EXPERIMENTAL INVESTIGATION OF THERMAL CONDUCTIVITY AND HEAT CAPACITY OF COAL–WATER FUEL

V. A. Pinchuk,1,* T. A. Sharabura,1 & A. V. Kuzmin2,3

1National Metallurgical Academy of Ukraine, Dnepropetrovsk, Ukraine
2Institute for Engineering Thermophysics, National Academy of Sciences of Ukraine, Kiev, Ukraine
3Scientific-Production Innovation Company “Triacon”, Dnepropetrovsk, Ukraine

*Address all correspondence to: V. A. Pinchuk,
E-mail: valeriya.pinchuk@triacon.org

The paper is devoted to the study of the thermophysical properties of a coal–water fuel produced from high-ash coal or low-reactive coal. The thermal conductivity coefficient of the coal–water fuel was determined by combining a physical experiment with numerical modeling. It is shown that the thermal conductivity coefficient of the coal–water fuel varies from 0.41 to 0.81 W/(m·K) and its value increases with temperature. These values are significantly higher than the value of the same coefficient of natural coal. The coefficient depends on the metamorphic stage of the coal and on the amount of mineral impurities and water contained in the fuel. It was also determined that an increase in the fraction of mineral impurities in coal up to 10% leads to an increase in the thermal conductivity coefficient value to 9–10%. An increase in the water fraction in the coal–water fuel can lead either to an increase or to a decrease in the value of the thermal conductivity coefficient. The heat capacity of the coal–water fuel was investigated by using a calorimetric method. It is found that the heat capacity value of the coal–water fuel varies from 3.5 to 6.5 kJ/(kg·K). The value increases with temperature and depends on the fractions of mineral impurities and water in the fuel. The dependences of the thermal conductivity coefficient and heat capacity value of the coal–water fuel produced from coal of different metamorphic stages on the percentage fractions of water and coal phases in the fuel suspension and on the amount of mineral impurities are obtained from the analysis of experimental data.

KEY WORDS: coal–water fuel, thermal conductivity coefficient, heat capacity, coal metamorphic stage, experimental investigations, numerical modeling

1. INTRODUCTION

The coal–water fuel (CWF) is a disperse fuel system consisting of fine-dispersed coal (60–70%), water (39–29%), and a special plasticizer (≈1%). CWF has features that allow it to be used in various energy units of power plants instead of a traditional solid, liquid, or a gaseous fuel.
Mineral impurities, hazardous substances, and other undesirable components can be removed from coal in the process of CWF production. Also different chemical additives can be added to CWF to form the features of the fuel needed by the user, for example, to fix sulfur, when using coal with a high sulfur content or to increase ash melting temperature, when there is a risk of boiler slugging, etc. (Maltsev et al., 2014; Delyagin et al., 1994). Quite a low-emission thermal process satisfying the pollution level requirements can be organized by correctly choosing the fuel composition and appropriate thermal processing of CWF (i.e., direct burning, gasification, fluidized bed combustion, etc.) (Pinchuk, 2014b). Furthermore, there are possibilities of rationally using the CWF’s mineral part by extracting rare elements from ash and exhaust gases, producing materials for road construction, etc. during integrated thermal processing of fuel (Pinchuk and Potapov, 2009).

The implementation of integrated technology of using CWF makes it possible:

• to extend the source base of fuel for power engineering and industry due to the use of low-grade coals and wastes of coal enrichment plants;
• to decrease emission of pollutants and greenhouse gases;
• to clean vast territories from coal enrichment waste, to stop the contamination of the environment by them, to clear those territories for useful application;
• to optimize fuel and energy balances of enterprises by using criteria of minimum natural gas consumption;
• to minimize the cost of energy;
• to provide for the self-sufficiency of heat power for coal-mining and coal-enrichment plants.

As mentioned above, CWF is a disperse system. So, its thermophysical, electric, and rheological properties differ significantly from the properties of constituent substances. The characteristic feature of disperse systems is the presence of a large inter-phase surface and surface phenomena, i.e., adsorption, particle interaction, electrical double layer, etc. As a result, disperse systems have special molecular-kinetic properties and differ in many physical and chemical characteristics from heterogeneous systems of the same composition (Ulitin et al., 2007). It is necessary to know all the properties of CWF for using this fuel efficiently in power engineering and industrial applications with maximum environmental safety. Many researches are presented in different papers devoted to investigation of the rheological characteristics of CWF and of the influence of various factors and parameters on them. At the same time, there are almost no data on the thermophysical properties of CWF and their dependences on different parameters. However, the thermophysical characteristics of CWF define the choice of technological processes and designing solutions. They influence the energy parameters of equipment and also the operating modes of power generating facilities. Usually the thermal properties of CWF are set by the regularity of additivity in the carrying out calculation of the thermal processing of CWF (Popov et al., 1995). But this is incorrect, as will be shown below.
The thermal conductivity coefficient and heat capacity are important data for thermal processing of fuel. Moreover, it is very important to know both the values of these parameters, and their correlations with temperature changes, because various characteristics of the fuel combustion process (technological and constructional, as well as the modes) depend on them.

