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DETERMINATION OF THERMAL CONDUCTIVITY OF COAL-WATER FUEL BY COMBINING PHYSICAL EXPERIMENTS AND MATHEMATICAL MODELING

The possibility of the use of full-scale experiment in combination with mathematical modeling for solving thermal problems is shown. For the thermal conductivity of coal-water fuel determination it is used combination of the comparison method and the numerical simulation of the inverse heat conduction problem. The numerical solution of inverse heat conduction problem was carried out by multiple numerical solutions of direct heat conduction problem. Optimization of iterations was carried out with the golden section search.

The values of the thermal conductivity of samples of coal-water fuels by the proposed method in the temperature range from 40 to 150 ° C are obtained. It is shown that the thermal conductivity of coal-water fuels varies from 0.41 to 0.82 W/m · K, depending on the grade of the original coal, and it increases within the temperature range investigated, as expected.

Keywords: thermal conductivity, coal-water fuel, experimental facility, mathematical modeling

Introduction

According to its thermophysical, thermotechnical, rheological and electrical properties, coal-water fuel is a fuel type, the characteristics of which differ greatly from those of its constituent substances [1-4]. The choice of technological solutions, designs of installations and units, energy consumption figures, modes of operation depend on the thermophysical properties of the fuel. Data on the specific heat, thermal conductivity and thermal diffusivity of coal-water fuel and their change during the thermal processing are of greatest interest from the standpoint of thermal processing technology, as the duration, the technological parameters and the energy efficiency of the process are largely determined by these properties. Since different types of coal and waste coal may be used to prepare coal-water fuel, the mechanism of heat transfer and thermal properties of the resulting fuel are very diverse [5-7].

Statement of the problem and research objectives

Analytical description of the dependence of the thermal conductivity of coal-water fuel on various parameters is difficult because of the lack of physical model relevant to the real structure of coal-water fuel. This is due to the specific physical and chemical properties of disperse systems, complexity of coal structure and water

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modifications in the layers adjacent to the surface of the particles, and also surface layers of the particles themselves as compared with the structure of the original coal.

Physical experimental methods for determining the thermal conductivity give sufficiently accurate results, but require significant resource and time consuming, in addition, there are difficulties with the technical implementation of the boundary conditions due to the theory of the method.

Methods for determining the thermal properties of materials by means of mathematical modeling are significantly less expensive. However, in the course of mathematical modeling the lack of information characterizing the different physical parameters of the process is present. Therefore generalized analytical expressions and criterial dependences describing thermal processes are applied. This inevitably leads to the deflection of a mathematical model from a real modeling object, and as a consequence, leads to significant errors in the determination of thermal properties.

Therefore now quite an urgent task is to develop better methods to determine thermal conductivity, providing ease of implementation, high accuracy and operating speed. Using a combination of physical experiments and mathematical modeling is one of the effective methods for determination of thermal conductivity.

It is proposed to use the method of comparison, variations of which are described in [5] when carrying out a physical experiment.

Solution of the inverse heat conduction problem by repeated solution of the direct heat conduction problem is used as a method of numerical simulation. In this case the missing information on the boundary conditions, physical parameters and conditions of the real thermal process is determined directly in the course of experimental studies on the standard substance and subsequently used in the mathematical modeling.

Research methodology and analysis of the results

As part of the task to determine the values of the thermal conductivity of coal-water fuels an experimental facility was developed in the department of industrial Heat Power Engineering of the National Metallurgical Academy of Ukraine. The experimental facility consists of the measuring section and the system of control and recording instruments. Scheme of the measuring section of the experimental facility is shown in Fig. 1.

