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Simulation of intelligent information-measuring systems of thermophysical properties of materials and products

Z M Selivanova[1*], D S Kurenkov[1] and T A Hoang[2]

[1]*Tambov State Technical University*, Tambov, Russian Federation
[2]*High Tech Information Center - Vietnam Communication Troops*, Hanoi, Vietnam

[*1]E-mail: selivanova@mail.jesby.tstu.ru
[2]E-mail: futurevip1608@mail.ru

Abstract. The article contains a formalized description of functioning of intelligent information measuring system for non-destructive testing of materials and products thermal properties. System simulation has been fulfilled, and as a result of it the mathematical models for transformation of measurement data in the intelligent system in Mathcad software during thermophysical measurements. The mathematical pattern of decision-making in the intelligent system allows to improve the accuracy of parameter determination of thermophysical properties of tested materials and the efficiency of the functioning system.

Introduction

The functioning of intelligent information measuring system (IIMS) in thermophysical measurements in the face of uncertainty is connected with solving the actual problem of formalized description of IIMS. The uncertainty in process of thermophysical measurements includes: vagueness of the mathematical description of the structure of the system and its constituent elements, models of tested materials, external factors, operation algorithm of IIMS, measuring methods for testing thermophysical properties of materials and products, metrological support, information and measurement situations. Moreover, there is the complexity of accounting for external and internal factors that affect the materials studied, the system and process of thermophysical measurements, limited and insufficient reliability of a prior and current information.

IIMS using methods of artificial intelligence are shown in works of famous foreign scientists that are founders of smart measurements, ambient intelligence and smart environments – D. Hofmann and K. Karaya [1]. Works of Russian scientists (Romanova V.N., Soboleva V.S., Tsvetkova V.I., Ranneva G.I.) contain problems of creation of intelligent measuring instruments [2]. Analysis of the works shows that studied IIMS have not enough high speed and significant measurement errors of the parameters studied due to destabilizing factors.

The aim of this investigation is to improve the accuracy of determining the parameters of the thermophysical properties of material (TPM) as a result of using data of simulation IIMS in Mathcad software taking into account the above types of uncertainty.

Results and discussion

The formalized description of IIMS when operating under uncertainty is represented by the following sets [3-5]:

a) a set of operating modes of IIMS:

$$\boldsymbol{Y} = \{Y_i\}, \quad (1)$$

where $i = 1,2,\ldots,n$ – quantity of IIMS modes ($Y_к$ –control mode, Y_u – thermophysical measurement mode, Y_o – processing mode of measurement results);

b) a set of structures of IIMS:

$$\boldsymbol{S} = \{Y_i\}, \quad (2)$$

where $j = 1,2,\ldots,m$ – quantity of IIMS structures (the structure of the system for the implementation of thermophysical measurements in the assessment of the parameters of the material thermophysical properties: low, medium and high thermal conductivity);

c) a set of information situations:

$$\boldsymbol{I} = \{I_k\}, \quad (3)$$

where $k = 1,2,\ldots,l$ – quantity of information situations in the functioning of IIMS (information situations include data from the intelligent database of the system about thermophysical properties of tested materials, measuring methods, structures of IIMS, methods of metrological analysis and processing of the thermophysical measurements, of the acting destabilizing factors, the user and the expert information, information accuracy (deterministic, vague, fuzzy);

d) a set of measurement situations:

$$\boldsymbol{X} = \{X_c\}, \quad (4)$$

where $c = 1,2,\ldots,p$ – quantity of measuring situations in functioning of IIMS (measurement situations are formed on the basis of the analysis of the test results of thermophysical measurements and include information about the ranges of the materials thermal conductivity, methods of thermophysical measurements, acting destabilizing factors, optimal operating parameters of thermophysical measurements);

e) a set of tested materials:

$$\boldsymbol{M} = \{M_N\}, \quad (5)$$

where $N = 1,2,\ldots,d$ – quantity of materials under study during thermophysical measurements for different ranges of the materials thermal range (low, medium, high);

f) a set of control signals of IIMS :

$$\boldsymbol{U} = \{U_v\}, \quad (6)$$

where $v = 1,2,\ldots,q$ — quantity of control signals in the implementation of the modes of IIMS operation (control signals transfer IIMS from the control mode to the measurement modes and then the results processing of thermophysical measurement; implementation of the selected measurement method, the optimal mode parameters, the structure of IIMS depending on the information and measuring situations).

