Algorithmic support for solution of classification problems and image recognition of the studied objects by the intelligent information and measuring system

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Abstract. At the manufacturing plants producing thermal insulation materials that are used in a climate of the Arctic, non-destructive testing of thermo-physical properties to ensure the quality of the products is necessary. Therefore, the use of intelligent information and measuring system with appropriate algorithmic software to control the thermo-physical properties of the objects under study is important and relevant. The aim of research is to improve the accuracy and efficiency of determining thermo-physical properties as a result of solving the classification and image recognition problems of the studied objects in production and operation to prevent deterioration of thermal insulation properties under the effect of external influential factors. Image recognition algorithms are proposed for cases when the processed information is reliable or falls into the category of fuzzy. The algorithm of decision-making in the intelligent measuring system for the choice of the non-destructive testing method of thermo-physical properties in accordance with the class of materials under study is presented. The results of experimental studies of the intelligent information and measuring system implementing the developed algorithms for image classification and recognition of the studied objects are represented, these results confirming the increase in the accuracy of non-destructive testing in thermo-physical properties of materials.

1. Introduction

To ensure the quality of manufactured materials, various methods for operational non-destructive parameters testing in thermo-physical properties (TPP) of the studied objects are used [1–5], these parameters being thermal conductivity and thermal diffusivity coefficients (λ and α). TPP material control is performed at the stages of industrial processes in manufacturing and the conformance of the output TPP parameters to the normalized values is checked. When choosing thermal insulation for buildings and structures, as well as during the operation of facilities in a climate of the Arctic, it is necessary to control the thermo-physical properties of the used thermal insulation materials, since the heat-shielding coating is adversely affected by external destabilizing factors (DF).

An important step in determining the thermo-physical properties of the materials under study (MS) in intelligent information and measuring system (IIMS) [6] is the classification of study objects. As a result of the studied materials classification, the class of the material under study is determined by the dominant feature of TPP of materials, that is thermal conductivity. According to the classification results, intelligent image recognition procedures and the selection of the appropriate method of non-destructive testing for TPP of materials are implemented, and measurement situation for each class of materials under study is determined. When performing thermal-physical measurements, generation of measurement situation lies in choosing one of the applied methods and the optimal regime parameters for measuring TPP of materials (heat exposure power, number and duration of thermal pulses acting the studied object). The classification results are evaluated by the loss functions and misclassification probability.

IIMS using artificial intelligence methods are considered in the works of famous foreign scientists Laghi, L., Pennecchi, F. and Raiteri, G., the founders of intelligent measurements, ambient intelligence systems and smart environments (Ambient Intelligence & Smart Environments) [7]. In the works of Russian scientists V. N. Romanov, V. S. Sobolev, V. I. Tsvetkov, and G. G. Rannev the issues of smart instrumentation development are stated [8]. The analysis of the papers shows that the represented IIMS are not of a high-speed performance and have a significant measurement error of studied parameters due to the influence of destabilizing factors.

2. Problem statement

The research objective is to develop algorithmic support for solving problems of classification, image recognition and selection of a method for non-destructive testing of thermo-physical properties of the studied objects to improve the accuracy of TPP material control [9].

Then the classification of parameters and properties that characterize the SM and affect the thermo-physical measurement is to be performed. For certain measuring situations the limits, measures of proximity and existing relationships of parameters and properties of the materials under study should be determined. Then the loss function and the probability of misclassification should be evaluated. Image recognition is performed on the basis of intelligent decision-making procedures depending on the degree of reliability of information obtained, that is either to calculate the Euclidean distance or apply fuzzy set theory.

The task to create intelligent decision-making procedures to choose the control method of thermo-physical measurements corresponding to a certain measurement situation is stated.

3. Theory

The algorithm for classification of the studied materials is as follows. SMs are described using criteria and parameters that are taken into account in the corresponding formed sets in the formalized description of the materials under study. Information about the study materials are specified either a priori or based on experimental data obtained before a thermo-physical measurement when performing test measuring experiments. Test measurements allow one to preliminary estimate parameters of thermo-physical properties and to specify the class of the studied materials.

Image recognition methods are used to process the obtained measurement information. According to the degree of information reliability, two methods are used.

Method 1. It is used if the measurement information is reliable.