The physical and chemical properties of coal change in a wide range due to the different stages of metamorphosis and the presence of various additional substances in its content. Because of the fact that CWF can be made of different types of coal and also of coal enrichment wastes, the thermophysical properties of the fuel produced vary greatly, as well as heat transfer processes in CWF.

The thermal conductivity coefficient of coal lies in the range 0.11–0.25 W/(m·K) and depends on different factors, as described above. The coal structure is porous. Addition of water to dispersed coal increases the thermal conductivity of coal powder as the air in the pores and between the particles is replaced by water, and the thermal conductivity coefficient of water is significantly higher than that of air. Moreover, the effect of the surface forces leads to the binding of the coal particles, so that the total thermal resistance of material decreases (Agroskin, 1969, 1980; Aronov and Nesterenko, 1960; Lipovich et al., 1988).

The heat capacity of coal changes from 0.67 to 2 kJ/(kg·K). This parameter grows linearly with increase in the coal moisture content. This is due to the fact that the heat capacity of water is significantly higher than the heat capacity of the organic matter of coal (Agroskin, 1969, 1980; Aronov and Nesterenko, 1960; Lipovich et al., 1988).

At the present time, the kinetic and thermodynamic theory allows one to predict various characteristics of gases and solids including their thermophysical properties. As regards the thermal conductivity and heat capacity of disperse systems, multicomponent liquids, and suspensions, a global theory that would describe their properties is not available. So, one has to use an experimental method to obtain data on the thermophysical properties of CWF as a disperse system for carrying out an analysis and generalization, and to define the regularities of heat transfer processes in it.

2. THERMAL CONDUCTIVITY OF CWF

Many techniques have been developed for determining the thermal conductivity coefficient. Most of them operate well in normal pressure conditions. Our aim was to determine the thermal conductivity coefficient in the temperature range from 20 to 250°C most abundant in industrial and power engineering applications. Due to the presence of water in CWF composition, researches at temperatures higher than 100°C should be carried out at increased pressure values and therefore the experimental working section should be sealed for this reason, which limits the use of many methods of determination.
As noted in (Pinchuk, 2014a), preference is given to using a combination of physical experiment with numerical modeling for achieving the best results in experimental researches with minimum expenses of time and resources.

A comparison method of determining the thermal conductivity coefficient was accepted as the method of a physical experiment. Variations of this method are described in detail in (Chirkin, 1957). In essence, the core of this method is to place the material investigated and the standard material into identical heat transfer conditions at the same time. During the experiment temperature measurements are made in both cases. Then, by using the data for the standard material the heat transfer process parameters are calculated. In the simplest form of one-dimensional thermal conductivity the heat flux through the standard material is calculated. This value of the heat flux is then used for calculating the thermal conductivity coefficient of the material investigated.

In our case, due to the complexity of the experimental facility and the necessity of its sealing it was not possible to use one-dimensional model for calculations. However, due to the fact that the experimental setup is fully axisymmetric, we could limit the model dimensions to two dimensions. So, we used the core of comparison method. Also it was modified to fit the time division procedure (Pinchuk, 2014a).

During the experiment, we measured temperatures at the characteristic points of the working section, and then the solution of the thermal conductivity inverse problem was performed.

For the solution of the inverse problem it was necessary to define a number of parameters, such as boundary conditions, some physical characteristics, and specific features of the real heat transfer process. Those data were determined directly during experimental and numerical investigations of the heat transfer process by using a standard material.

The experimental setup for determining the thermal conductivity coefficient of CWF has been developed. It consists of the working section, measurement equipment, and a semi-automated control system. The core of the working section is presented in Fig. 1.

It consists of heater 1, upper 2 and bottom 3 steel flanges, and cooler 4. Copper discs 5 and 7 are attached to both flanges.

Heater 1 is made from nichrome wire wound around a massive copper cylinder. The cylinder is heat insulated on all sides, except for the bottom. The side surfaces of both flanges are heat insulated also. The insulation is not shown in the figure. The bottom of the heater is attached to the upper flange 2. To form the cell for the sample investigated 6 there is PTFE bushing 8 installed between the flanges.

Before the experiment, the processing cell 6 is filled with investigated material. When the section is assembled, the bottom surface of copper disk 5 contacts with the investigated material. There were not air gaps between the surface of copper disks 5 and 7 and the investigated material. When the construction is assembled, it is sealed and resists the inside pressure of up to 3 MPa.
Labels 9–16 point the locations of thermocouples: 12 and 13 are the thermocouples sited to get the temperatures of the copper disks surfaces, which contact directly with the material investigated. Due to the very high value of the thermal conductivity coefficient of copper, the temperatures of disk surfaces can be taken as the temperatures of the outside surfaces of investigated sample. Special channels were made for installing the thermocouples as shown in the figure. Thermocouples 11 and 14 are sited on the bottom surface of flange 3 and upper surface of flange 2, respectively. Their data was used as boundary conditions for numerical simulation. Thermocouples 9, 10, 15, and 16 are installed on the sides of flanges 2 and 3 in diametrically opposite locations to determine radial heat transfer.

