Method for determination of thermophysical properties of polymer composite materials

Vladimir Sharshin, Denis Sukhorukov and Elena Sukhorukova
Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky Street, Vladimir, 600000, Russian Federation

E-mail: info@inlittech.ru

Abstract. The paper presents the results of studies of thermophysical properties: heat capacity, thermal conductivity, thermal diffusivity and heat storage ability of polymeric polymer composite materials. A method is proposed for determining these properties, based on the well-known method for determining thermophysical properties by eliminating variables. The experimental values of the thermophysical properties of polymer composite materials with the addition of powder particles of various fractions of aluminium, iron, carbon and copper are obtained. The effectiveness of the proposed method is shown by comparing the known values of the specific heat and thermal conductivity of polyurethane with experimental.

1. Introduction
Polymer composite materials (PCM) based on two-component injection molding compounds are widely used in industry as structural materials [1-4]. The high technological properties of the compounds make it possible to manufacture castings from PCM based on them with a significant (up to 50–70 wt.%) amount of additives of powdered or fiber fillers [5-7]. Therefore, the properties of PCMs can vary over a wide range, sometimes differing significantly. This circumstance, as well as significant economic advantages (compared with metal structural materials) make PCMs based on polyurethane compounds particularly attractive.

The possibility of varying properties, especially thermophysical, made it possible to use these PCMs in the manufacture of foundry tool parts for the production of expanded polystyrene products by blowing with hot steam, which is of great importance for ensuring the quality of the obtained castings [8, 9]. In the specified technological process, the walls of the mold work in non-stationary alternating thermal regime of heating/cooling. Under these conditions, the special thermophysical properties of the material become very important: thermal diffusivity and heat storage ability, characterizing the heating rate of the material and its ability to absorb heat. The quality of the products made of expanded polystyrene depends significantly on the values of these properties: surface condition and mechanical strength.

Control of thermophysical properties by known methods in a foundry laboratory is almost impossible. This requires special expensive precision equipment. The aim of this work is to develop a simple, affordable and relatively accurate method for determining the thermophysical properties of polymer composite materials, suitable in real production conditions.

2. Methods
The proposed methodology is based on the well-known method for determining thermophysical properties by eliminating variables. This method was developed in the second half of the twentieth century by the famous professor A.I. Veinik and academician, specialist in the field of thermophysics of metallurgical processes G.A. Anisovich in the application to foundry molding mixtures.

The technique was tested on samples of sheet polyurethane of Russian and foreign production (red and yellow) with known thermophysical properties (heat capacity and thermal conductivity), as well as samples made from injection polyurethane ADV-13-2, and samples of a polymer composite material.
made from ADV-13-2 with the addition of aluminum PAP-1 powder in an amount of 54.5%. The thermophysical properties of ADV-13-2 polyurethane are not reported by the manufacturer. Using these materials, samples were made in the form of small tiles with dimensions of 70x70 mm and a thickness of 25 mm. These samples simulated the wall of the mold for the manufacture of products from expanded polystyrene foam.

In studies, a thermostat was used, which was a box with thick walls and a lid made of heat-insulating material. As a heat-insulating material, a set of asbestos-cement slabs with a thickness of 25 mm was used, fastened in several layers with metal studs and nuts. The thermostat had an internal space of 70x70x50 mm.

In the lateral part of the thermostat there are special openings for thermocouples. The temperature of the samples in the experiments was measured by thermocouples. Thermocouples were placed along the thermal axis of the sample in isothermal planes parallel to the contact surface with the heater at a distance of 2, 5, 10, 15 mm. A copper ingot measuring 70x70 mm and 25 mm thick with a thermocouple mounted in it was used as a heater. This ingot with known thermophysical properties in the experiment simulated the steam supply process that occurs in the manufacture of gasified models by the method of internal thermal shock.

To reduce the influence of thermal resistances on the result of the experiment, in the gap between the heated ingot and the sample, as well as between hot junctions of thermocouples and controlled bodies, all contact surfaces were treated with organosilicon heat-conducting paint. Thermocouple readings were taken and recorded on a PC.

The studies were carried out as follows. The test sample with installed thermocouples was placed in the working space of the housing. Thermocouples through the controller were connected to a personal computer. A heater was prepared in the form of a copper ingot. For this, it was previously preheated uniformly in an oven to a temperature of 120 °C. A heated copper ingot was placed in a thermostat on the test sample. Then the thermostat was quickly closed with the top cover.

3. Results and Discussion

The duration of the experiments was determined by the time before the heating of the test sample to a depth of 15 mm from the plane of contact from the changes in the readings of the thermocouple located here. The size of 15 mm corresponds to the average wall thickness of metal molds used for the manufacture of foundry models. In the experiment, chromel-alumel thermocouples with an electrode diameter of 0.5 mm were used, connected to a PC through the KONTEL KI220-2.5 controller and a normalizing temperature converter NPT 1.2A, with a measurement range of 0-200 °C. Thermocouple readings in the form of temperature field graphs were recorded on a personal computer and then processed.