To determine the class of SM, the Euclidean distance $d(O_i,O_j)$ is calculated according to the following dependence [10]

$$d(O_i,O_j)=\sqrt{\sum_{k=1}^{\pi}\nu_k(\bar{d}_{ik}-\bar{d}_{jk})^2}\ ,$$

where ν_k are the weight coefficients of the *k*-th indicator, which are determined for the *i*-th and *j*-th material (O_i,O_j). When setting the indicator as an interval value, the Euclidean distance $\bar{d}_{ik}\left(\bar{d}_{jk}\right)$ is determined by the class mark.

$$\bar{d}_{ik} = 0{,}5\left(d_{ik}^{1} + d_{ik}^{\mathrm{h}}\right),$$

here d_{ij}^{1}, d_{ij}^{h} are the lower and upper limits of the interval value of the *j*-th characteristic for the *i*-th SM, respectively.

The importance and dimension of the *k*-th parameter take into account the weight coefficient calculated by the formulas

$$\nu_k = C_k\left(\frac{d_k^{\max} - d_k^{\min}}{2}\right)^{-2}, \quad k = \overline{1,\pi},$$

$$d_k^{\max} = \max_i\left\{\bar{d}_{ik}, i = \overline{1,N}\right\}, \; d_k^{\min} = \min_i\left\{\bar{d}_{ik}, i = \overline{1,N}\right\}.$$

The coefficient C_k is selected from the conditions

$$\sum_{k=1}^{\pi} C_k = 1, \; C_k \in (0;1) \text{ or } \forall k \in \{1;\pi\}, \; C_k = 1.$$

Method 2. It is used if the measurement information is fuzzy. In this case, the theory of fuzzy sets, which are assigned on the basis of membership functions, is applied.

Figure 1 and 2 show the example of the membership function for TPP parameters of different class materials (thermal diffusivity (α) and thermal conductivity coefficient (λ)).

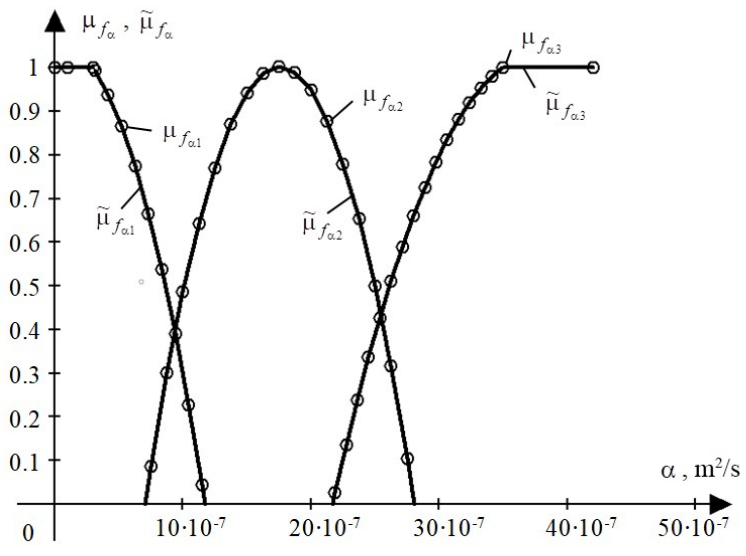

Figure 1. Characteristic curves of fuzzy set membership functions $\mu_{f_{\alpha s}}$.

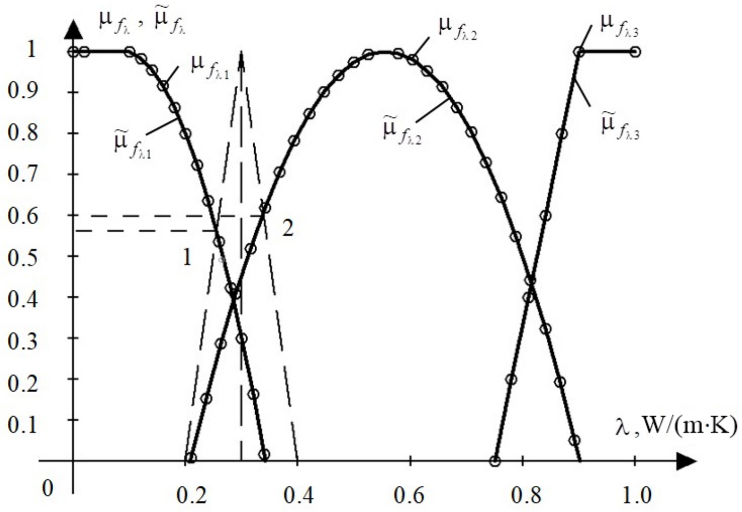

Figure 2. Characteristic curves of fuzzy set membership functions $\mu_{f_{\lambda K}}$.