All thermocouples were made from Chromel–Alumel pairs with wire diameter of 0.2 mm. Individual calibration procedures were carried out for each of them and individual correlation equations \( t = f(U) \) were established. The temperature range of thermocouple calibration was 20–250°C.

The heat flux from heater 1 passes through the sample investigated in cell 6 to cooler 4. Some amount of heat passes around cell 6 through flanges 2 and 3. Heater power was controlled by an automated system. Cooler 4 is the aluminum radiator with a fan attached. The fan speed can change from 0 to 300 rpm to provide the cooling level needed. Thermocouples data collected by TopSCCC’s EX-9018 input module operated in the analog input mode. The time interval between data collection requests is 0.1 Hz. At one time all thermocouples inputs are requested. Thermocouples data is transferred to the computer-based measurement and control unit. The total observational error of the measurement system was 0.85–1%.

FIG. 1: Central part (core) of the working section
During the experimental process the power of preset level is supplied to heater 1, and the temperature data from thermocouples and environment temperature near the experimental facility are recorded permanently. At the moment of stabilization of temperatures at all measurement points the thermocouples data are fixed. These fixed temperature data are used for numerical calculations.

As noted above, the inverse problem was solved to determine the thermal conductivity coefficient of the sample material investigated with recorded temperature data. For solving the inverse problem, the method of repeated iterative solution of the thermal conductivity direct problem (Luikov, 1967) was chosen. For the optimization of the iteration numbers, the golden section search (Moiseev et al., 1978) was used. The average of deviation between the measured and calculated temperatures at all measurement points was used as optimization criteria.

The tridiagonal matrix algorithm, also known as the Thomas algorithm, was realized to numerically solve the direct thermal conductivity problem.

An orthogonal grid with a step of 0.5 mm on both coordinates was constructed to perform calculations. The geometrical dimensions of the calculated area were equal to the real facility.

At the first step of the physical experiment a standard sample was investigated. We use distilled water as a standard material. The results of experimental investigation in the temperature range from 40°C to 210°C made it possible to determine the boundary conditions, thermophysical characteristics of some elements of the experimental setup, and the specific features of the real heat transfer process.

The adjustment coefficients for convective heat transfer on the outside boundary of the experimental setup were calculated using the data obtained. Thereafter the testing of the experimental setup and methodology were carried out with a standard material for verification. Deviation of the thermal conductivity coefficient of distilled water determined in the verification experiments from real data was ±1–3%.

The next step was the experimental investigation of the thermal conductivity of CWF. Investigations were carried out with the fuel prepared from the coal of various metamorphic stages. The technology of producing CWF included the phases of coal wet grinding in a ball mill and cavitational processing. During the process of CWF production the maximum fraction of solid content, the minimal viscosity of the composition, and the needed sedimental stability of the fuel were provided. The sodium lignosulfonat was used as a plasticizer. The characteristics of CWF samples investigated are presented in Tables 1–3.

The values of the thermal conductivity coefficient of CWF $\lambda$ obtained during the experiments are presented in Fig. 2.

The analysis of the data in Fig. 2 shows that the thermal conductivity coefficient of CWF is significantly higher than this parameter of coal itself and lies in the range from 0.41 to 0.81 W/(m·K). Its value increases with temperature in that range for all
**TABLE 1:** Basic content of CWF samples

<table>
<thead>
<tr>
<th>Type of Source Coal by Metamorphic Stage</th>
<th>Fraction of Solid, %</th>
<th>Source Coal Characteristics</th>
<th>Source Coal Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Fraction of Mineral Impurities $A^d$, %</td>
<td>Fraction of Moisture $W^w$, %</td>
</tr>
<tr>
<td>Brown</td>
<td>58</td>
<td>23.31</td>
<td>18.5</td>
</tr>
<tr>
<td>Flame (long-flame)</td>
<td>65</td>
<td>36.8</td>
<td>12.23</td>
</tr>
<tr>
<td>Gas (gaseous)</td>
<td>65</td>
<td>60.8</td>
<td>3.48</td>
</tr>
<tr>
<td>Fat (bituminous)</td>
<td>70</td>
<td>50.5</td>
<td>4.11</td>
</tr>
<tr>
<td>Nonbaking (lean)</td>
<td>68</td>
<td>18</td>
<td>4.48</td>
</tr>
<tr>
<td>Anthracite</td>
<td>70</td>
<td>44.1</td>
<td>5.16</td>
</tr>
</tbody>
</table>

Note: The superscripts denote the following: d, "in/to the dry" coal mass; w "in/to the working" (full) fuel mass (organic matter + mineral impurities + water); daf "in/to the dry organic matter" of coal – no water, no mineral impurities.

