Intelligent information-measuring system for operational control of thermo-physical properties of heat insulating materials

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Abstract. The quality of materials is evaluated by non-destructive testing of their thermo-physical properties in the manufacturing process. A relevant aspect in determining the quality of products at the manufacturers is the development and application of an intelligent information and measurement system for operational control in the quality properties of heat insulating materials. The objective of the study is to improve the efficiency and accuracy of determining the thermo-physical properties of the test materials by solving the problem of reconfiguring the system structure in accordance with the specified algorithm of operation, making decisions on the choice of a method for non-destructive testing of thermo-physical properties of materials, and an approach to building the structure of an intelligent measuring system. The solution for the problem of system architecture configuration with artificial intelligence methods according to information and measurement situations in the operation of the system is proposed. Intelligent decision-making procedures are presented when choosing a method for controlling the thermo-physical properties of materials as a result of identifying the measuring situation. An approach to the construction of the intellectual information-measuring system structure for operational control of material quality properties based on the selection of system structure and control method for thermo-physical properties of materials adaptive to the class of test materials by thermal conductivity to improve the efficiency and accuracy of thermal measurements is created. The results of experiments to determine the thermo-physical properties of heat insulating materials using an intelligent information and measurement system are presented. The analysis of the obtained results confirms the control accuracy increase in the thermal properties of materials.

1. Introduction
At industrial enterprises producing heat insulating materials, prompt and accurate definition of thermo-physical properties (TPP) of materials by non-destructive testing (NDT) using intelligent information and measurement systems (IIMS) directly in the production shops is required to improve the quality of manufactured materials and reduce product defects.

Some information and measurement systems (IMS) are known, for example, TRSYS01 produced by Hukseflux (Delft, Netherlands). Laghi, L., Pennecchi, F., and Raiteri, G. describe the IMS manufactured by UnithermTM 2022 in their paper [1]. These systems determine the thermal conductivity of materials quite accurately, but less-than-promptly. In work [2], the IIMS is considered, which determines the thermal conductivity of materials promptly, but there is no remote control of the...
thermal conductivity. Intelligent information and measurement systems with artificial intelligence methods are considered in the works of well-known scholars abroad, the founders of intelligent measurements, ambient Intelligence and smart environments, namely D. Hoffman, and L. Finkelstein [3]. Intelligent systems described in the work of Karavaeva I. S. et al. are of low performance [4]. In the work of Rannev G. G., the issues of creating smart instrumentation are outlined [5]. However, having been analyzed, the IIMS proved to have insufficient accuracy of parameter measurements due to the influence of destabilizing factors.

The use of artificial intelligence methods in the IIMS of NDT TPP materials allows increasing the efficiency and accuracy of determining material TPP [6].

Material TPP control is performed at the stages of technological processes during their manufacture, and the conformance of the output TPP parameters with the reference values is checked. To ensure the quality of manufactured materials, various methods of operating nondestructive control of thermo-physical properties for the materials such as heat conductivity and thermal diffusivity coefficients ($\lambda$ and $\alpha$) are used. The method for determining the TPP of heat insulating materials is presented in [7]. Pulse methods are used to determine mass transfer characteristics in thin [8] and solid [9] products made of porous materials. To improve the control accuracy, various methods are used to search for optimal operating parameters of experiments [10]. The analysis of TPP material control methods in [11] shows that it is preferable to use pulse methods to determine the TPP of heat insulating materials.

The effectiveness of intelligent information and measurement systems for monitoring the TPP of materials is largely defined by the applied method of TPP material test and the IIMS architecture. Therefore, in thermo-physical measurements, it is important to select the structure, algorithm of functioning and method of TPP test in accordance with the class of thermal conductivity of the tested materials.

2. Problem statement
The problem of the research is to develop a methodology with artificial intelligence elements for reconfiguring the IIMS structure in accordance with the information situation of system operation. The next task is to create intelligent decision-making procedures for choosing a non-destructive testing method for thermo-physical measurements identifying measurement situation.

Another problem is to create an approach to construct the IIMS of NDT TPP for thermal insulating materials by choosing the appropriate system structure and operational method for NDT of material TPP with adaptation to the class of tested materials by thermal conductivity in order to increase efficiency and accuracy of thermal measurements.

The solution to the problems is based on the thermal conductivity theories and systems, and methods of artificial intelligence.