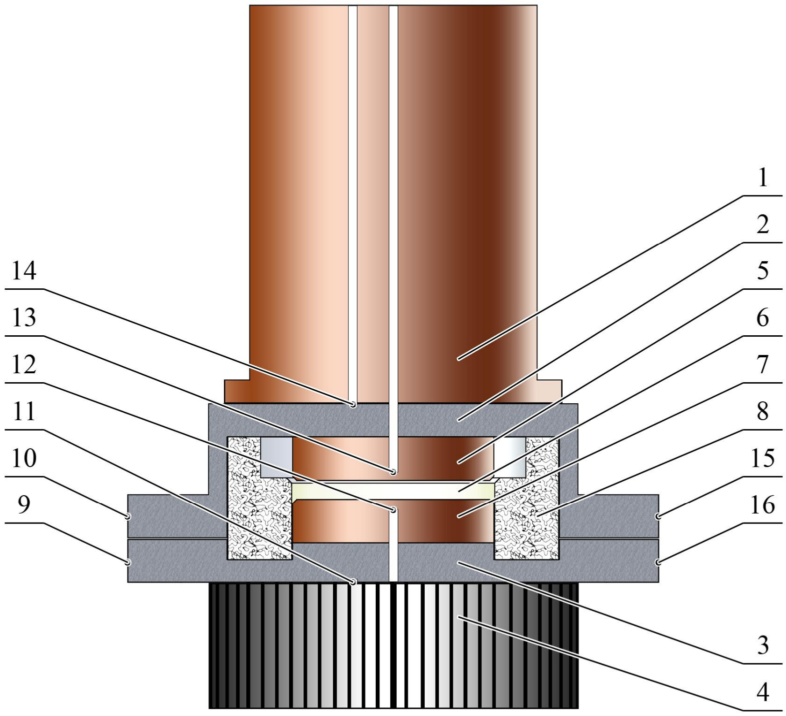

Fig. 1. Scheme of the measuring section of the experimental facility for determining the thermal properties of coal-water fuel: 1 – heater; 2 – upper housing; 3 – lower housing; 4 – cooler; 5 – upper thermodisc; 6 – lower thermodisc; 7 – compartment for coal-water fuel; 8 – PTFE inserts; 9-16 – thermocouples

The measuring section comprises the heater 1, the upper 2, the lower 3 parts of the housing made of stainless steel and the cooler 4. The heater is made of a nichrome wire wound on a solid copper cylinder, which is thermally insulated on all sides except the bottom part contacting with the upper housing part (heat insulation is not shown in Fig. 1.). Upper housing part 2 is connected with the upper thermodisc 5 made of copper, and represents nonseparable construction during the operation. The lower part of the body is connected to the lower thermodisc 6, also made of copper. In order to reduce heat loss through the housing compartment for coal-water fuel 7 and the adjacent surfaces are insulated with the PTFE insert 8. At the top and bottom of the housing thermocouples 9-16 are mounted. The chromel-alumel thermocouples are used in research. Temperature measurement range, according to DSTU 2837-94 makes from - 270 °C to + 1372 °C. In order to provide high accuracy temperature measurement (± 0,01 °C), individual calibration of thermocouples was made. The assembled construction is hermetically sealed and can withstand pressures up to 3 MPa.

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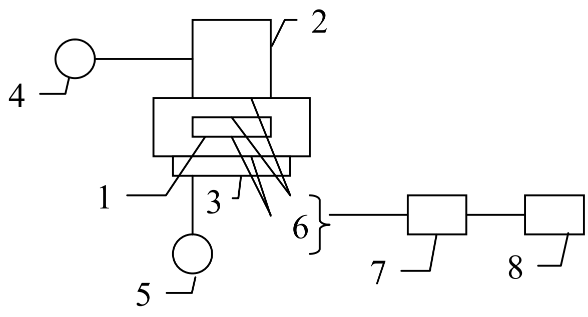
Schematic diagram and a photograph of the experimental facility for determining the thermal properties of coal-water fuel is shown in Fig. 2.