**TABLE 2:** Chemical composition of mineral impurities, %

<table>
<thead>
<tr>
<th>Component</th>
<th>Brown</th>
<th>Flame</th>
<th>Gas</th>
<th>Fat</th>
<th>Nonbaking</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO$_2$</td>
<td>47.0</td>
<td>52.0</td>
<td>52.3</td>
<td>53.0</td>
<td>49.9</td>
<td>51.4</td>
</tr>
<tr>
<td>Al$_2$O$_3$</td>
<td>18.6</td>
<td>24.0</td>
<td>25.5</td>
<td>21.7</td>
<td>22.3</td>
<td>22.4</td>
</tr>
<tr>
<td>Fe$_2$O$_3$</td>
<td>11.6</td>
<td>14.0</td>
<td>12.4</td>
<td>16.8</td>
<td>17.5</td>
<td>15.3</td>
</tr>
<tr>
<td>CaO</td>
<td>18.2</td>
<td>2.8</td>
<td>3.2</td>
<td>3.2</td>
<td>4.0</td>
<td>3.8</td>
</tr>
<tr>
<td>MgO</td>
<td>2.3</td>
<td>1.6</td>
<td>1.3</td>
<td>1.6</td>
<td>1.6</td>
<td>1.6</td>
</tr>
<tr>
<td>K$_2$O</td>
<td>0.7</td>
<td>4.0</td>
<td>3.2</td>
<td>2.0</td>
<td>2.8</td>
<td>3.3</td>
</tr>
<tr>
<td>Na$_2$O</td>
<td>0.7</td>
<td>0.8</td>
<td>1.5</td>
<td>1.0</td>
<td>1.2</td>
<td>1.5</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>0.9</td>
<td>0.8</td>
<td>0.6</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
</tbody>
</table>

**TABLE 3:** Distribution of particle sizes in the solid fraction of CWF

<table>
<thead>
<tr>
<th>$d$, μm</th>
<th>wt.%</th>
</tr>
</thead>
<tbody>
<tr>
<td>250–100</td>
<td>45.5</td>
</tr>
<tr>
<td>100–80</td>
<td>13.3</td>
</tr>
<tr>
<td>80–20</td>
<td>25.1</td>
</tr>
<tr>
<td>20–10</td>
<td>6.3</td>
</tr>
<tr>
<td>10–5</td>
<td>7.3</td>
</tr>
<tr>
<td>5–0</td>
<td>2.5</td>
</tr>
</tbody>
</table>
samples investigated. The dependence of the thermal conductivity coefficient of distilled water is added to the graph in Fig. 2 for comparison.

At the first glance there is no any correlation between the source coal metamorphic stage and the value of the thermal conductivity coefficient. It seems logical that the metamorphic stage of coal, fraction of water (moisture), and the amount of mineral impurities all are affecting the thermal conductivity coefficient of the fuel. So, the

**FIG. 2:** The thermal conductivity coefficient as a function of temperature of CWF produced from coals of different metamorphic stages
next phase of experimental investigation was devoted to the determination of the mineral impurities and water fraction in the CWF content that affect the thermal conductivity of it.

### 2.1 Influence of Mineral Impurities

Mineral impurities exert a significant influence on the thermal conductivity of coals. The value of the thermal conductivity coefficient of the organic matter of coal is much smaller than that of the thermal conductivity coefficient of mineral impurities. On increase in the fraction of mineral impurities in coal, its density grows, which leads to an increase in the thermal conductivity too. For example, as shown in (Agroskin, 1980), at a temperature of 100°C the coal with mineral impurities amounting to 7.7% has the thermal conductivity coefficient equal to 0.116 W/(m·K). Coal of the same metamorphic stage but with mineral impurities equal to 25.2% has the thermal conductivity coefficient of 0.128 W/(m·K). In general, it is possible to assume that each additional 10% of mineral impurities fraction in the coal content increase the thermal conductivity coefficient of coal by 5.5–5.7%.

The influence of the fraction of mineral impurities in the source coal, from which CWF is produced, on the CWF thermal conductivity coefficient was studied experimentally. Figure 3 presents some results of these experiments with CWF samples, produced from anthracite. For coal of this metamorphic stage the fractions of mineral impurities in the coal were $A_w^w = 1.5\%$ and $A_w^w = 30.5\%$.

As can be seen from the figure, on average the thermal conductivity coefficient of CWF with a higher content of mineral impurities is larger by about 35–40%. The re-

![FIG. 3: Effect of the fraction of mineral impurities on the thermal conductivity coefficient of the anthracite CWF](image)
results for samples from other coal metamorphic stages are similar to these data. From a detailed analysis of the experimental results it was concluded that each 10% increase of the fraction of mineral impurities in CWF lead to an increase in its thermal conductivity by 9–10%. This correlation does not depend on the coal metamorphic stage.

2.2 Influence of Moisture (Water) Content

The fraction of water in CWF can lie in the range from 25 to 50%, which, of course, affects its thermophysical properties. Numerous data were obtained in our work regarding the influence of water fraction on the thermal conductivity of CWF for all coal metamorphic stages (listed in Table 1). All data are valid in the temperature range from 40 to 200°C.

As an example, some results of the experiments are shown in Fig. 4. We selected only most characteristic results from our wide-ranging database to show the specifics of the influence. In Fig. 4, the data given with the same color correspond to coal of the same metamorphic stage. The dark points and solid lines indicate the results for lesser water content, and vice versa, the light points and dashed lines indicate larger water fraction in the CWF.