3. Theoretical basis
The tasks in choosing the structure of intelligent information and measurement systems and the method for determining the parameters of thermal properties in thermal insulating materials are aimed at improving the efficiency, accuracy of results and system performance in conducting thermo-physical measurements. When solving the problem of IIMS structure synthesis and algorithm of its functioning in accordance with the current information situation, it is necessary to reconfigure the system structural components using the created knowledge base for the given subject applying measurement and control functions implemented by the software module. The synthesis of a sustainable IIMS structure involves prompt calculation of optimal operating parameters for thermal measurements and decision-making when choosing the IIMS structure and adapting to the class of tested materials by thermal conductivity, as well as the accuracy of determined parameters of material TPP.

The problem of selecting the IIMS structure to control the thermo-physical properties of tested materials (TM), depending on the information situation, is formulated as follows. The following sets
are assigned. \( V_S = \{ V^{S}_{H}, V^{S}_{C}, V^{S}_{B} \} \) is the set IIMS structure (S) modules \( (V_{SH}, V_{SC}, V_{SB} \) are the structures for heat insulating materials TPP control of low \( (SH) \) [(0.02...0.04) W/m·K], average \( (SC) \) [(0.041...0.1)W/m·K] and high \( (SB) \) [(0.11...0.2)W/m·K] thermal conductivity, respectively, differing in structural components: smart sensors (SS), measurement channels (MC), knowledge bases (KB), stabilized power supply units (SPSU), micro-controllers (MC); \( V_M = \{ V^{M}_{1}, \ldots, V^{M}_{k} \} \) is the set of control methods which can be used in various IIMS structures, here \( V^{M}_{i} \) is the \( i \)-th control method; \( V_{MS} = \{ V^{MS}_{1}, \ldots, V^{MS}_{k} \} \) is the set of metrological support modules; \( V_{SW} = \{ V^{SW}_{1}, V^{SW}_{2}, V^{SW}_{3} \} \) is the set of software modules; \( V_{SM} = \{ V^{SM}_{1}, V^{SM}_{2}, V^{SM}_{3} \} \) is the set of mathematical software modules, which include models of tested materials, subject area, and decision making in IIMS; \( V_{IS} = \{ V^{IS}_{1}, \ldots, V^{IS}_{k} \} \) is the set of data intelligence modules; \( V_{TM} = \{ V^{TM}_{1}, V^{TM}_{2}, V^{TM}_{3} \} \) is the set of IIMS structures of the corresponding structure; \( V_{PR} = \{ V^{PR}_{1}, \ldots, V^{PR}_{k} \} \) is information about TM properties (thermal conductivity, thermal diffusivity, thermal capacity, density, etc.); \( V_{DF} = \{ V^{DF}_{1}, V^{DF}_{2}, V^{DF}_{3} \} \) is the set of data on destabilizing factors (DF) relative to the IIMS structures; \( V_{cin} = \{ V_{det}, V_{ind}, V_{fuz} \} \) is the set of TM information certainty levels \( (V_{det} \) is deterministic, \( V_{ind} \) indefinite, and \( V_{fuz} \) is fuzzy information).

Having specified the given sets, it is necessary to choose the structure of the intelligent information and measuring system \( V_{S_{i}} \in V_S \), \( i = 1, \ldots, 3 \) that corresponds to the featured sets. The general problem includes subproblems. The first is to develop a mathematical structure of the set defining the measurement situations \( H \), then to build the model "Information situation – IIMS structure" (IS - IIMS), next to identify the information situation and, finally, to choose the structure of the system. Designing an intelligent system and creating a KB the first two subproblems are solved, and at the beginning of the thermo-physical measurement the second two subproblems are solved.

To form a set of information situations, the Cartesian product of the given sets is used \( H \)

\[
H = V_S \times V_M \times V_{SW} \times V_{SM} \times V_{TM} \times V_{PR} \times V_{DF} \times V_{cin} = \{ h_{i,j,l,n,m,c,d,p,b,f} \} : i \in \{ H, C, B \}, j = 1, \ldots, k_{CH}; l = 1, \ldots, k_{MS}; n \in \{ SIP, SMP, SHP \} ; m = \{ SIM, SMM, SHM \}; c = 1, \ldots, k_{CI}; d \in \{ SIT, SMT, SHT \}; p = 1, \ldots, k_{PR}; b \in \{ SID, SMD, SHD \}; f \in \{ det, ind, fuz \} \}
\]

The elements \( h_{i,j,l,n,m,c,d,p,b,f} \) in the set \( H \) that correspond to the information situations are specified as the tuples:

\[
h_{i,j,l,n,m,c,d,p,b,f} = \{ V^{S}_{i}, V^{M}_{j}, V^{SW}_{n}, V^{MS}_{m}, V^{IS}_{c}, V^{TM}_{d}, V^{PR}_{p}, V^{DF}_{b}, V^{cin}_{f} \} .
\]

Creating a sustainable structure of an intelligent measurement system \( (V_{S_{i}} \in V_S) \), such system structure is selected that corresponds to the specified input data and certain information situations.

