Technique of determining the effective temperature conductivity coefficient of organic raw material porous layer

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Abstract. It is necessary to know for calculation of solid household wastes thermal processing thermophysical characteristics. Existing methods consider the solid household waste layer as a multicomponent mix which thermophysical characteristics are defined taking into account volume fractions and properties of components, layer porosity thus not. A technique is proposed for determining the effective coefficient of thermal diffusivity of a multicomponent porous layer, constructed on the basis of the solution of the inverse heat conduction problem. The base of problem-solving procedure is the method of the discrete satisfaction of boundary conditions (DSBC). According to the proposed method, the dependence of the effective coefficient of thermal diffusivity of solid communal waste of the average morphological composition on the temperature and porosity of the layer was determined. The proposed technique can be used to determine the effective coefficient of thermal diffusivity of bodies with different porosity structures.

1. Introduction

The municipal solid wastes (MSW) are the waste generated in the population, in commercial enterprises, institutions, municipal services. MSW are a heterogeneous mixture of complex morphological structure, including: paper, textiles, plastics, food and vegetable ingredients, stones, bones, leather, rubber, wood, ferrous and non-ferrous metals, glass.

Widespread waste disposal technologies are thermal methods, which include pyrolysis and gasification. Thermal processing of raw materials not only allows you to get a flammable gas, but also to solve the environmental problems associated with urban pollution and land reclamation.

Municipal solid wastes are subjected to thermal treatment in special shaft furnaces - thermal reactors [1, 2]. The reactor layer of solid waste passes successively processes heating, drying, pyrolysis and gasification of solid carbonaceous residue. The resulting processing combustible gas is used as fuel. Frequently, a pre-treatment of MSW takes place which consists in sorting and drying.

To calculate the heating process layer of solid waste on the basis of the differential equation, the heat conductivity is necessary to know the thermophysical properties (TPP).

In engineering practice, the thermophysical properties of the MSW are determined by the properties of the mixture components known from the literature and the value of their volume fractions [3]. At the same time, the porosity of the layer and its influence on TPP are, as a rule, not taken into account, which leads to an increase in the error in calculating the process parameters of the process reactor (temperature field and consumption of combustible gas).
2. Statement of the Problem

Consider a layer of solid waste as a conventional isotropic porous body, endowed with effective thermal properties: density \( \rho_{\text{eff}} \), thermal conductivity \( \lambda_{\text{eff}} \) and heat capacity \( c_{\text{eff}} \), bound together the effective thermal diffusivity \( a_{\text{eff}} \).

\[
a_{\text{eff}} = \frac{\lambda_{\text{eff}}}{c_{\text{eff}} \rho_{\text{eff}}} \tag{1}
\]

One of the promising approaches to the determination of TPP of porous bodies is the conduct of thermophysical studies based on the processing of experimental data by inverse thermal conductivity problem (ITCP) methods, when, based on the results of measuring the temperature or heat flux at a given boundary and the temperature at internal points of the sample, effective thermophysical characteristics of this body \([4, 5]\).

The technique of ITCP solution for the MSW layer is proposed, which does not require knowledge of the parameters of external heat exchange \([6]\). The essence of the technique is that the sample is heated by the random monotonically changing heat flow. On the base of the experimentally measured temperature surface \( T(1, F_0) \) and thermal center \( T(0, F_0) \) layer and the approximation of a given value of the effective thermal diffusivity is calculated the sample temperature field \( T(X, F_0) \). The calculated values of the temperature at the center point are compared with the experimental data at the same point while minimizing the standard deviation calculation and experiment.

The method of discrete satisfy the boundary conditions (DSBC) is put on the basis of the proposed solution of the ITCP \([6]\). According to the DSBC method, the thermal conductivity differential equation satisfied continuously, while the boundary conditions - in discrete time points, \( g \), evenly on the viewing of the selected time interval \( F_0 \). Time moments for which the boundary conditions are formulated, defined by the expression \( \frac{F_0}{g} \) where \( i \in \{1, g\} \). The higher the value, the more accurate approximate solution, but the solution of the problem more difficult. If \( g \to \infty \), an approximate solution tends to the exact. Authors recommend, in engineering practice for the calculation of the thermally thin bodies temperature fields is enough to take \( g = 3 \div 5 \), and for the calculation of the heat thermally massive bodies \( g = 3 \div 5 \). Where in the calculation error does not exceed 3\% \([6]\). The initial conditions in the DSBC method are also catered discretely at \( m \) points evenly distributed over the heated body thickness. When solving applications with an error not exceeding 3\%, you can take \( m = 2 \div 3 \) \([6]\).