For the thermal diffusivity fuzzy sets $\mu_{f_{\alpha s}}$, $s = 1; 2; 3$ (Figure 1) are defined by membership functions, which are represented as analytical expressions (1)-(3):

$$\tilde{\mu}_{f_{\alpha 1}}(\alpha) = \begin{cases} 1, \quad \alpha \in \left[0; 3 \cdot 10^{-7}\right); \\ -0.008\alpha^2 + 0.008\alpha + 1.0, \quad \alpha \in \left[3 \cdot 10^{-7}; 12 \cdot 10^{-7}\right); \\ 0, \quad \alpha \geq 12 \cdot 10^{-7}; \end{cases} \tag{1}$$

$$\tilde{\mu}_{f_{\alpha 2}}(\alpha) = \begin{cases} 0, \quad \alpha \leq 7 \cdot 10^{-7}; \\ -0.009\alpha^2 + 0.318\alpha - 1.787, \quad \alpha \in \left[7 \cdot 10^{-7}; 28 \cdot 10^{-7}\right); \\ 0, \quad \alpha > 28 \cdot 10^{-7}; \end{cases} \tag{2}$$

$$\tilde{\mu}_{f_{\alpha 3}}(\alpha) = \begin{cases} 0, \quad \alpha \leq 22 \cdot 10^{-7}; \\ -0.004\alpha^2 + 0.313\alpha - 4.816, \quad \alpha \in \left[22 \cdot 10^{-7}; 34 \cdot 10^{-7}\right); \\ 0, \quad \alpha \geq 34 \cdot 10^{-7}. \end{cases} \tag{3}$$

For the coefficient of thermal conductivity, the corresponding membership functions (Figure 2) are described by the dependences (4)-(6):

$$\tilde{\mu}_{f_{\lambda 1}}(\lambda) = \begin{cases} 1, \quad \lambda \in [0; 0.1]; \\ -15\lambda^2 + 2.5\lambda + 0.9, \quad \lambda \in [0.1; 0.35); \\ 0, \quad \lambda \geq 0.35; \end{cases} \tag{4}$$

$$\tilde{\mu}_{f_{\lambda 2}}(\lambda) = \begin{cases} 0, \quad \lambda \leq 0.21; \\ -8.333\lambda^2 + 9.25\lambda - 1.567, \quad \lambda \in [0.21; 0.9); \\ 0, \quad \lambda > 0.9; \end{cases} \tag{5}$$

$$\tilde{\mu}_{f_{\lambda 3}}(\lambda)=\begin{cases}0, & \lambda<0.75;\\ -6.667\lambda-5, & \lambda\in[0.75;0.9);\\ 1, & \lambda\geq 1.\end{cases} \tag{6}$$

The algorithm for selecting the TPP control method for SM is performed using the fuzzy set membership function based on the linguistic approximation procedure and includes the following:

1. The dominant feature of SM q_{d} properties is established.

2. The user specifies the range of expected values q_{d}, that is, $[q_{\mathrm{d}}^{\mathrm{l}}, q_{\mathrm{d}}^{\mathrm{h}}]$ and the degree of membership $SP_{\mathrm{per}}=0.1$.

3. The membership function of a triangular form using class limits and taking into account the dominant feature as a fuzzy set is constructed.

$$\mu_f(q_{\mathrm{d}})=\begin{cases}0, & (q_{\mathrm{d}}<q_{\mathrm{d}}^{\mathrm{l}})\cup(q_{\mathrm{d}}\geq q_{\mathrm{d}}^{\mathrm{h}});\\ \dfrac{q_{\mathrm{d}}-q_{\mathrm{d}}^{\mathrm{l}}}{\Delta q_{\mathrm{d}}}, & q_{\mathrm{d}}\in(q_{\mathrm{d}}^{\mathrm{l}}, q_{\mathrm{d}}^{0});\\ \dfrac{q_{\mathrm{d}}^{\mathrm{h}}-q_{\mathrm{d}}}{\Delta q_{\mathrm{d}}}, & q_{\mathrm{d}}\in(q_{\mathrm{d}}^{0}, q_{\mathrm{d}}^{\mathrm{h}}).\end{cases} \tag{7}$$

4. Points of intersection $\mu_f(q_{\mathrm{d}})$ with $\mu_{f\,s}(q_{\mathrm{d}})$, $s=1;2;3$ and the degree of membership for these points SP_1, SP_2 of the studied materials to a certain class are defined.

