Nondestructive method of thermophysical properties monitoring and its implementing system using microwave heating

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Abstract. An adaptive microprocessor information-measuring system is proposed, in which a new method of determining thermophysical characteristics (heat conductivity and temperature conductivity) of construction materials is implemented by measuring the temperature of two points on the surface of a sample exposed to pulse thermal impact from the microwave radiation of the given power focused into a line. If the steady state excess temperature at the checkpoint is equal to the set value, the repetition rate and the number of pulses are adaptively set by the system. Experimental verification confirmed the operability of the system implementing the proposed method as well as the correctness of the theoretical conclusions underlying the method.

1. Introduction

Today, in order to save energy resources in the construction of facilities for various purposes, newly synthesized materials are used, which, compared to natural traditional materials, have lower coefficients of heat and temperature conductivity. This is an undeniable advantage, as it solves the problem of energy saving, which is currently relevant due to the growing cost of energy carriers. Furthermore, the modern industry of nanotechnologies makes it possible to upgrade the already existing construction materials by the use of nano-additives. This results in significant improvement of the characteristics of building materials and changes their thermophysical properties. For example, in [1] the ideal characteristics of nano-enhanced materials, their thermophysical properties, applications, and the problems of this new material are discussed. However, information on new thermophysical characteristics (TPC) of such materials is insufficient to assess their thermal protection properties.

Traditional methods are those that use contact heating of the test material. For example, in [2] a method in which the test material is placed between two materials with known thermophysical characteristics is described. One of the disadvantages of this method is the long testing time. In [3] a contact method to determine the thermophysical properties of composite materials is used as well. A common disadvantage of such methods is the influence of contact thermal resistance at the points of contact of the heater and the thermocouple with the object under investigation, which introduces significant errors in the measurement results.

Methods for investigating the thermophysical properties of materials using infrared thermography are well known. For example, in [4], a number of such methods are considered to obtain information on
heat losses through building enclosures. In [5] a method for determining thermophysical parameters of bamboo is proposed. However, the proposed method strongly depends on the humidity of the test sample.

Special attention is given to nondestructive monitoring methods using microwave energy as a source of heat exposure. They allow measuring the thermophysical parameters of the analyzed materials non-invasively and without damaging the analyzed materials and articles. However, most existing methods are aimed at detecting defects in materials. For example, in [6] the microwave techniques for nondestructive monitoring and evaluation of the structural integrity of glass fibre-reinforced polymer composites, also used in the construction field, are applied. In [7] the integrated approaches to the nondestructive monitoring of building materials and structures, including microwave sensing techniques developed for the nondestructive monitoring of flat and sloping building materials in civilian infrastructure are discussed. In [8] the contactless microwave method and the corresponding information and measuring system for determination of thermophysical properties of construction materials and products is considered.

Obviously, the methods of monitoring, using microwave energy as a source of heating of the test materials and articles, have a number of significant advantages, such as contactless, which allows to eliminate the influence of contact thermal resistances and to improve measurement accuracy, agility, preservation of integrity of the test materials and articles, as it is not necessary to produce a sample for carrying out research of his thermophysical properties. Therefore, the development of such methods is an urgent task.

2. Methods and materials
Non-destructive microwave methods of determining the TPC of materials and articles are based on the use of dependence of temperature change on the surface of the investigated objects on their thermophysical properties when absorbing a certain dose of microwave radiation. Since most building materials are heterogeneous, the use of microwave energy makes it possible to warm up a large volume of the material under study. This enables to get integral and volume-averaged TPC values and thus more accurate and reliable data on the thermal shielding properties of the building material. Besides, it is not necessary to manufacture samples, and therefore the object of monitoring does not need to be dismantled or suspended its operation, it is not necessary to interfere physically in the investigated medium.

Methods of determining thermophysical characteristics of materials and articles are based on analytical theory of thermal conductivity, thermodynamics, mathematical physics, theory of electromagnetic field and electromagnetic wave propagation, metrology and metrological experiment.

The theory of propagation of electromagnetic waves in SHF range in loss dielectric materials, which are the most construction materials, is well developed. In addition, the industry produces a sufficient number of different microwave equipment, which makes it easy to develop information and measurement systems for the implementation of microwave methods of non-destructive monitoring of TPC.