On the basis of the above mentioned information it follows that each state of the functioning of IIMS under uncertainty is characterized by a six consisting of elements of six sets (1)...(6) $\boldsymbol{Y}$, $\boldsymbol{S}$, $\boldsymbol{I}$, $\boldsymbol{X}$, $\boldsymbol{M}$, $\boldsymbol{U}$,and a state of the IIMS in the functioning under uncertainty can be written in the form of the set:

$$Q = \{Y_i, S_j, I_k, X_c, M_N, U_v\}.$$

In formalizing the functioning modes description of IIMS Y_i for thermophysical measurements, we take into account that each operation mode of MS Y_i corresponds to the structure of IIMS, the information and measuring situation, tested material. In turn, the operation modes of IIMS are implemented by control signals U_v .

Consequently, the implementation of the operation modes of IIMS is carried out in three functional situations:

a) functional situation control mode:

$$\{y_c, U_v\};$$

b) functional situation of the thermophysical measurement mode:

$$\{y_m, U_v\};$$

c) functional situation of the processing mode of measurement results:

$$\{y_p, U_v\}.$$

Thus, the set of states of IIMS when functioning in conditions of uncertainty can be divided into three subsets Q_1, Q_2, Q_3, which elements include the elements of the set Q:

$$(Q_1, Q_2, Q_3) \in (\boldsymbol{Y} \times \boldsymbol{S} \times \boldsymbol{I} \times \boldsymbol{X} \times \boldsymbol{M} \times \boldsymbol{U}).$$

To ensure the accuracy of determining of the materials thermophysical properties of IIMS, mathematical models of signals from the measuring probe of Mathcad software system are developed and investigated [6-8].

When transmitting the measuring information of IIMS the transmitted signal is affected by perturbing effects of a random nature, as a result of which random functions are introduced into the mathematical model of the signal from the measuring probe (7) corresponding to the measured temperature under the thermal influence of the linear heater on the product under study:

$$T(x,\tau) = L(\tau) \cdot \frac{C}{\tau} \exp\left(\frac{D}{\tau}\right) + F(\tau), \tag{7}$$

where $T(x,\tau)$ – temperature; $L(\tau)$ и $F(\tau)$ – functions corresponding to random errors of the measurement probe of IIMS as a result of destabilizing factors, $\frac{Q}{4\pi\lambda} = C$; $-\frac{x^2}{4\alpha\tau} = D$; Q – thermal power; τ – time; x – distance from control point to linear heat source, λ and α – thermal and temperature conductivity coefficients characterizing the thermophysical properties of tested materials and products.

Model parameters (7) in Mathcad software are determined by the interval values:

$$C \in [0\ldots 50];\ D \in [100\ldots -50];\ L(\tau) \in [0{,}5\ldots 10];\ F(\tau) \in [0\ldots 0{,}001].$$

Mathematical model of transformation of the measuring information $U(\tau)$ in IIMS of thermophysical properties of materials is presented in the general form [9]:

$$U(\tau) = B(\tau) + F(\tau), \tag{8}$$

where $B(\tau)$ –function depending on the signal of the measuring probe of IIMS, entering the measuring channel of the system; $F(\tau)$ – random function not depending on the signal that generates noise or an additive interference.

A mathematical model of the measuring channel of IIMS (8) has been developed, taking into account the conversion of the signal from the measuring probe:

$$B(\tau) = T(x,\tau)S(\tau) = T(x,\tau)[K_U + I(\tau)] + E(\tau) \tag{9}$$

where $S(\tau)$ – function corresponding to the process of converting the signal $T(x,\tau)$ in the measuring channel of the system; K_U – gain of measuring channel amplifier; $I(\tau)$ – function describing the distortion of the measuring signal in the amplifier ; $E(\tau)$ – function taking into account the error of the signal conversion in the analog-to-digital converter.

The noise model as an additive mixture of narrow-band random processes has the following view [10]:

$$F(\tau) = A(\tau)\cos[\omega(\tau) + \varphi(\tau)], \tag{10}$$

where $A(\tau)$, $\omega(\tau)$, $\varphi(\tau)$ – respectively the amplitude, the frequency and the phase of the random noise signal.