The specific feature of the influence of water fraction is clearly visible in Fig. 4. It is that the thermal conductivity coefficient of CWF is less than this parameter of water at the same temperature. An increase in the water fraction in the fuel leads to

![FIG. 4: Effect of the fraction of water on the thermal conductivity coefficient of CWF: 1, 2) anthracite CWF, water fraction is equal to 30% and 45%, respectively; 3, 4) gas coal’s CWF, water fraction is equal to 35% and 42%, respectively; 5, 6) nonbaking (lean) coal’s CWF, water fraction is equal to 32% and 45%, respectively; 7) known data for distilled water](image-url)
an increase in the thermal conductivity coefficient of the CWF (see series labeled 5 and 6), and vice versa, in the case where the thermal conductivity coefficient of fuel is larger than that of water, the drop in the thermal conductivity coefficient occurs on addition of water to CWF (series 1–2 and 3–4 relate to this case).

Furthermore, a qualitative analysis of experimental results shows that the difference between the values of the thermal conductivity coefficient of CWF with a larger and lesser fraction of water in it depends on the absolute difference between the thermal conductivity coefficient of CWF and that of distilled water.

This is clearly demonstrated by the data series 1–2 and 3–4 in Fig. 4. As is seen in the figure, the data on anthracite CWF with lesser water content (series 1) are located farther away from distilled water data (series 7), as compared to the results for gas coal CWF (series 3). Increase in the water fraction causes greater displacement of the results for anthracite CWF (series 2) than for gas coal CWF (series 4). Thus, the thermal conductivity coefficient of CWF tends to the value equal to the thermal conductivity coefficient of distilled water on increase in the water fraction in CWF. It seems quite logical.

A quantitative analysis of experimental data in regard to the influence of various CWF parameters on its thermal conductivity coefficient made it possible to generalize all data by the following expression:

\[ \lambda = \lambda_{\text{eff}} \cdot f(W) \cdot f(A) \cdot f(M) + \lambda_{w} \cdot W_{w}, \quad (1) \]

where \( \lambda_{\text{eff}} \) is the effective thermal conductivity coefficient of coal \([\text{W/(m·K)}]\); \( f(W) \) is the function to account for the effect of water fraction in CWF; \( f(A) \) is the function to account for the effect of the fraction of mineral impurities in CWF; \( f(M) \) is the function to account for the effect of coal metamorphic stage; \( \lambda_{w} \) is the thermal conductivity coefficient of distilled water = \( f(t) \) \([\text{W/(m·K)}]\); \( W_{w} \) is the moisture of CWF, mass fraction.

The effective thermal conductivity coefficient of coal is calculated by the equation

\[ \lambda_{\text{eff}} = \lambda_{c} \cdot (1 - A_{d}) + \lambda_{m,i} \cdot A_{d}. \quad (2) \]

Here \( \lambda_{c} \) is the thermal conductivity coefficient of the organic matter of coal by \( t = 20^\circ\text{C} \) (see Table 4) \([\text{W/(m·K)}]\); \( \lambda_{m,i} \) is the thermal conductivity coefficient of mineral impurities by \( t = 20^\circ\text{C} \) [average value for mineral impurities contained in the Ukrainian coals is 19.8\cdot10^{-2} \text{ W/(m·K)}]; \( A_{d} \) is the fraction of mineral impurities in CWF, mass fraction.

The function accounting for the effect of the fraction of water in CWF \( f(W) \) is determined by the following empirical equation:

\[ f(W) = k_{w} \cdot (1 - W_{w})^{1.21}, \quad (3) \]

where \( k_{w} \) is the empirical coefficient taking into account the influence of temperature \( t \). It can be calculated by the expression derived in processing the experimental data:
The metamorphic stage of CWF’s coal is calculated by our empirical formula

$$f(M) = k_m t + b_m,$$

where $k_m$ and $b_m$ are the empirical coefficients (their values calculated from the processed experimental results are given in Table 4) and $t$ is the temperature [$^\circ$C].

The function $f(A)$ accounting for the effect of the fraction of mineral impurities in CWF is determined by the following empirical equation:

$$f(A) = k_a A^c + b_a,$$

where $k_a$ and $b_a$ are the empirical coefficients accounting for the influence of temperature $t$. They can be calculated from the dependences given below which were derived by processing experimental data:

$$k_a = 0.67 + 1.66 \times 10^{-4} | t - 225 |^{1.4},$$

$$b_a = 0.71 + 7.5 \times 10^{-5} | t - 225 |^{1.4}.$$

In Eqs. (7) and (8) the symbol $|...|$ denotes the magnitude (absolute value).

Empirical expressions (1)–(8) together with the data from Table 4 can be used to calculate the thermal conductivity coefficient of CWF produced from various coals. The equations cover all the main coal metamorphic stages with the content of mineral impurities $A^d$ in the range 0.5–60%, water fraction in the fuel composition $W^w$ lying in the range 25–50%, and the temperature ranging from 40 to 200$^\circ$C.