A new non-destructive method of monitoring TPC using microwave heating and its implementing system, which allows determining heat conductivity and thermal conductivity of finished products is proposed in this article. The proposed method is as follows.

Since the penetration depth of the electromagnetic field of the SHF range, and therefore the speed of scattering (loss) in the depth of the dielectric, is most dependent on the frequency of microwave radiation, the surface of the analyzed object is affected by a pulse of a high-frequency electromagnetic field (microwave radiation) with a frequency of not less than 20 GHz. At this frequency, almost all thermal power of the construction materials is released in the near-surface layer with a depth of 1-2 mm. Thus microwave radiation is focused with a lens made of radiotransparent material into a line with a length of at least 8-10 cm, and a width of about 0.2 cm. The length of the microwave exposure line is set to an order of magnitude greater than the distance from this line to the temperature control point so that terminal effects caused by limited length of the thermal exposure line do not affect the temperature field to be monitored.
First, the object under investigation is heated with a single pulse of the given power $Q$, and the time interval $\tau_{\text{imp}}$ is determined from the beginning of the thermal action to the moment when the temperature at the control point becomes equal to the initial temperature of the $T_0$. After that the pulse repetition frequency is determined [9],

$$F_{\text{min}} = \min \left( \frac{1}{\tau_{\text{imp}}} \right)$$  \hspace{1cm} (1)

at which there is no temperature increase in the investigated object.

Then the frequency of heat pulses supply is increased by law

$$\Delta F = F_{\text{min}} + K_{i} \Delta T_{i} + \frac{1}{K_{2} \tau_{i}} \int_{0}^{\tau_{i}} \frac{\Delta T(\tau)}{d\tau} d\tau + K_{3} \int_{0}^{\tau_{i}} \frac{d \Delta T(\tau)}{d\tau} d\tau$$  \hspace{1cm} (2)

where $\Delta T(\tau) = T_{\text{set}} - T(x_1, \tau)$ – the difference between beforehand preset value $T_{\text{set}}$, established in a point $x_1$, and the current value of controlled temperature; $\Delta T_{i} = T_{\text{set}} - T(\tau_{i})$ – the difference between the preset and current temperature in the time points determined by a ratio $\tau_{i} = K_{4} \sum_{k=1}^{i} \Delta T_{k}$; $K_{1} \div K_{4}$ – proportionality coefficients which values are set in $K_{1}=1 \div 10$ ranges; $K_{2}=1 \div 100$; $K_{3}=1 \div 50$; $K_{4}=0$, $1 \div 1$. The frequency increase is performed until steady-state value of excess temperature at control point becomes equal to preset value $T_{\text{set1}}$, with defining the repetition rate of thermal pulses $F_{x1}$. After that the frequency of thermal pulses supply is increased until value of excess temperature at control point becomes equal to the second preset value $T_{\text{set2}}$. In this case, the frequency of heat pulses supply is determined $F_{x2}$ (figure 1). The temperature values are set to be 20-30% lower than the thermodestruction temperature of the test material. This avoids melting or burning of the material and preserves its integrity.

![Figure 1](image.png)

**Figure 1.** Heating thermogram and type of thermal impact at adaptive change of frequency of thermal pulses.

The TPC required are calculated from the formulas prepared as follows. The process of heat propagation on the thermally insulated from the environment surface of a semi-infinite in terms of heat body under the action of a linear heat source is described by solving the problem of thermal conductivity, which has the form [10]:

$$T(x, \tau - \tau_{i}) = \sum_{i=1}^{n} \frac{q_{u}}{2\pi\lambda(\tau - \tau_{i})} \exp \left[ -\frac{x^2}{4\alpha(\tau - \tau_{i})} \right]$$  \hspace{1cm} (3)
where \( x \) is the distance from the linear heat source to the control point, m; \( \tau \) – time, s; \( \tau_i \) – the moment of application of the \( i \)-th thermal impulse on the surface of a body, s; \( \lambda \) – the product thermal conductivity coefficient, \( \text{W/(m-K)} \); \( q_0 \) is the amount of heat generated from the unit length of the linear source, \( \text{J/m} \); \( a \) – coefficient of temperature conductivity, \( \text{m}^2/\text{s} \).