5. The selection of the appropriate method to determine TPP of materials is performed according to the rules:

IF $|SP_1-SP_2|>SP_{\mathrm{per}}$, THEN the method that corresponds to $SP_{\max}$ is applied;

IF $|SP_1-SP_2|<SP_{\mathrm{per}}$, THEN it is recommended to use two methods corresponding to the adjacent classes.

The following notation is introduced in the rules: SP_{per}, $SP_{\max}$ are the degrees of membership, the maximum and allowable, respectively.

Let us consider the algorithm for the second method, which is used in the IIMS of materials TPP, the membership functions are given in the expressions (4) - (6) and Figure 2: λ is the thermal conductivity coefficient and is the dominant attribute; the user specifies the tentative lower λ^{l} and upper λ^{h} limits of the range of SM thermal conductivity, $\lambda^{\mathrm{l}}=0.2$ W/(m * K) $\lambda^{\mathrm{h}}=0.4$ W/(m·K); for the average value of the thermal conductivity coefficient $\lambda_{\mathrm{avg}}=0.3$ W/(m·K) $\mu_{\max}$ is determined (the maximum value); using (7) a triangular membership function is constructed μ_{λ}; a set of linguistic variable λ is checked for the conformance of membership formulas μ_{λ_1}, μ_{λ_2} is checked for the conformance to membership functions $\mu_{f_{\mathrm{SM}}}$; the degrees of membership to classes 1 and 2 are found, which are equal to 0.55 and 0.60, for intersection points 1 and 2 and for the membership functions $\mu_{f_{\lambda_1}}$ and $\mu_{f_{\lambda_2}}$; if $\mu_{f_{\lambda_2}}\approx\mu_{f_{\lambda_1}}$ the examined material corresponds to the boundary of classes 1 and 2. In this case, the TPP is controlled by two methods that are defined for these classes. Measurement results are presented in the form of average values obtained using the recommended methods.

When there are no membership functions, in addition to the considered algorithm for selecting the method of TPP control of the SM, an algorithm based on production rules is used. Production rules are given as an example:

IF $V_{\mathrm{dat}}^{i}\equiv V_1$ and $V_{\mathrm{req}}^{i}\in\{V_{\mathrm{n}}, V_{\mathrm{s}}\}$ and $V_{\mathrm{DF}}^{n}\equiv V_{\mathrm{DF}}^{1}$ and $V_{\mathrm{dis}}^{m}\in\{V_{\mathrm{det}}, V_{\mathrm{fuz}}\}$, THEN $h_{i,j,n,m}\in H_1$ and $V_{\mathrm{M}}=V_{\mathrm{M1}}$;

IF $V_{\text{dat}}^{i} \equiv V_2$ and $V_{\text{req}}^{i} \in V_{\text{req}}$ and $V_{\text{DF}}^{1} \in V_{\text{DF}}$ and $V_{\text{dis}}^{m} \in \{V_{\text{amb}}, V_{\text{fuz}}\}$, THEN $h_{i,j,n,m} \in H_2$ and $V_{\text{M}} = V_{\text{M2}}$;

IF $V_{\text{dat}}^{i} \equiv V_3$ and $V_{\text{req}}^{i} \in V_{\text{req}}$ and $V_{\text{DF}}^{n} \in V_{\text{DF}}$ and $V_{\text{dis}}^{m} \in \{V_{\text{amb}}, V_{\text{fuz}}\}$, THEN $h_{i,j,n,m} \in H_3$ and $V_{\text{M}} = V_{\text{M3}}$,

