Experimental study of thermal conductivity of pyrolysed materials by means of a flat layer

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Abstract. Recycling of tires is currently a very important task. One of the areas of recycling tires is their low-temperature pyrolysis to produce marketable products – liquid fraction and a solid coke residue. For the development of the pyrolysis installation it is important to know the thermal conductivity of the coke residue at different temperatures of pyrolysis of initial material. As a property of matter, thermal conductivity depends in general on temperature and pressure. For materials with some structure, such as porous materials, the thermal conductivity depends on the characteristics of the structure. The thermal conductivity of the porous coke residue at pyrolysis temperatures of 300 °C, 400 °C, 500 °C and atmospheric pressure was studied experimentally at the laboratory unit of the department of “Theoretical basis of heat engineering” using the method of the flat layer in the temperature range 5...100 °C. Experimentally proved temperature dependencies of the coefficient of thermal conductivity of the coke residue are built to improve the accuracy of calculations of constructive and regime parameters of the pyrolysis installation.

1. Introduction

Around the world the question of utilization of the fulfilled automobile tires is urgent as the structure and composition of rubber do them extremely steady against biological decomposition. Annually in the world more than 285 million fulfilled automobile tires appear [1]. Growth of volumes of rubber waste and limited opportunities for their burial result in need of development of new, innovative methods of utilization and processing of the fulfilled tires.

Gasification of tires with receiving synthesis gas (CO and H₂) [2], and also pyrolysis with receiving liquid fuel, gaseous fraction and solid fraction – the coke residue or industrial carbon [3] are among perspective thermochemical methods of processing. The number of researches of process of pyrolysis of the crushed automobile tires, including with different additives of carbon-containing materials [4 - 10] is executed.

Pyrolysis of the crushed automobile tires can be realized in the rotating drum furnaces. For modeling of thermal work and engineering development of such pyrolysis furnaces it is important to know heat conductivity of the coke residue at different temperatures of pyrolysis of initial material (figure 1). Besides, data on heat conductivity of the fine coke residue unloaded from the furnace are necessary for search of effective ways of its cooling.
Figure 1. The coke residue at the temperature of pyrolysis of initial material 400 °C

2. Description of the method

According to Fourier's hypothesis, the vector of heat flux density is proportional to temperature gradient vector:

$$\vec{q} = -\lambda \cdot \text{grad}(t)$$

(1)

Constant of proportionality $\lambda$ in (1) is called the thermal conductivity of substance and is the physical property of substance.

Generally the thermal conductivity of solid bodies depends by nature substances and on temperature.

The method of the flat layer belongs to stationary methods of definition of thermal conductivity of materials. If the temperature field stationary and temperature changes only on thickness of the flat layer, then the heat flow through the layer of material is defined by the equation:

$$Q = \frac{\lambda}{\delta} \cdot (t_1 - t_2) \cdot F,$$

(2)

where $Q$ – the heat flow, W; $\delta$ – thickness of the flat sample of material, m; $t_1$ – material temperature on the hot surface, °C; $t_2$ – material temperature on the cooled surface, °C; $F$ – heat exchange surface, m$^2$; $\lambda$ – integral average value of thermal conductivity of the studied material in the range of temperatures $[t_1, t_2]$. If dependence $\lambda(t)$ of material is linear, then value $\lambda$ equal to value of heat conductivity of this material at the temperature equal to the arithmetic average from temperatures: $[t_1, t_2]$.

Thus, if to measure $Q$, $t_1$, $t_2$ and $F$, from the equation (1) it is possible to define integral average value of thermal conductivity $\lambda$.

3. Description of experimental installation

For the research of heat conductivity of materials in Heat pumping Systems laboratory of Theoretical basis of heat engineering (TOT) department the experimental installation (figure 2) was created.

The principle of operation of the installation is put into implementations of the method of the flat layer and consecutive measurement of dynamic temperature fields of installation to reach quasisteady conditions of work [11, 12]. In steady conditions calculation of the thermal conductivity of the studied material is made.