Taking advantage of the decomposition into a series \( e^x = \sum_{i=0}^{\infty} \frac{x^i}{i!} \), we limit ourselves to two components, since the value of \( x \) is close to zero, and from (3) we get a system of equations to determine the steady-state temperatures at the control point

\[
T_{set1} = \frac{QF_{x1}}{2\pi\lambda}\left(\sum_{i=1}^{n_1} \frac{x^2F_{x1}}{4a} \sum_{i=1}^{n_1} \frac{1}{i^2}\right),
\]

\[
T_{set2} = \frac{QF_{x2}}{2\pi\lambda}\left(\sum_{i=1}^{n_2} \frac{x^2F_{x2}}{4a} \sum_{i=1}^{n_2} \frac{1}{i^2}\right).
\]

By performing mathematical transformations of formulas (4) and (5), we obtain expressions for determining coefficients of heat conductivity and temperature conductivity

\[
a = \frac{x_1^2}{4} \sum_{i=1}^{n_1} F_{x1} \sum_{i=1}^{n_1} \frac{1}{i^2} - T_{set2} F_{x1} \sum_{i=1}^{n_1} \frac{1}{i}.
\]

\[
\lambda = \frac{QF_{x1}}{2\pi T_{set1}} \sum_{i=1}^{n_1} \exp\left(-\frac{x^2F_{x1}}{4ai}\right).
\]

For the practical implementation of the proposed microwave method, a microprocessor information-measuring system (IIS) has been developed, the diagram of which is shown in figure 2.

![Figure 2. Diagram of microprocessor IIS implementing adaptive microwave method of non-destructive monitoring of TPC of construction materials and articles.](image-url)

In order to carry out microwave impact on the analyzed sample (1) electromagnetic radiation of the microwave generator (2) with a lens made of radiotransparent material (3) is focused into a line (4) of specified dimensions. Heating of the analyzed object (1) is performed by pulse impact of high-frequency electromagnetic field along the line (4) from radiating horn antenna (5) with lens (3) installed in it and
connected to microwave generator (2). After microwave exposure, excess temperature on the thermally
insulated from the environment surface of the investigated object at the control point located at distance
x from electromagnetic exposure line is monitored by contactless primary measuring transducers (PMT)
(6) of infrared temperature focused on the surface of the investigated object, which is connected to a
microprocessor (10) through a switch (7), normalizing precision amplifier (8) and analog-to-digital
converter (ADC) (9). In the experiment, the distance x is usually 15 mm. The microprocessor (10) is
connected via an I/O port (11) to the microwave generator (5) and the switch (7), normalizing an algorithm based on the procedures of the proposed method. The experiment data is output to the indicator (12). Using the measurement information obtained during the thermophysical experiment, in the microprocessor (10), the desired TPC is calculated using algorithms based on the analytical ratios (6) and (7) describing thermal processes in the analyzed semi-limited in terms of heat
object. Figure 3 shows a block diagram of the operation of the microprocessor IIS, which implements
the developed method.

3. Results and discussion
In order to verify the operability of the proposed method, experiments were carried out on the
construction materials such as silicate brick, claydite concrete and foam concrete. Heating of the samples
was carried out at ambient temperature 20 ± 2 °C. The surface of the analyzed sample during
experiments is heat-insulated from the environment, except for the line of thermal impact and
temperature control point x (in the heat-insulating coating there is a slot of specified sizes for linear
heating and an opening for focusing the contactless PMT).

The experimental test data of the proposed method for silicate brick, claydite concrete and foam
concrete are shown in table 1. For estimation of method error the reference data on investigated materials
are given. The heating temperature of the test materials and articles is $T_{set1} = 55 ^\circ C$ and $T_{set2} = 70 ^\circ C$.