The solid and dashed lines in Figs. 2–4 were calculated by the system of equations (1)–(8), except for the line for the thermal conductivity of water. Good correspondence is observed between the experimental results and calculated data.

As mentioned above, there are several theoretical approaches to the determination of the thermal conductivity of mixtures and compositions. Until our researches were

### TABLE 4: Values of empirical coefficients for calculation of the thermal conductivity of CWF

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Brown</th>
<th>Flame</th>
<th>Gas</th>
<th>Fat</th>
<th>Nonbaking</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_m \cdot 10^4$</td>
<td>14.4</td>
<td>6.31</td>
<td>0.91</td>
<td>1.6</td>
<td>9.3</td>
<td>0</td>
</tr>
<tr>
<td>$b_m$</td>
<td>0.27</td>
<td>0.79</td>
<td>0.81</td>
<td>0.66</td>
<td>0.49</td>
<td>1</td>
</tr>
<tr>
<td>$\lambda_c \cdot 10^2$, W/(m·K)</td>
<td>17.5</td>
<td>11.6</td>
<td>11.4</td>
<td>11.9</td>
<td>13.4</td>
<td>14.9</td>
</tr>
</tbody>
</table>

$$k_w = 20 - 34 \left( t + 150 \right)^{-0.15}.$$
carried out, these approaches were used to calculate the thermal conductivity coefficient of CWF. We compared the results for the thermal conductivity coefficient of CWF calculated by the theoretical expression from (Agroskin, 1980; Chudnovsky, 1962; Dulnev and Zarichnyak, 1974) with the real data, obtained in our experiments. The results of comparison for anthracite CWF are presented in Fig. 5.

It is clearly seen that A. Eucken's and G.N. Dulnev's expressions and the regularity of additivity provide values 2–2.5 times lower than the real data. Calculations by A. F. Chudnovsky's equation yield the value for the thermal conductivity coefficient by 60% higher than the data obtained in experiments. So, all of them cannot be used for calculating the thermal conductivity of CWF.

3. EXPERIMENTAL INVESTIGATION OF THE HEAT CAPACITY OF CWF

According to the recommendations given in (Preobrazhensky, 1978; Grigoryev and Zorin, 1983; Gerashchenko et al., 1984), to determine the heat capacity of CWF we used the calorimetric method of measurement. A special experimental setup was designed for the purpose. The schematic diagram of the experimental setup is shown in Fig. 6.

The working section of the experimental setup is an adiabatic calorimeter. Its container 1 is made from brass and is sealed by lid 2. Thermocouple 3 passes through lid 2

---

**FIG. 5:** Comparison of CWF thermal conductivity coefficient values calculated by different expressions: 1) A. Eucken's expression (Agroskin, 1980); 2) G. N. Dulnev's expression (Dulnev and Zarichnyak, 1974); 3) regularity of additivity (Popov et al., 1995); 4) expressions (1)–(8) together with the data of Table 4 — line, experimental data — dots; 5) A. F. Chudnovsky's expression (Agroskin, 1980)
inside the container. When it is assembled, the construction is sealed and maintains the inside pressure of up to 3 MPa.

There is heater 4 wound on the outside cylindrical surface of the container. The heater is made from nichrome wire 0.25 mm in diameter.

On the outside surfaces of the container, thermocouples are sited for monitoring and controlling heat losses through the surfaces (not shown in the figure).

During the experiment, container 1 is placed into heat-insulated shield 5 and then into a Dewar flask (not shown in the figure).

Heater 4 is controlled by a computer-based automatic system (CBAS) 8 that monitors temperatures of the container outside and inside by means of thermocouples; the electric power is supplied to the heater by ammeter 6 and voltmeter 7.

The steps of the experimental procedure are the following:

1. An investigated sample is weighed on digital scales and is placed into container 5. Lid 2 is sealed, thermocouple 3 is immersed into the sample.
2. The container is warmed up by the heater to the temperature needed for experimental measurements and is kept for some time for temperature stabilization. During the stabilization process, the heater acts as a compensator of heat losses. The data recorded by the thermocouples sited on the outside surfaces of the container are used for monitoring and controlling the stabilization by CBAS 8.
3. After the end of the stabilization process, the temperature $t_1$ measured by thermocouple 3 is recorded by CBAS and the electric power is supplied to the heater during the time interval $\Delta \tau$. In our experimental investigation it required 10 s controlled by CBAS. During this interval the values of electric current $I$ from ammeter 6 and voltage $U$ from voltmeter 7 are recorded also.
4. Then heater 6 starts to work as a compensator of heat losses again and the temperature stabilization process begins, after which the temperature $t_2$ of the investigated sample is recorded by CBAS.
Steps 2–4 are repeated at all temperatures needed. The experimental results were processed with the aid of the known expression for heat capacity:

\[ c = \frac{k_s Q}{m(t_2 - t_1)}, \text{ kJ/(kg·K)} \]

where \( Q \) is the electric energy supply [kJ]. It can be calculated by the formula \( Q = IU\Delta\tau \), where \( I \) [A] and \( U \) [V] are the electric current and voltage recorded at step 3, \( \Delta\tau \) is the time interval [s] from step 3. The quantity \( k_s \) is the system constant determined by verification experiments; \( m \) is the mass of the sample investigated defined at step 1 [kg]; \( t_1 \) and \( t_2 \) are the temperatures of the sample investigated before (step 3) and after (step 4) supply of electric power [°C].