The sample of the studied material represents disk volume with a diameter of 130 mm and 6 mm thick (thickness of samples can be increased to 15 mm). Samples are located between the heater and the refrigerator. They have to adjoin densely to hot (heater) and cold (refrigerator) surfaces of the device. Density of contact of all elements of the device is reached by purity of processing of the
adjoining surfaces, exact adjustment of the interfaced details, and also provided with tightening of the push screws.

**Figure 2.** The photo of the experimental installation for definition of the thermal conductivity by method of the flat layer

The electric heater executed from the isolated vein twisted from the nichrome wire, is placed in the brass case which for improvement of distribution of temperature in the case of the heater is filled with heat-conducting paste, which thermal conductivity \( \lambda = 0.8 \text{ W} / \text{mK} \). Electric isolation of the heater is executed from the fluoropolymer layer. Maximum temperature of the hot surface of the heater is limited to 100 °C.

For reduction of radial heat leakages the case of laboratory installation in which the heater and refrigerators are placed is executed from the micarta which thermal conductivity \( \lambda_{\text{ins}} \approx 0.14 \text{ W} / \text{mK} \). Temperature of surfaces of the studied material is taken by K-type thermocouples. Current (I, A) and voltage drop (U, V) on the heater are determined by the indications displayed on digital indicators of the adjustable Matrix MPS-6005L-1 power supply unit (figure 2). Heat losses of installation to the environment are controlled in the contactless way by means of the SAT S-280 thermal imager (figure 3). The scheme of the laboratory installation is presented on the figure 4. Hydraulically the cooling system of the device is connected with other installations and the measuring equipment of laboratory (figures 5, 6)

**Figure 3.** Thermal image of elements of the laboratory unit
0, 1 - thermocouples on the studied sample from the cold side; 2,3,4,5 - on the studied sample from the hot side; 6,7 - thermocouples on the entrance and the exit of the cooling system of installation

**Figure 4.** The scheme of the experimental unit for definition of the thermal conductivity by method of the flat layer.

**Figure 5.** Scheme of hydraulic accessions of laboratory installation to the equipment of Heat pumping Systems laboratory of TOT department: 1, 2 - the exit and the entrance of the soil heat exchanger; 4, 5 – the exit and the entrance of laboratory installation by definition of the thermal conductivity by method of the flat layer; 3 – bypass of laboratory installation; 6 – feeds of the cooling circuit; 7, 8 – the exit and the entrance to the heat pump’s evaporator; 10 – giving of the pump of the 1st contour of heat pump unit – the cooler of installation (see figure 6).
Figure 6. Module of pumping of the coolant, pressure monitoring and flow rate

The recommended upper limit of the current flowing via the heater makes 2.5 A. Voltage drop on the heater at such value of current $\approx 26$ V. Power consumed by the heater is 65 W.

The installation is equipped with system of the automated data collection and processing as a part of the ADC USB4718 module connected to the computer and the corresponding software allowing to write down and process signals of 8 thermocouple channels with the different time step. At the same time the measuring circuit provides automatic corrective action on temperature of the cold thermocouple junctions which are at the room temperature. Room temperature $t_{\text{room}}$ is taken by the precision mercury thermometer. For determination of the power consumed by the electric heater voltage drop (U, V) and current (I, A) by means of the voltmeter and the ampermeter is measured.

4. Processing of results of the experiment

The data which are taken off in the experiment are processed in specially created MS Excel™ template, the example of such table is presented in figure 7 for temperature of pyrolysis 300 °C.

Figure 7. The table of the MS Excel™ template for preprocessing of results of the experiment

Further one present experimental data in the reduced form (figure 8).
Three columns of the matrix mean respectively:

- power of the electric heater $W$, watt, or that the same, heat flow of $Q$;
- averaged on 4 internal thermocouples (2-5 in figures 4, 7) value of temperature $t_1$, °C;
- averaged on 2 external thermocouples (0, 1 in figures 4, 7) value of temperature $t_2$, °C.