The method is based on the heat conduction problem exact analytical solution for the simplest forms bodies with the type 1 boundary conditions. For an infinite plate this solution has the form:

\[
T(X, F_0) = \phi(F_0) - 2\sum_{i=1}^{g} \left( \frac{(-1)^{i+1}}{\delta_i} \cos(\delta_i \cdot X) \cdot \exp(-\delta_i^2 \cdot F_0) \right) \int_{0}^{F_0} \exp(\delta_i^2 \cdot F_0) \frac{\partial \phi(F_0)}{\partial F_0} dF_0 + \frac{2 \sum_{i=1}^{g} \cos(\delta_i \cdot X) \cdot \exp(-\delta_i^2 \cdot F_0)}{\int_{0}^{F_0} [T(X, 0) - T(1, 0)] \cdot \cos(\delta_i \cdot X) dX}, \tag{2}
\]

where \( \phi(F_0) = T(1, F_0) \) - given boundary conditions type I, \( T(X, 0) \) - initial condition, \( \delta_i \) - characteristic numbers, \( \delta_i = \frac{2i-1}{2} \cdot \pi, X = \frac{x}{R} \) - dimensionless coordinate; \( F_0 = \frac{a \cdot t}{R^2} \) - dimensionless time; \( R \) -calculated plate size, \( m \); \( a \) - coefficient of thermal diffusivity, \( m^2/s \); \( t \) - time, s.

The first two terms on the right hand side of equation (2) - a component of the temperature field of action of the boundary conditions. The third term - a component of the temperature field of action of the initial conditions.

In accordance with the DSBC method solution (2) is represented as

\[
T(X, F_0) = T(1, F_0) - \sum_{i=1}^{g} A_i \cdot \phi_{X,s}(F_0) + \sum_{i=1}^{m} A_i \cdot s_{X,s}(F_0), \tag{3}
\]

where \( \phi_{X,s}(F_0) \) - auxiliary functions of the temperature field component from the boundary conditions; \( s_{X,s}(F_0) \) - auxiliary functions of the temperature field component from the initial conditions;
\[
\Phi_{x,n}(Fo) = 2\sum_{l=1}^{n} (-1)^{l+1} \cdot \cos(\delta \cdot X) \cdot \Phi_{x,n}(l,Fo),
\]
where \(\Phi_{x,n}(l,Fo) = \frac{n}{2} \exp(-\delta^2 \cdot Fo) \int_0^{\infty} \exp(\delta^2 \cdot Fo) \cdot Fo^{-\frac{1}{2}} \, dFo\).

\[
f_{x,n}(Fo) = 2\sum_{l=1}^{n} \cos(\delta \cdot X) \cdot f_{x,n}(l,Fo),
\]
where \(f_{x,n}(l,Fo) = \exp(-\delta^2 \cdot Fo) \int_0^{1} (X^2 - 1) \cos(\delta \cdot X) \, dX\).

In the DSBC method the heated surface temperature of the body, as a function of time, is approximated by a polynomial

\[
T(l,Fo) = T_o + \sum_{n=1}^{\infty} A_n Fo^{-\frac{1}{2}},
\]
and the initial temperature field of the body – by a polynomial

\[
T(X,0) = T(0,0) + \sum_{n=1}^{\infty} a_n \cdot X^n
\]

Here \(A_n\) - the coefficients defined by discrete satisfaction of the boundary conditions; \(a_n\) - the coefficients defined by discrete satisfaction of the initial conditions.

From the solution of (3) the temperature of the unexposed surface of the plate

\[
T(0,Fo) = T(l,Fo) - \sum_{n=1}^{\infty} A_n \cdot \Phi_{x,n}(Fo) + \sum_{n=1}^{\infty} a_n \cdot f_{x,n}(Fo)
\]

Pre-calculated values of the functions \(\Phi_{x,n}(Fo), \Phi_{l,n}(Fo), \Phi_{0,n}(Fo), \Phi_{0:1:n}(Fo), f_{x,n}(Fo), f_{l,n}(Fo), f_{0:n}(Fo), f_{0:1:n}(Fo)\) are presented in [7].