When solving the problem \( q \) - of subsets \( H_{i}, i = 1, \ldots, q \) are defined in the structure of the set \( H \). For these subsets, one specific structure of an intelligent information and measurement system is usually used.

When implementing the "IS – IIMS" model, production rules are used in accordance with the selected subsets \( q \) – in the set structure \( H \):

\[
\text{IF } h_{i,j,l,n,m,c,d,p,b,f} \in H_{i}, \text{ THEN we apply the structure of the system } V_{S_{i}} ;
\]

\[
\ldots
\]
IF \( h_{i,j,n,m,c,d,p,b,f} \) \( \in \mathbf{H}_q \), THEN we apply the structure of the system \( V_{s_i} \).

The result of solving problems when choosing the structure of an intelligent information and measurement system can be in finding structurally similar systems. In this case, the optimization problem is solved by taking into account the probabilities for choosing the optimal variant of the system structure.

The choice of a valid method to control thermal properties of heat insulating materials is a complex task that is solved under conditions of uncertainty, if the classes of tested materials in terms of thermal conductivity and the acting destabilizing factors are unknown. The selected sustainable method must correspond to the measurement situation in the process of thermo-physical measurements. The measurement situation is determined by the technical characteristics of the test objects, the measurement conditions, the requirements for the efficiency and accuracy of measurements, and the imposed restrictions.

A formalized representation of the solution to the problem of selecting a method for controlling the TFS of materials is presented as follows. The following sets are assigned:

a) data on the thermo-physical properties of the tested materials, namely, thermal conductivity, thermal diffusivity, thermal capacity, density, etc.

\[ V_{PR} = \{ V_{s}^{PR}, s = 1, \ldots, k_{PR} \} \]  

(1)

b) information about the requirements for the geometric dimensions of the study object

\[ V_{req} = \{ V_{n}^{req}, V_{sm}^{req}, V_{sh}^{req} \} \]

(2)

where \( V_{n}^{req}, V_{sm}^{req}, V_{sh}^{req} \) are the TM dimensions, normal and small respectively, and the shape of the tested material;

c) levels of destabilizing factors

\[ V_{DF} = \{ V_{n}^{DF}, V_{m}^{DF}, V_{h}^{DF} \} \]

(3)

where \( V_{n}^{DF}, V_{m}^{DF}, V_{h}^{DF} \) are the DF levels, low, medium, and high, respectively;

d) levels of information certainty about the test objects

\[ V_{fuz} = \{ V_{det}, V_{ind}, V_{fuz} \} \]

(4)

where \( V_{det}, V_{ind}, V_{fuz} \) is deterministic, indefinite, and fuzzy information, respectively;

e) methods used in the intelligent measurement system (pulse method with linear or flat heaters, methods with a flat heater and constant heating)

\[ V_{m} = \{ V_{i}^{m}, i = 1, \ldots, k_{M} \} \]

(5)

where \( V_{i}^{m} \) is the \( i \)-th control method.

Using sets (1) - (4), it is necessary to select the control method \( V_{i}^{m} \in V_{m} \) that matches the information provided in the sets.

When solving the problem of selecting the method for TPP material control of TFS, a mathematical structure is developed for the set "measurement situation" \( \mathbf{H} \), a model "Measurement situation – control method" is created, the measurement situation is identified, and then the choice of control methods is made.

Using the Cartesian product of sets (1) – (4) allows us to form the set \( \mathbf{H} \)

\[ \mathbf{H} = V_{PR} \times V_{req} \times V_{DF} \times V_{fuz} = \{ h_{i,j,n,m,c,d,p,b,f}, i = 1, k; j \in \{ n, m, h \}, n \in \{ n, m, h \}, m \in \{ \text{det, ind, fuz} \} \} \]

(6)
The elements $h_{i,j,n,m}$ of the set $H$ determine a number of measurement situations that are defined by the following tuples:

$$h_{i,j,n,m} = \left\{ V^\text{PR}_i \times V^\text{req}_j \times V^\text{DF}_n \times V^\text{CRM}_m \right\}$$

At the stages of the intelligent information and measurement system life cycle, it is possible to correct the set (6) as a result of changing the constituent elements of the sets (1) – (5).