Such representation well illustrates the main idea of the experiment. Set the power of the heater and control difference of temperatures in the layer. The difference of temperatures depends on the material thermal conductivity, and by means of further data processing [13] we will calculate its values.

Calculate the value of the heat flow determined by the power of the electric heater $W$, watt

$$Q = W = I \cdot U$$

Evaluate heat losses through side thermal insulation $Q_{\text{lost}}$, W

$$Q_{\text{lost}} = \frac{2\pi H \lambda_{\text{ins}} (\bar{T} - t_0)}{\ln(D_2/D_1)}$$

Here $D_1 = 130$ mm, $D_2 = 180$ mm, $H = 50$ mm – the sizes of isolation; $t_0$, °C - the average temperature of the surface fixed with the help of the thermal imager; $\bar{T}$, °C, is determined by the equation

$$\bar{T} = \frac{t_1 + t_2}{2}$$

At the final stage of processing of experimental data integral average value of the thermal conductivity is calculated $\lambda$ and temperature of reference $t_m$ as arithmetic average value of temperature of the flat layer:

$$\lambda = \frac{q}{t_1 - t_2}, \quad t_m = \frac{t_1 + t_2}{2},$$

where $q$ - heat flux through samples, W/m²

$$q = \frac{Q - Q_{\text{lost}}}{2F}, \quad F = \frac{\pi D_1^2}{4}.$$  

Applying the technique (3-7) to data of the experiment (figure 7) at the schedule of loading submitted in figure 9a, we will receive change of the thermal conductivity in time - figure 9b.

On graphics of the figure 9b the site to quasisteady conditions is fixed and for final values of the thermal conductivity by means of the least-squares method dependence $\lambda(t_m)$ is obtained.
Figure 9. Schedules of the experiment for temperature of pyrolysis 300 °C: a) heat loading of samples; b) change of the thermal conductivity coefficient

5. Results of numerical and experimental definition of the thermal conductivity

In the figure 10 as the example results of one of experiments on definition $\lambda(tm)$ for temperature of pyrolysis 300 °C are presented. Similar graphics are received for temperatures of pyrolysis 400 °C and 500 °C. As a result of carrying out not less than three series of experiments for each sample are shown that at temperatures of pyrolysis of 300 °C, 400 °C, 500 °C and atmospheric pressure it is possible to describe thermal conductivity of the porous coke residue by linear relation:

$$\lambda(t) = a + b \cdot t$$  (8)

Coefficients of the equation (8) for temperatures of pyrolysis 300 °C, 400 °C, 500 °C are presented in table 1.

Table 1. Coefficients of the equation (8).

| Pyrolysis temperature, °C | Coefficients | a     | b      |
|---------------------------|--------------|-------|--------|
| 300                       |              | 0.1022| 0.0007 |
| 400                       |              | 0.1368| 0.0003 |
| 500                       |              | 0.2435| 0.00004|

Figure 10. The example of graphics of numerical and experimental definition $\lambda(tm)$ for temperature of pyrolysis 300 °C
6. Conclusion
The thermal conductivity of the porous coke residue at pyrolysis temperatures of 300 °C, 400 °C, 500 °C and atmospheric pressure was studied experimentally at the laboratory unit of the department of "Theoretical basis of heat engineering" using the method of the flat layer in the temperature range 5...100 °C. The surface temperature of the test material was measured by 6 K-type thermocouples, two of them laid on surfaces of refrigerators, and the rest on the heated surfaces and inside the heater. By using ADC boards, thermal EMF of the thermocouple is transferred to the computer in real time, providing high precision control of reaching the stationary mode of operation. Thermal parameters of the installation were controlled also with the thermal imager, which allowed to more accurately determine the thermal balance of the experimental modes. The experimentally proved temperature dependencies of the coefficient of thermal conductivity of the coke residue are built to improve the accuracy of calculations of constructive and regime parameters of the pyrolisys installation.

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