Verification experiments carried out to test the operating modes of the experimental equipment and to determine the system constant \( k_s \) were carried out at the beginning of the experimental investigations. The sample studied was distilled water. Deviation of the experimental data on the heat capacity of distilled water from the known values was ±4%.

Figure 7 presents the results of experimental investigations of the heat capacity of CWF. The CWF produced from coals of various metamorphic stages, listed in Table 1, were investigated. The temperature ranged from 40 to 200°С.

It has been found that the heat capacity of CWF lies in the range 3.5–6.5 kJ/(kg·K). It is larger than the heat capacity of coal itself, whose values change from 0.67 to 2 kJ/(kg·K),

**FIG. 7:** Heat capacity of CWF produced from coals of various metamorphic stages: 1) brown coal; 2) flame coal; 3) nonbaking coal; 4) fat coal; 5) gas coal; 6) anthracite
as was noted in Section 1. Moreover, as it is seen in Fig. 7, the value of the heat capacity of CWF increases as the temperature of a fuel grows.

Like the thermal conductivity coefficient, the heat capacity of CWF depends on different factors, including the metamorphic stage of coal, fraction of mineral impurities in the coal, and the fraction of water in the fuel composition. During the experimental process we investigated the effect exerted by the parameters on the heat capacity of CWF.

### 3.1 Influence of Mineral Impurities on the Heat Capacity of CWF

We have carried out many experiments to understand how the fraction of mineral impurities in CWF affects the heat capacity of the fuel. CWF samples were investigated that differed by the metamorphic stage of coal. For each metamorphic stage we investigated samples with various fractions of mineral impurities. The results of the experimental investigations provide a wide-ranging database. Some of them demonstrate the general regularities presented in Fig. 8. To demonstrate the results, we used CWF samples produced from brown coal (labels 1 and 2) and anthracite (labels 3 and 4), which are characterized by the opposite metamorphic stages.

The values in the parentheses present the percentage mass of the fraction of mineral impurities \( A^d \) in the CWF’s source coal. As can be seen from the figure, the heat capacity of CWF falls when the fraction of mineral impurities increases.

### 3.2 Influence of the Fraction of Water in the CWF Content on the Heat Capacity of Fuel

Like for the thermal conductivity coefficient, there is the dependence of the heat capacity of CWF on the amount of water in the fuel. To establish correlation between

![FIG. 8: Effect of the fraction of mineral impurities on the heat capacity of CWF](image-url)
the fraction of water in CWF and its heat capacity, experimental investigations were carried out.

Some of the results are presented in Fig. 9. Due to the limits of the figure's visible area, we presented only the opposite coal metamorphic stages: brown coal (labels 1, 2) and anthracite (labels 3, 4). The fraction of water in the CWF samples is shown in the parentheses near the labels. Label 5 points to the known dependence for the heat capacity of distilled water.

An analysis of experimental results made it possible to determine that the heat capacity of CWF tends to a value equal to the heat capacity of distilled water as the fraction of water in CWF increases. This observation is in full correspondence with the same regularity displayed by the thermal conductivity coefficient, which is described above. A quantitative analysis of the experimental investigations on the influence of the fraction of water in CWF on the heat capacity of fuel allowed us to generalize the experimental data by the relations given below. The generalization procedure was chosen identical to that of the processing of the thermal conductivity coefficient. Thus, the heat capacity of CWF can be calculated from the following expression:

\[ c = c_{\text{eff}} f(W) f(A) f(M) + c_w W^w, \]  

(10)

where \( c_{\text{eff}} \) is the effective heat capacity of coal [kJ/(kg·K)]; \( f(W) \) is the function accounting for the influence of the fraction of water; \( f(A) \) is the function accounting for the influence of the fraction of mineral impurities; \( f(M) \) is the function accounting for the influence of the coal metamorphic stage; \( c_w \) is the heat capacity of distilled water as \( f(t) \) [kJ/(kg·K)]; \( W^w \) is the fraction of water in CWF, mass fraction.