When constructing the "Measurement Situation – Control Method" model, in the set $H$, $k$ - of the subsets $H_i, i = \overline{1,k}$ with the following conditions are extracted:

a) as a result of any pairs of subsets $H_i \subset H, H_j \subset H$ intersection, an empty set is formed

$$H_i \cap H_j = \emptyset, i, j = \overline{1,k}, i \neq j; \quad (7)$$

b) the elements of the subsets $H_i, i = \overline{1,k}$ define the measurement situation $h_{i,j,n,m}$

$$\bigcap_{i=1}^{k} H_i = H; \quad (8)$$

c) one of the control methods applied $V_i^m$ is included in each subset $H_i$.

The application of conditions (7), (8) determines the solution of the problem in which the set $H$ includes disjoint subsets $k$.

This specific problem has the following important features, for example, if for one set (1) – (4), one of the elements cannot be defined in a real situation. Thus, the set $V^\text{DF}_n$ includes destabilizing factors related to the level $V^\text{DF}_n$ and to the level $V^\text{DF}_m$. For this case, the set $V^\text{DF}$ is supplemented with the element $V^\text{DF}_m$.

The considered partition of the set $H$ allows us to develop a model "Measuring Situation – Control Method", in which production rules are applied:

IF $h_{i,j,n,m} \in H_i$, THEN we apply the non-destructive testing method $V_i^m$,

$$\ldots$$

if $h_{i,j,n,m} \in H_k$, THEN we apply the non-destructive testing method $V_k^m$.

The formation of production rules (9) involves the use of various criteria to evaluate the functioning of the intelligent information and measurement system: errors of measurement, performance, and complex indicators. The IIMS knowledge base contains information that is used to solve the multivariate splitting problem and to quickly determine the most appropriate method for nondestructive control of the TPP parameters of materials during the operation of the system.

The general task in selecting NDT methods in an intelligent system includes the following tasks.

The first is to determine the set of methods (DSM) used in the system without taking into account the IIMS intelligent sensors (DSM task 1).

The second is to determine the set of methods used in the system, taking into account the IIMS intelligent sensors (DSM task 2).

Setting the DSM1 task.

It is necessary to define a subset $V^i_m \subseteq V_m$ using known information about TM (1) - (2), destabilizing factors (3), methods for NDT of material TPP (5), permissible values of measurement
errors $\Delta Y_{\text{prm}}$ and efficiency $\Delta T_{\text{prm}}$, ensuring the implementation of the applied restrictions to the accuracy and efficiency indicators when determining the thermo-physical properties of materials

$$\Delta Y \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}} \right) \leq \Delta Y_{\text{prm}},$$

$$\Delta T \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}} \right) \leq \Delta T_{\text{prm}},$$

where $\Delta Y \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}} \right)$, $\Delta T \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}} \right)$ are the error and efficiency values obtained when using a set of methods $V^1_{\text{m}}$ for certain values $V_{\text{pr}}, V_{\text{req}}$ and $V_{\text{DF}}$.

Setting the DSM 2 task is characterized by the introduction of an additional restriction on the number of SS used in the measurement system ($N_{\text{ms}}$). Then the inequalities (10) - (11) can be represented as follows

$$\Delta Y \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}, N_{\text{ms}}} \right), \Delta T \left( \frac{V^1_{\text{m}}}{V_{\text{pr}}, V_{\text{req}}, V_{\text{DF}}, N_{\text{ms}}} \right).$$

The considered problems used in the selection of methods and formation of the set of NDT methods for material TPP include an element $V^1_{\text{m}} \in V_{\text{s}}$ that means the method of thermal influence on the study object and determination of heat insulating material TPP using the fundamental theory of thermo-physics. A component of this method is the processing measurement information technique, which allows us to increase the accuracy and reliability of non-destructive testing in TPP parameters of materials.

The proposed solutions in choosing the structure and method of control for material TPP parameters ($P_{\text{TPP}}$) are used to create an intelligent information and measuring system and enhance the efficiency and accuracy of nondestructive testing of insulating material TPP.