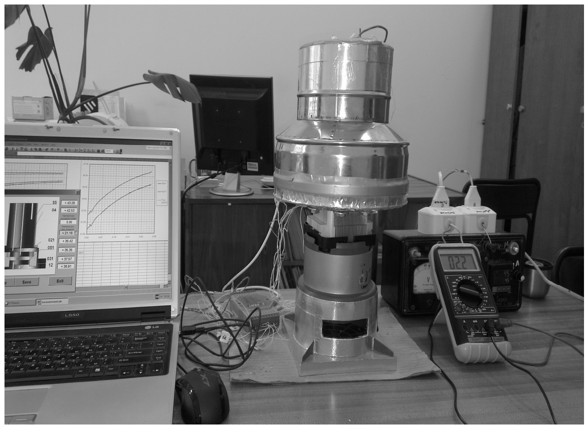


Fig. 2. Schematic diagram and a photograph of the experimental facility for determining the thermal properties of coal-water fuel: 1 – compartment for coal-water fuel; 2 – heater; 3 – cooler; 4 – power regulator; 5 – speed control; 6 – thermocouples; 7 – hardware measuring complex; 8 - computer

Test sample of coal-water fuel (25 ml) is placed in a special compartment 1. Heat flow allocated heater 2, passes through the fuel sample and is perceived by cooler 3. Heater power is adjusted with the regulator 4 (maximum heating power makes 300 W). The high thermal conductivity of the heater housing and the availability of thermodisc made of copper, provide a uniform temperature distribution over the surface in contact with the coal-water fuel. Test sample of coal-water fuel is adjacent to the upper and lower surfaces of the housing tightly and without air gaps. The cooler is a fan attached to the bottom surface of the housing. Rotational speed of the fan can be controlled by the regulator 5, which provides the ability to align and maintain the desired temperature on the cooling surface. Indications of thermocouples 6 are transferred to hardware-measuring complex 7, which allows to control, manipulate and display parameter values on the computer 8 screen in real time. The experimental facility is not tied to a specific type of coal-water fuel and allows the study of a wide range of changes in the characteristics of raw materials (coal grade, amount of mineral impurities and an aqueous phase, particle size etc.).

In order to determine thermal conductivity of the resulting experimental temperature distribution it is necessary to perform the inverse heat conduction problem solution. As a method of numerical solution of the inverse heat conduction problem, the repeated solution of direct heat conduction problem [8] method was chosen, including the optimization of iterations with the golden section method [9]. As the function for which the minimum was found with the golden section method, an absolute deflection between calculated and measured temperatures at the control points was used.

The heat equation describing the heat transfer in the considered experimental facility is as follows:

$$\frac{\partial t}{\partial \tau} = \frac{\partial}{\partial r}\left(a \cdot \frac{\partial t}{\partial r}\right) + \frac{a}{r} \cdot \frac{\partial t}{\partial r} + \frac{\partial}{\partial z}\left(a \cdot \frac{\partial t}{\partial z}\right), \quad (1)$$

where t – temperature, ^{o}C:

τ – time, s;

r – radius vector, m;

z – applicate, m;

a – thermal diffusivity $a = f(t, z, r)$, m^2/s.

$$a = \frac{\lambda}{\rho \cdot c}, \quad (2)$$

where λ – thermal conductivity coefficient, $\lambda = f(t, r, z)$, W/(m·K);

ρ – matter density $\rho = f(t, r, z)$, kg/m3;

c_V – Isochoric heat capacity of a mass unit $c = f(t, r, z)$, J/(kg·K).

For complete mathematical description of the particular features of heat transfer in the considered experimental facility the initial and boundary conditions of the I, II, III and IV kind were formulated.

The above differential equation of heat conduction (1) with the boundary conditions was solved by the sweep method, which is well known and is quite effective numerical method for solving similar problems [10]. Calculations were made to reach stationary mode.

To implement the sweep method differential heat equation (1) and the boundary conditions are turned to a discrete form, where derivatives are used instead of their finite-difference approximations. The whole solutions area is represented as a set of nodes of the computational grid. After performing the sampling, a system of linear algebraic equations for determining the local temperature at each node of the grid is obtained.

