbers in the Figure, °C).

sample. This variation in temperature entails heterogeneity in the pyrolysis degree. When the heating temperature and residence time increase, the coal mass at the workpiece boundaries almost completely turns into semi-coke, leading to the production of brittle briquettes upon pressing. In contrast, at low temperatures and short residence times, the workpiece may not have sufficient time to achieve the required conversion.

Thus, an optimization problem arises concerning the selection of thermal conditions for heating coal packing prior to the pressing process.

V. Results and Discussion

The model was used to calculate the pyrolysis process of coal packing (with a weight of 80 g and a fixed height) across various maximum temperatures and heating intervals. For simplicity, we assumed that the gas temperature in the muffle furnace rose linearly at a rate of 10 K/min until achieving the maximum temperature, at which point it remained constant. The dependences for the proportion of softened mass and the maximum temperature difference are demonstrated in Fig. 5 and 6. Expectedly, the decomposition degree increases as the maximum temperature rises. With a heating time of up to 2000 s, the curves are close, but a notable decline in the fraction of organic mass in the plastic state occurs at high temperatures. At the same time, as seen in Fig. 6, the temperature difference across the coal particle layer gradually decreases.

The regions with a slightly changing high temperature gradient correspond to the drying stage [46]. The drying stage significantly overlaps with decomposition of the organic matter of coal. The presented model does not factor in possible cross-effects (e.g., the effect of water vapor on the dynamics of release and the composition of the products), therefore, the effect of drying is reduced to the thermal interaction between the phase transition and heat transfer processes. At long heating times, the temperature gradient diminishes, resulting in values around 50–100 K at 3000 s, similar to those observed in the previous Section.

To assess the heterogeneity of the distribution of coal mass in the plastic state across the packing height, the following criterion can be proposed:

$$F = \frac{M\left(t_{end}, x\right) - M\left(t_{end}, x\right)}{E\left[M\left(t_{end}, x\right)\right]},$$

where $M(t, x)$ is the local content of the coal mass in the plastic state and E is the estimate of the mean value. Thus, the heterogeneity criterion is the range of values normalized to the mean value. The dependence of heterogeneity on the pyrolysis conditions is shown in Fig. 7. Heterogeneity increases with temperature, albeit non-monotonically, at heating periods of up to 2000 s. The choice of a high temperature leads to considerable packing heterogeneity, making the briquettes extremely unstable after pressing. However, it is impossible to unambiguously select the optimal conditions from the results of numerical modeling. Even for the maximum heating temperature of 400°C, there can be a range of conditions (at shorter heating times) within which acceptable workpiece homogeneity can be expected. These results need to be verified experimentally.

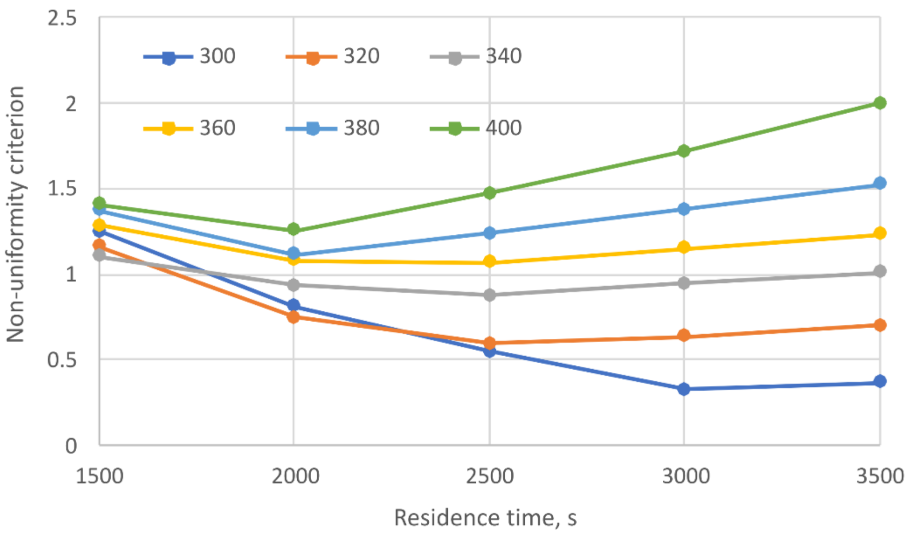

Fig. 7. The dependence of the heterogeneity criterion on residence time and maximum temperature (numbers in the Figure, °C).

A more significant outcome of the study is the development of a mathematical model of heat transfer processes and physicochemical processes in coal packing. This model not only qualitatively reproduces the heating curves but also provides a highly accurate estimation of the final mass. Such a tool (given corrections for the reactive and thermal properties of materials, as well as a more detailed consideration of processes within the packing) can be used to find optimal conditions for thermal briquetting of coals. In addition to mechanical strength, it is also crucial to consider energy consumption, which increases with long heating times. The development of new, highly efficient schemes with coal pyrolysis can become one of the ways to reduce emissions and the carbon footprint of semi-coke production.

VI. Conclusions

The paper presents the results of experimental measurements and numerical calculations achieved when studying the processes of heating and pyrolysis of coal packing before pressing them into briquettes. The findings reveal that briquettes produced at heating temperatures of 375–400°C are brittle. To analyze the causes behind this, a simplified mathematical model was developed to estimate the degree of the composition and temperature heterogeneity within the briquette during laboratory heating. The calculation results indicate that with an increase in temperature and heating time, the degree of coal conversion into semi-coke rises, which deteriorates the quality of the packings. Variant calculations allow us to determine the range of heating conditions for pre-treatment of coal before briquetting.

A crucial strand for further research is the consideration of processes within the particles. The sintering of particles during pressing relies heavily on adhesion, making it essential to have comprehensive information on the surface state. Various modifications of the layer model have been proposed to consider the processes within the particles [47]. Integrating chemical reactions with transfer processes and solid mechanics, especially in coal processing, needs a more detailed analysis, additional experiments, and new theoretical approaches.

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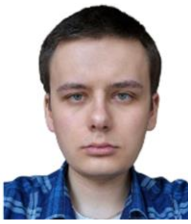

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