where H_1, H_2 are the subsets that are used when linear or planar heater is used in the measuring probe pulse techniques; H_3 are the subsets that are used if the method of constant heat and flat heater is applied; $V_{\text{dat}} = \{V_s^{\text{dat}}, s = 1,\ldots,k_{\text{dat}}\}$ is the set of data about the characteristics of SM (density, thermal conductivity and thermal diffusivity, etc.); $V_{\text{req}} = \{V_{\text{n}}^{\text{req}}, V_{\text{s}}^{\text{req}}, V_{\text{f}}^{\text{req}}\}$ is a set of requirements to the geometric dimensions of the studied materials, here $V_{\text{n}}^{\text{req}}$, $V_{\text{s}}^{\text{req}}$ are normal and small sizes of SM; $V_{\text{f}}^{\text{req}}$ is the shape of SM; $V_{\text{dis}} = \{V_{\text{det}}, V_{\text{amb}}, V_{\text{fuz}}\}$ is the set for data ambiguity levels of the studied material, where, $V_{\text{det}}, V_{\text{amb}}, V_{\text{fuz}}$ are, respectively, the deterministic, ambiguous and fuzzy types of information; $V_{\text{DF}} = \{V_{\text{l}}^{\text{DF}}, V_{\text{avg}}^{\text{DF}}, V_{\text{h}}^{\text{DF}}\}$ is the set of data on the influencing DF, here, V_{l}^{DF}, $V_{\text{avg}}^{\text{DF}}$, V_{h}^{DF} are, respectively, low, medium and high levels of DF; $V_{\text{M}} = \{\text{M}_i, i = 1,\ldots,k_{\text{M}}\}$ is the set of non-destructive testing methods used in IIMS of materials TPP, where M_i is the *i*-th control method.

4. Experimental results

The proposed methods applied in the image recognition and choice of methods for determining the parameters of TPP of SM (the coefficients of thermal conductivity and diffusivity) are implemented in intelligent information and measuring system for non-destructive testing of TPP materials, this system being fully functional in the production of insulating materials. The results of experimental studies of IIMS to determine the coefficients of thermal conductivity and diffusivity (λ and α) of the SM are represented in table.1.

Table 1. Results of experimental studies of iims.

MATERIALS UNDER STUDY	λ and α REFERENCE		λ and α MEASURED		ERRORS OF MEASUREMENTS	
	$\alpha \cdot 10^{-7}$, m^2/s	λ, W/m·K	$\alpha \cdot 10^{-7}$, m^2/s	λ, W/m·K	δ_α, %	δ_λ, %
Plastic foam	5.12	0.034	5.33	0.035	4.10	2.94
Mineral wool	3.74	0.052	3.92	0.054	4.81	3.85
Felt	3.98	0.07	4.15	0.073	4.27	4.28
Polymethylmethacrylate	1.09	0.195	1.13	0.201	3.67	3.08

Analysis of the experimental study results for IIMS of materials TPP allows us to establish that the relative measurement error for the coefficients of thermal conductivity and diffusivity (δ_α and δ_λ) is not more than 5% and is within the permissible limits for this class of measuring instruments, which indicates an increase in the accuracy of IIMS.

5. Results discussion

The problem of the studied materials classification with the operating conditions of SM being taken into account, and the requirements for the accuracy of measurement results was formulated and solved.

The algorithm for classification of the studied materials is developed, the novelty being in the use of test measurements for preliminary assessment of the SM class and methods of image recognition.

Algorithms of selecting the non-destructive testing method for TPP of SM differ in the use of the linguistic approximation technique or production rules.

The algorithmic support for solution of the stated problems improves accuracy and efficiency of determining the TPP of materials, since the class of SM, method of control and relevant operating parameters are pre-determined before performing thermal measurements in IIMS. As a result, the user receives promptly reliable and accurate information about the TPP of the SM.

6. Conclusion

The classification algorithm is applied for studying the TPP of the studied objects of IIMS based on the implementation of intelligent decision-making procedures in image recognition and choice of one of the methods used for non-destructive testing of thermal properties of materials.

The results of the classification should be used in the development of adequate mathematical models of the studied materials and identification of SM using the obtained models.

Intelligent decision-making procedures for the recognition of IM images are proposed, in which two methods are used in accordance with the degree of reliability of the obtained measurement information: when information is reliable, Euclidean distance is calculated; when measurement information is fuzzy, mathematical apparatus of the fuzzy sets theory is used, these sets being assigned using membership functions.

The choice of the method for determining the TPP of the studied materials in accordance with the measuring situation is performed using intelligent decision-making procedures based on the membership functions of fuzzy sets and production rules.

A practical example of the application of image recognition methods in determining the SM class by thermal conductivity and choosing the appropriate method of non-destructive testing of materials TPP is considered.

The use of the developed algorithmic support in the IIMS in solving problems of classification and image recognition allows us to increase the efficiency and accuracy of determining the parameters of TPP of materials with a permissible error for this type of measuring instruments of not more than 5%.

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