For the approximation of the heat differential equation (1) space-time grid is introduced with the coordinates of:

$$r_i=(i-1)\cdot\Delta r;\;\; z_j=(j-1)\cdot\Delta z;\;\; \tau_n=n\cdot\tau \quad (3)$$

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where i – number of grid point in the coordinate r,
j – number of grid point in the coordinate z,
n – number of time step τ.

The considered grid is presented in Fig. 3.

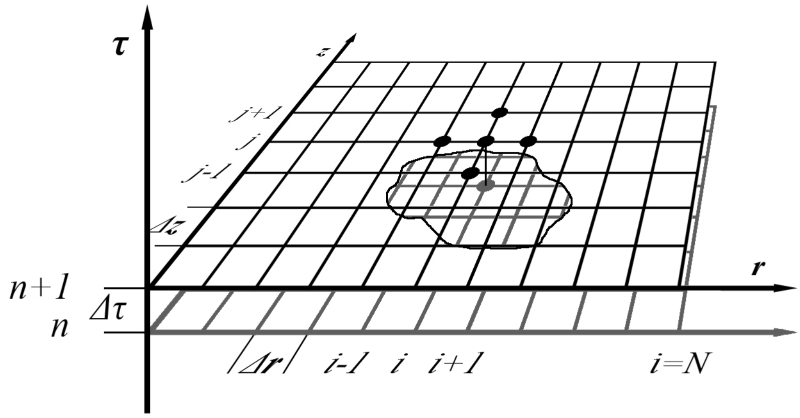

Fig. 3. Space-time grid

Approximation of equation (1) is performed based on the locally one-dimensional scheme according to the recommendations [10]. This scheme is implicit, is stable and has the property of total approximation. The basis of the approach is the breakdown of the whole of the time step in two stages. In intermediate temporary half-step sampling of a two-dimensional differential equation (6) only by r is carried out, which results in one-dimensional equation. The result of its solution is an intermediate temperature value $t_n+1/2$.

Then, the sampling of the equation (1) by z is performed, as a result of which one-dimensional equation is obtained, and after its solution the temperature value is calculated on the whole time step. The obtained intermediate temperature value is taken as the initial temperature value during this calculation step. Calculation scheme in the intermediate time step is shown in Fig. 4.

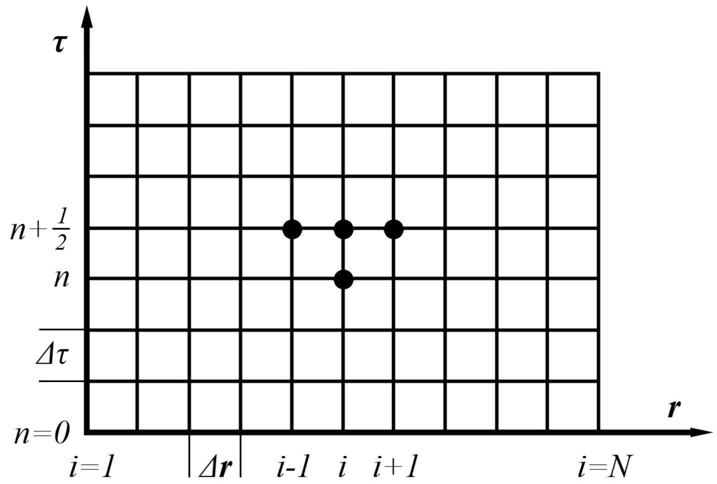

Fig. 4. Calculation scheme in the intermediate time step

When creating an algorithm the orthogonal uniform computational grid with a step of 0.5 mm in both coordinates was used. Geometric dimensions of the settlement scheme match the size of the experimental facility. Numerical integration was carried out with a time step $\Delta\tau = 3$ s, which is defined in the test calculations.