The coefficients \(a_n\) are determined by a discrete satisfaction of given initial temperature distribution \(T(X,0)\) in \(m\) coordinates, evenly spaced over the plate thickness.

\[
T(X_j,0) = T(0,0) + \sum_{n=1}^{\infty} a_n \cdot X_j, \quad j \in \{1, m\}
\]

where \(T(X_j,0)\) initial temperature set points.

3. Solution algorithm
The algorithm for finding the effective temperature coefficient is based on the use of equation (6) and reduces to solving systems of algebraic equations (3) and (8). The values of \(T(l,Fo)\) and \(T(0,Fo)\) are given from the experimental data.

Solving the system (3) we obtain the values of the coefficients \(A_n\) as a function of yet unknown values of the effective diffusivity \(a_{eff}\). Substituting \(A_n(a_{eff})\) in (8), we obtain \(g\) equations with the unknown \(a_{eff}\). The system is solved using one of the iterative methods. The proposed algorithm for calculating the effective coefficient of thermal diffusivity is implemented in the software package MATHCAD.

4. Results and Discussion
The developed technique was used to determine the effective coefficient of thermal diffusivity of a sample of the MSW layer of the average morphological composition [8, 9]. For this purpose, a series of laboratory experiments was performed to heat MSW samples in an installation, the scheme of which is shown in Figure 1. The experimental setup includes a closed container, insulated from the ends and from below with asbestos. A heating element was used as the container cover.

The experimental procedure was as follows. The test material (a sample of a MSW layer of an average morphological composition 160 mm in height with a previously determined porosity of 0.5 and zero moisture) was placed in a container. On the height of the layer along the axis, as shown in Fig. 1, two thermocouples of the type TXA (k) were installed. The signal from the thermocouples came to the
analog module MBA-8 and then processed on the computer. The thermocouple readings were recorded with an interval of one second.

![Figure 1](image1.png)

**Figure 1.** The scheme of the experimental setup:
1 - container,
2 - asbestos,
3 - thermo-couples,
4 - heating element,
5 - MSW,
6 - input module.

To increase the accuracy of temperature measurements in the dried sample, thermocouple openings were indicated with a thin steel needle with a movable limiter. The stopper allows you to place the thermocouples precisely at a given distance from the surface. To avoid heat transfer through the electrodes, thermocouples were installed from the end of the container and paved in isothermal surfaces. To minimize the experimental error, the temperature measurement points were chosen on the body axis, in which the temperature gradients along the width of the container were zero.

During the heating of the MSW sample, the temperature in the calculated cross sections along the height of the layer was measured (Figure 1). To obtain more reliable results and to avoid the effect of random errors, the same experiment was repeated at least 5 times. As initial data for further calculations, the temperatures averaged over the number of runs for the given heating regime were taken (Fig. 2). The experimental results are presented graphically in Figure 2.

![Figure 2](image2.png)

**Figure 2.** The experimental temperature values of the MSW sample with a porosity of 0.5:
1 - temperature of the heated surface \( T(1, \text{Fo}) \);
2 - temperature of the unheated surface \( T(0, \text{Fo}) \).

To assess the effect of porosity on the value of the effective coefficient of thermal diffusivity, similar experiments were performed for MSW samples with a porosity of 0.62 and 0.7. Using the values of \( T(1, \text{Fo}) \) and \( T(0, \text{Fo}) \) obtained from the experiment, by accessing the software implementation of the ITCP solution algorithm, the effective temperature-conductivity coefficient values were found fulfilling the condition of providing a mean-square deviation of the calculated and experimental data not more than 3%.

The dependence of the effective coefficient of thermal conductivity on temperature for different values of the porosity of the MSW layer is shown in Figure 3.
From the analysis of Figure 3 it can be seen that the porosity of the layer exerts a significant influence on the value of the effective coefficient of thermal diffusivity. With increasing porosity, the numerical value of the effective coefficient of thermal diffusivity increases. With increasing temperature, the effective coefficient of thermal diffusivity increases insignificantly for small values of the porosity of the layer (up to 0.5) and is more significant for large values of porosity (more than 0.7).

5. Conclusions

1. A technique based on the method of discrete satisfaction of boundary conditions, is proposed for determining the effective coefficient of thermal diffusivity of a porous layer.

2. The dependence of the effective coefficient of temperature conductivity on temperature for a layer of previously dried solid municipal waste with a porosity of 0.5 to 0.7 in the temperature range from 20 to 100 °C was recommended, which is recommended for calculation of heat exchange in technological reactors for the processing of MSW.

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