The developed IIMS with a reconfigurable structure is shown in Figure 1.

**Figure 1.** Block diagram of IIMS for TPP NDT of heat insulating materials.

The methodological support module includes the applied methods for controlling the TPP of materials. The software module contains programs for implementing methods to determine the TPP of TM, selecting the structure of IIMS and the method of NDT for material TPP depending on the class of thermal conductivity for heat insulating materials, and the algorithm for the intelligent measurement system operation. The metrological support module includes methods for calculating and analyzing errors in measurement results and their characteristics. The IIMS structure module performs the functions of connecting the corresponding module $V^1_{\text{s}}, V^1_{\text{M}}, V^1_{\text{MSM}}, V^1_{\text{SW}}, V^1_{\text{SW}}, V^1_{\text{IS}}$ with the structure.
selection and experiment control device (SS and ECD) employing decision-making procedures and the knowledge base.

The knowledge base includes information on study subjects, data for each measurement situation, and information on operating parameters of the implemented method and algorithm for determining the TPP. Smart sensors are comprised of a micro-controller as part of the measuring circuit that implements functional procedures for obtaining information from temperature sensors in thermophysical measurement. This micro-controller corrects measurement data taking into account influencing factors, technical self-diagnostics and metrological self-control. Also the structural components of SS are a measuring cell with an appropriate heater depending on the class of material to generate the required power of the thermal effect on the tested material and sensors to control temperature when the material is heated, normalizing amplifiers and analog-to-digital converters. A liquid-crystal display (LCD) indicates the defined material parameters $P_{tpp}$.

4. Experimental results

The results of experimental studies of IIMS parameters for material TPP, namely, thermal conductivity and thermal diffusivity coefficients ($\lambda$ and $\alpha$), that implement the proposed approach to building IIMS, are shown in table.1.

| Study subjects                      | Reference information | Experimental information | Measurement errors |
|-------------------------------------|----------------------|--------------------------|--------------------|
|                                     | $\alpha \cdot 10^{-7}$, m$^2$/s | $\lambda$, W/mK          | $\lambda$, W/mK    | $\delta_{\alpha}$, % | $\delta_{\lambda}$, % |
| Semi-rigid mineral wool             | 3.93                 | 0.043                    | 4.08               | 0.045               | 3.82                  | 4.65                  |
| Polymethylmethacrylate              | 1.08                 | 0.199                    | 1.03               | 0.209               | 4.62                  | 5.00                  |
| vinyl leather-HT                    | 1.55                 | 0.056                    | 1.48               | 0.058               | 4.52                  | 3.57                  |
| Wood                                | 4.84                 | 0.152                    | 4.60               | 0.159               | 4.96                  | 4.61                  |
| Mineral cotton "Izolayt"           | 6.60                 | 0.032                    | 6.40               | 0.033               | 3.03                  | 3.13                  |

Data analysis of the experiments of IIMS for material TPP allows us to establish the relative error of thermal conductivity and thermal diffusivity coefficients ($\delta_{\alpha}$ and $\delta_{\lambda}$) measurement being 3-5% and within acceptable limits for this class of measuring instruments, and this indicates the increased accuracy of IIMS.

5. Results discussion

The solution to the problem of selecting the structure of the IIMS for NDT of material TPP, with the use of a formalized representation of the structure in the form of mathematical sets and production rules is presented, the information situation for each class of test materials being taken into account.

The problem of selecting the method for material TPP control with the adaptation of this method to the level of thermal conductivity of the test material is solved.

The approach to building the intelligent information-measuring system for TPP NDT of heat insulating materials with selecting the structure of IIMS and TPP control method that correspond to the class of test materials by thermal conductivity is created.

6. Conclusion

The problem of reconfiguring the IIMS structure is solved in accordance with the information situation of the system functioning and the use of artificial intelligence methods.

The proposed solution to the problem of choosing the method to determine the test material TPP is implemented using intelligent decision-making procedures with measuring situation and production rules being identified.
The approach to build the structure of IIMS for insulating material TPP NDT by choosing the IIMS structure and NDT method of material TPP adaptive to the class of test materials by thermal conductivity to improve the efficiency and accuracy of material TPP parameters is created.

The proposed approach makes it possible to exclude additional measurement procedures and, consequently, increase the efficiency and accuracy of determining the thermal conductivity and thermal diffusivity coefficients of thermal insulation materials with a relative measurement error of 4-5%.

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