Boundary conditions, physical parameters and conditions of the real thermal process were defined according to the results of physical experiments on the standard substance (distilled water) and the solution of the inverse heat conduction problem. The experimental data on the standard material were used to verify the adequacy of the developed thermal conductivity determination mathematical model. The discrepancy between the obtained data and the known values of the thermal conductivity of water at various temperatures, amounted 1.3 %.

The next step of the research was to perform physical experiment on the test substance (coal-water fuel) under experimental conditions similar to the experimental conditions on the standard substance. During the experiment, the distribution of the temperature fields was recorded. During the numerical simulation, the experimental conditions on the coal-water fuel were reproduced, and the distribution of non-stationary temperature fields was calculated repeatedly until the stationary mode was reached. At the same time certain value of coal-water fuel thermal conductivity was set previously. The temperature values at the points corresponding to the points of thermocouple setup in the experimental facility were selected from the resulting stationary temperature distribution. Calculated and experimental values were compared. If the difference between them exceeded the predetermined error, the value of the thermal conductivity changed, the calculation repeated.

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Thus, as a result of repeated calculations of the direct heat conduction problem for each of the experimentally measured temperature distribution, the values of thermal conductivity of coal-water fuel prepared from different types coal were obtained.

The results of determining the values of the thermal conductivity of samples of coal-water fuels with the proposed method of combining physical experiments and mathematical modeling in the range of 40 – 150 °C temperature change are shown in Fig. 5.

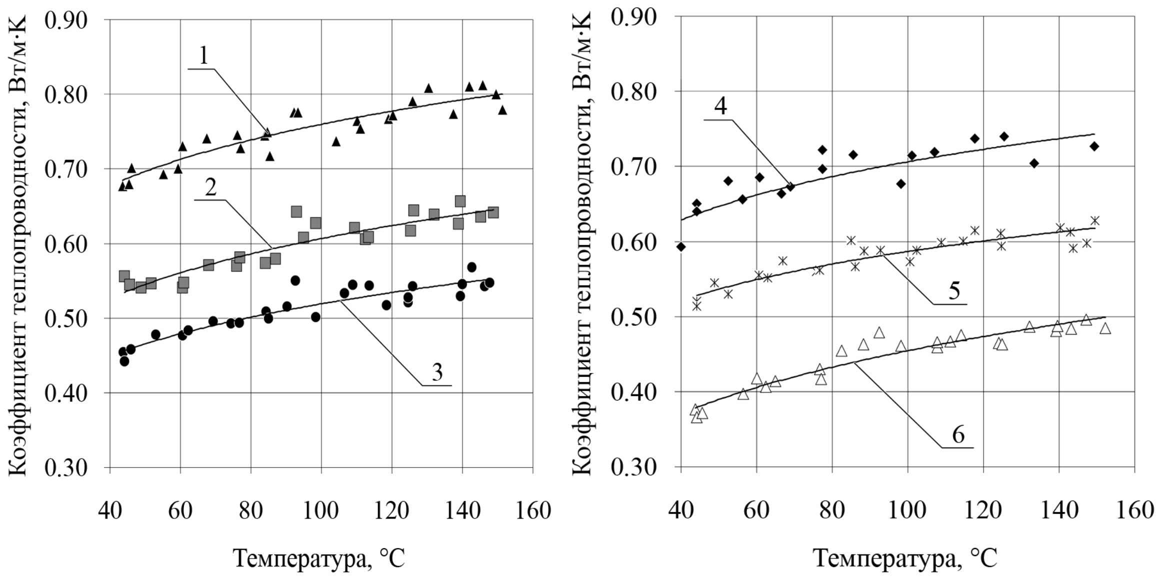

Fig. 5. Dependence of thermal conductivity on temperature for coal-water fuels prepared from different types of coal: 1 – coal-water fuel from anthracite; 2 – coal-water fuel from subbituminous coal; 3 – coal-water fuel from brown coal; 4 – coal-water fuel from gas coal; 5 – coal-water fuel from fat coal, 6 – coal-water fuel from lean coal.