| Table 1. Determination of TPC of the construction materials. |
|---|---|---|---|---|---|
| No | $\tau_{rel}, \ s$ | $F_1, 10^2 \ Hz$ | $F_2, 10^2 \ Hz$ | Data obtained from the proposed method | Reference data | Error of the proposed method |
| | | | | $a \cdot 10^{-6}, \ m^2/s$ | $\lambda, \ W/(m \cdot ^\circ C)$ | $a \cdot 10^{-6}, \ m^2/s$ | $\lambda, \ W/(m \cdot ^\circ C)$ | $\delta a \cdot 10^{-6}, \ %$ | $\delta \lambda, \ %$ |
| Silicate brick | | | | | | | | | |
| 1 | 442 | 11.3 | 12.4 | 0.511 | 0.664 | 0.558 | 0.721 | 8.42 | 7.91 |
| 2 | 438 | 10.7 | 11.6 | 0.513 | 0.665 | 0.558 | 0.721 | 8.06 | 7.77 |
| 3 | 441 | 11.1 | 12 | 0.512 | 0.663 | 0.558 | 0.721 | 8.24 | 8.04 |
| 4 | 439 | 10.9 | 11.8 | 0.511 | 0.664 | 0.558 | 0.721 | 8.42 | 7.91 |
| 5 | 443 | 11.5 | 12.8 | 0.512 | 0.663 | 0.558 | 0.721 | 8.24 | 8.04 |
| Claydite concrete | | | | | | | | | |
| 1 | 697 | 7.9 | 8.3 | 0.259 | 0.516 | 0.283 | 0.562 | 8.48 | 8.19 |
| 2 | 703 | 8.2 | 8.5 | 0.260 | 0.517 | 0.283 | 0.562 | 8.12 | 8.01 |
| 3 | 702 | 7.4 | 8 | 0.261 | 0.518 | 0.283 | 0.562 | 7.77 | 7.82 |
| 4 | 704 | 7.7 | 8.4 | 0.261 | 0.518 | 0.283 | 0.562 | 7.77 | 7.82 |
| 5 | 698 | 7.5 | 8.2 | 0.260 | 0.517 | 0.283 | 0.562 | 8.12 | 8.01 |
| Foam concrete | | | | | | | | | |
| 1 | 765 | 7.6 | 8 | 0.220 | 0.300 | 0.239 | 0.326 | 7.95 | 7.97 |
| 2 | 769 | 8.3 | 8.8 | 0.219 | 0.299 | 0.239 | 0.326 | 8.37 | 8.28 |
| 3 | 766 | 7.8 | 8.5 | 0.221 | 0.301 | 0.239 | 0.326 | 7.95 | 7.97 |
| 4 | 765 | 7.8 | 8.2 | 0.220 | 0.300 | 0.239 | 0.326 | 7.95 | 7.97 |
| 5 | 768 | 8.3 | 8.9 | 0.219 | 0.299 | 0.239 | 0.326 | 8.37 | 8.28 |
Figure 3. Block diagram of operation of the microprocessor IIS of the developed adaptive microwave method of non-destructive monitoring of TPC of construction materials and articles.
The results obtained during the experiment show that the proposed method is faster than the known methods of determining thermophysical properties of materials and articles, is suitable for determining TPC of anisotropic heterogeneous construction materials due to heating of a large volume of the analyzed material. The accuracy of the proposed method is also confirmed by the results of the experiment. The possibility of non-contact heating using microwave energy and temperature control by non-contact sensors allows investigating the TPC of the finished products without the need to dismantle or destroy the analyzed product for sample production, as well as significantly increases the accuracy of the obtained results. Noise protection of the method is increased by taking of measurement information in digital form, rather than in analog form, as in known methods.

4. Conclusion
The analysis of the data given in the table showed the operability of the proposed method, the novelty of which is as follows. First, since the adaptive search for the optimum thermal impact allows to heat the investigated objects to a preset temperature, which is taken by 20-30% lower than the temperature of thermodestruction of this material, the method makes it possible to monitor thermophysical characteristics without damaging the integrity and operational characteristics of the investigated objects, guaranteed to exclude melting and burning of the material.

Second, heating of the analyzed object and temperature measurement are carried out contactless, that allows avoiding influence of contact thermal resistance in the contact zone of the heater and temperature measurement sensors and improving measurement accuracy.

Third, in the proposed method, information control is carried out in frequency-pulse form (while in traditional methods – in analog form), which significantly reduces the share of random component of measurement error due to reduction of impact of random interference on informative parameter.

Fourth, since most construction materials are dispersed and heterogeneous, the reliability of the results is improved by heating a large volume of construction material to produce an integral and volume-averaged controlled temperature.

The experimental test showed that the proposed method is sufficiently accurate for the technological monitoring of TPC of the investigated materials and products, which allows using it in the practice of thermophysical measurements, in construction heat engineering and in various industries.

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