Figure 1 shows the dynamics of changes in the temperature of the ingot and the sample from ADV 13-2 polyurethane, as well as its temperature field at the time of completion of heating to a depth of 15 mm. Similar plots were obtained for all samples participating in the experiment. The construction of temperature fields was carried out using the KOMPAS-3D V12 software.

The calculation of the coefficient of heat storage capacity, as well as heat capacity was carried out based on the obtained temperature field of the sample according to the formulas:

\[
b_{obr} = \frac{R \cdot \rho_{nag} \cdot q_{nag}}{\Delta t \cdot \frac{2n}{n+1} \cdot \tau}
\]

\[
c_{obr} = \frac{R \cdot \rho_{nag} \cdot q_{nag} \cdot (n+1)}{X \cdot \rho_{obr} \cdot \Delta t}
\]

where R is half the wall thickness of the heated ingot, m; \( q_{nag} \) – specific effective heat transferred by the heated ingot to the sample, J/kg; \( \Delta t \) is the excess temperature of the heating of the sample, measured from its initial temperature, °C; n is the degree of parabola (Fig. 1), \( n = \frac{S_1}{S_2} \); \( \tau \) is the time until the...
sample is heated to a depth of \( X \) (m), \( s \); \( \rho_{\text{ing}} \), \( \rho_{\text{obr}} \) is the density of the heated ingot and the test material, respectively, kg/m\(^3\).

The values of \( \Delta t \), \( S_1 \), \( S_2 \), \( \tau \) were determined when plotting with the built-in means of KOMPAS-3D V12.

The thermal conductivity and thermal diffusivity of the material of the samples were found from the known relations:

\[
\lambda_{\text{obr}} = \frac{\rho_{\text{obr}}}{c_{\text{obr}} \cdot \rho_{\text{obr}}} \quad (3)
\]

\[
a_{\text{obr}} = \frac{\lambda_{\text{obr}}}{c_{\text{obr}} \cdot \rho_{\text{obr}}} \quad (4)
\]

where \( b_{\text{obr}} \) is the coefficient of heat storage capacity of the sample, W \( \cdot \) s\(^{0.5}\)/(m\(^2\) \( \cdot \) °C); \( S_{\text{obr}} \) is the heat capacity of the sample, J/(kg \( \cdot \) °C).

By this method, the thermophysical properties of the pure polyurethane compound ADV 13-2, as well as sheet polyurethane of Russian and foreign production (red and yellow), as well as samples made from injection polyurethane ADV-13-2 and samples of the polymer composite material made from ADV-13-2 with the addition of aluminum powder PAP-1. The calculation results of the main thermophysical characteristics of the studied samples according to the above formulas in the form of average values obtained from three design points are presented in Table 1.
Table 1. Experimental values of the thermophysical characteristics of polyurethanes, as well as PCM with the addition of aluminum powder PAP-1

| Designation  | ADV 13-2 | Polyurethane sheet red | Polyurethane sheet yellow | PCM based on ADV 13-2 s PAP-1 |
|--------------|----------|------------------------|---------------------------|-------------------------------|
| Sample number | 1        | 2                      | 3                         | 5                             |
| Heat storage capacity, Ws/(m²·°C) | 697.4 | 715.7 | 708.3 | 697.0 |
| Heat capacity, J/(kg·°C) | 2086.1 | 1420.6 | 1396.1 | 1040.4 |
| Thermal conductivity, W/(m·°C) | 0.18 | 0.20 | 0.21 | 0.27 |
| Thermal diffusivity, (m²/s)·10⁻⁸ | 6.8 | 7.6 | 7.8 | 14.5 |

The heat capacity of polyurethane is directly related not only to the chemical composition, molecular structure of the substance, but also to its density, which varies from 30 to 300 kg/m³. Therefore, the heat capacity can vary over a wide range of values with an average value of 1.38 kJ/(kg · °C). The thermal conductivity coefficient is in the range of 0.19 - 0.25 W/(m · °C).

A comparative analysis of the obtained (Table 1) and known values showed the following. The experimental values of the heat capacity of sheet polyurethanes practically correspond to the known values, although they differ somewhat in numerical terms. In view of the above, this discrepancy can be recognized as quite acceptable. The experimental value of the heat capacity of the injection polyurethane compound ADV 13-2 corresponds to the known value in order of magnitude, but differs significantly in numerical terms. The indicated discrepancy should be attributed to significant differences in the technologies for the production of materials. The experimental value of thermal conductivity practically corresponds to the known values.

Regards the thermophysical properties of PCM, the addition of PAP-1 aluminum powder in an amount of 54.5% made it possible to reduce the heat capacity by half, increase the thermal conductivity by half, and increase the thermal diffusivity of ADV 13-2 polyurethane compound by more than two.

Further development of the proposed technical solutions may be their adaptation to other types of functional composite materials, including those based on aluminum alloys [10-12].

4. Conclusions

A method is proposed for determining these properties, based on the well-known method for determining thermophysical properties by eliminating variables. The experimental values of the thermophysical properties of polymer composite materials with the addition of powder particles of various fractions of aluminum, iron, carbon and copper are obtained. The values obtained by the proposed method can be generally considered as satisfactory, and the method itself is recommended for practical use in the development of new polymer composite materials.

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