FIG. 9: Influence of the fraction of water in CWF on the heat capacity of fuel
The effective heat capacity of coal is given by the formula

\[ c_{\text{eff}} = c_c \left(1 - A^d\right) + c_{m,i} A^d, \]  

(11)

where \( c_c \) is the heat capacity of the organic matter of coal [kJ/(kg·K)] (Table 5); \( A^d \) is the fraction of mineral impurities in CWF, mass fraction; \( c_{m,i} \) is the heat capacity of mineral impurities at \( t = 20^\circ \text{C} \) [kJ/(kg·K)]. It can be calculated by the known formula (Agroskin, 1980):

\[ c_{m,i} = \left(0.18 + 7 \cdot 10^{-5} \left[t + 273\right]\right) 4.19. \]  

(12)

The function \( f(W) \) accounting for the influence of the water fraction is calculated by the empirical relation

\[ f(W) = b_w \left(1 - W^w\right), \]  

(13)

where \( b_w \) is the empirical coefficient derived in processing the experimental data:

\[ b_w = 3.63 + 5 \cdot 10^{-6} \left[t - 60\right]^{2.2}. \]  

(14)

The function \( f(A) \) is determined by the formula

\[ f(A) = k_a A^c + b_a, \]  

(15)

where \( k_a \) and \( b_a \) are the empirical coefficients derived in processing the experimental data:

\[ k_a = 0.001t - 0.41, \]  

(16)

\[ b_a = 1.18 - 4 \cdot 10^{-4} t. \]  

(17)

For the influence of the coal metamorphic stage we have

\[ f(M) = b_m - k_m t, \]  

(18)

**TABLE 5**: Heat capacity of the organic matter of coal \( c_c \) for various metamorphic stages of coal, kJ/(kg·K) [adapted from Agroskin, (1980)]

<table>
<thead>
<tr>
<th>Temperature, °C</th>
<th>Brown</th>
<th>Flame</th>
<th>Gas</th>
<th>Fat</th>
<th>Nonbaking</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>1.15</td>
<td>1.12</td>
<td>1.13</td>
<td>1.09</td>
<td>1.00</td>
<td>0.93</td>
</tr>
<tr>
<td>100</td>
<td>1.28</td>
<td>1.33</td>
<td>1.31</td>
<td>1.26</td>
<td>1.17</td>
<td>1.06</td>
</tr>
<tr>
<td>150</td>
<td>1.45</td>
<td>1.43</td>
<td>1.41</td>
<td>1.37</td>
<td>1.28</td>
<td>1.15</td>
</tr>
<tr>
<td>200</td>
<td>1.54</td>
<td>1.56</td>
<td>1.52</td>
<td>1.48</td>
<td>1.39</td>
<td>1.23</td>
</tr>
</tbody>
</table>
where $k_m$ and $b_m$ are the empirical coefficients. Their data were derived in processing of experimental results and are presented in Table 6. The quantity $t$ denotes the temperature [°C].

The ranges of parameters valid for using relations (10)–(18) are

$$W^w = 25–50\%;$$

$$A^d = 0.5–60\%;$$

$$t = 40–200^\circ C.$$  

In Figs. 7–9, all the lines were calculated by using empirical formulas (10)–(18) and the data from Tables 5 and 6, while the dots present the results of experimental measurements. The results of calculation are in very good correspondence with experimental data.

Also we carried out a comparison of some known theoretical approaches used to calculate the heat capacity of wet coal and compositions of melted coal and water given in (Agroskin, 1980). The results of this comparison are presented in Fig. 10.

**TABLE 6:** Values of the coefficients $k_m$ and $b_m$

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Brown</th>
<th>Flame</th>
<th>Gas</th>
<th>Fat</th>
<th>Nonbaking</th>
<th>Anthracite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$k_m \cdot 10^5$</td>
<td>20.7</td>
<td>12.1</td>
<td>6.5</td>
<td>5.5</td>
<td>5.2</td>
<td>4.4</td>
</tr>
<tr>
<td>$b_m$</td>
<td>1.64</td>
<td>1.3</td>
<td>1.08</td>
<td>1.04</td>
<td>1.03</td>
<td>1</td>
</tr>
</tbody>
</table>

**FIG. 10:** Comparison of the heat capacity of CWF calculated by various relations: 1) our formulas (10)–(18); 2) regularity of additivity; 3) I. L. Klendenin's equation (Agroskin, 1980); 4) A.A. Agroskin’s equation (Agroskin, 1980)
Like for the thermal conductivity coefficient it has been proven that the approaches used for the composition of coal and water as well as for wet coal do not provide the realistic values of the heat capacity of CWF.

4. CONCLUSIONS

1. Wide-range experimental investigations for determining the thermal conductivity coefficient and heat capacity of coal–water fuels produced from coals of various metamorphic stages have been carried out. Huge information data were collected on the dependences of the thermophysical properties of CWF on various parameters.

2. It is shown that both the thermal conductivity coefficient and the heat capacity of CWF have higher values in comparison with coal itself. Also it was found that at first sight the fraction of water affects the thermal properties of CWF. However, the detailed consideration allowed us to find the tendency of the values of the thermal conductivity coefficient and heat capacity of CWF approaching the values of these parameters for distilled water on increase in the fraction of water.

3. The empirical equations for calculating the thermophysical properties of CWF produced from coal of various metamorphic stages have been obtained. These equations are valid in the most used ranges of the fractions of water and mineral impurities in CWF for the temperature range from 40 to 200°C.

4. It was shown that using theoretical approaches as well as formulas for wet coal and composition of coal and water does not allow us to obtain realistic values for the thermal conductivity coefficient and heat capacity of CWF.

REFERENCES