As seen, the thermal conductivity of coal-water fuel increases significantly compared to coal and varies from 0.41 to 0.81 W/(m · K), naturally increasing with the temperature rise in the investigated range. Practical application of the results of research on thermophysical properties of coal-water fuels can be directly related to the modeling of heat exchange processes of combustion and gasification [11], as well as the design of power equipment for thermal processing of coal-water fuels.

Conclusions

From the standpoint of thermal processing technology the data on the specific heat, thermal conductivity and thermal diffusivity of coal-water fuels and their changes during thermal processing are of greatest interest. Analytical description of the dependence of the thermal conductivity of coal-water fuel on various parameters is difficult because of the lack of physical model relevant to the real structure of coal-water fuel.

One effective method for determination of thermal conductivity is to use a combination of physical experiments and mathematical modeling. When carrying out a physical experiment the method of comparison is proposed to use. As a method of numerical solution of the inverse heat conduction problem, the repeated solution of direct heat conduction problem method was chosen, including the optimization of iterations with the golden section method. At the same time the missing information on the boundary conditions, physical parameters and conditions of the real thermal process is determined directly in the course of experimental studies on the standard substance, and subsequently used in the mathematical modeling. As part of the task to determine the values of the thermal conductivity of coal-water fuels the experimental facility was developed. The experimental facility is not tied to a specific type of coal-water fuel, and allows the study in a wide range of changes in the characteristics of the feedstock.

The results of determining the values of the thermal conductivity of samples of coal-water fuels with the proposed method of combining physical experiments and mathematical modeling in the range of 40 – 150 °C temperature change have shown that the thermal conductivity of coal-water fuels increases significantly compared to coal and varies from 0.41 to 0.82 W/(m · K), depending on the type of the original coal, naturally increasing with the temperature rise in the investigated range.

References

1. Pinchuk VA Use of coal-water fuel and its products in the energy and metallurgy / VA Pinchuk, MV Guba, BB Potapov / / Metalurgiyna teplotehnika: Collection of scientific works of the National Metallurgical Academy of Ukraine. - Dnipropetrovs'k "Nova ideologiya." - 2009. - Issue 1 (16). - P. 144 - 149.

2. Pinchuk VA Researches of electrical properties of coal-water slurries / VA Pinchuk, AM Dolzhansky / / Tehnichna teplofizika that Promyslova teploenergetika: Collection of scientific works. - Issue 5. - Dnipropetrovs'k: Nova ideologiya. - 2013. - P. 171-180.

3. Hodakov GS Coal-water slurry in Energy / GS Hodakov / / Thermal Engineering. - 2007. - № 1. - Pp. 35 - 45.

4. Makarov AS Highly concentrated suspensions based on waste coal. Preparation, rheological properties and energy value / AS Makarov., AI Egurnov, SD Boruk / / Himichna promuslovist Ukrainy. - 2007. - № 2 (79). - P. 56 - 60.

5. Chirkin VS Thermal conductivity of industrial materials / VS Chirkin. - M.: Mechanical Engineering, 1957. - 172.

6. MA Mikheev Fundamentals of Heat Transfer / MA Mikheev, IM Mikheev. - Moscow: Energiya, 1977. - 344.

7. Agroskin AA Thermophysics solid fuel / AA Agroskin. - Moscow: Nedra, 1980. - 256 p.

8. AV Lykov The theory of heat conduction / AV Lykov. - M.: "High School", 1967. - 599 p.

9. Optimization techniques / NN Moiseev, P. Ivanilov, EM carpenter / Textbook. manual for schools - Moscow: Nauka, 1978. - 351 p.

10. Samarsky AA The theory of difference schemes / AA Samarsky. - Moscow: Nauka, 1983. - 616.

11. Pinchuk VA Research and development modes gasification coal-water fuel / VA Pinchuk, TA Sharabura / / Modern science: research ideas, results, and technology. Issue number 3 (5) - Kiev "NPVK Triakon." - 2010. - P.192-195.