The mathematical model of the measuring channel of IIMS with use of dependence of transformation of a signal from the measuring probe $B(\tau)$ (9) and model of noise (10) is developed:

$$U(\tau) = T(x,\tau)[K_U + I(\tau)] + E(\tau) + A(\tau)\cos[\omega(\tau) + \varphi(\tau)].$$

The developed mathematical models for the conversion of measurement information in IIMS are used when conducting thermophysical measurements.

The block diagram of the developed IIMS for determining of thermophysical properties of materials and products that implements generated functional and measurement situations in the process of thermophysical measurements based on the created algorithmic, information and software provided in the developed knowledge base is shown in figure 1.

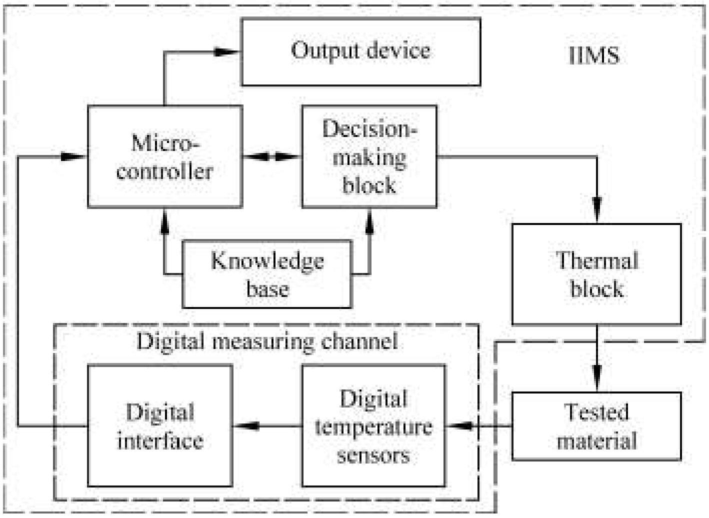

Figure 1. Block diagram of IIMS to control the thermophysical properties of materials and products.

The mathematical model that is offered was used when making decisions in IIMS to control the thermophysical properties of tested materials. Decision making in IIMS is based on the developed knowledge base and a number of criteria: time factor for the search of solutions, accuracy of the result with the assessment of accuracy and efficiency, obtaining optimal solutions based on the analysis of the measurement error of the parameters of the thermophysical properties of materials and products, time and computational costs in obtaining measurement results, the use of digital technologies for processing measurement information, the use of artificial intelligence (theory of fuzzy sets, pattern recognition) in identifying the thermal conductivity class of tested materials, the implementation of the synthesis of the corresponding IIMS structure, the metrological assessment of the determined parameters of the thermophysical properties of tested materials.

A mathematical model has been developed that is used in decision-making in an intelligent information-measuring system when the conditions for the functioning of the system are uncertain. The model is represented by the tuple:

$$\boldsymbol{M}_{dm} = \langle \boldsymbol{V}_m, \boldsymbol{V}_{tm}, \boldsymbol{V}_{ms}, \boldsymbol{K}, \boldsymbol{Z}, \boldsymbol{S}, \boldsymbol{V}_e \rangle,$$

where the following sets are given: $\boldsymbol{V}_m = \{V_i, i = 1,\ldots,m\}$ – applied methods; $\boldsymbol{V}_{tm} = \{V_{tm_i}, i = 1,\ldots,N\}$ – tested materials (TM); $\boldsymbol{V}_{ms} = \{V_{ms_i}, i = 1,\ldots,u\}$ – measurement situations; $\boldsymbol{K} = \{K_i, i = 1,\ldots,k\}$ – estimation test of thermophysical properties of materials and products; $\boldsymbol{Z} = \{Z_i, i = 1,\ldots,z\}$ – initial states of the measuring system; $\boldsymbol{S} = \{S_i, i = 1,\ldots,s\}$ – intelligent system structures, $\boldsymbol{V_e} = \{V_{e_i}, i = 1,\ldots,j\}$ – estimation methods of the effectiveness of the system (Dempster-Schafer, optimization of the operating parameters of IIMS).

The block diagram showing the stages of decision-making in IIMS to control the thermophysical properties of materials and products is presented in figure 2.

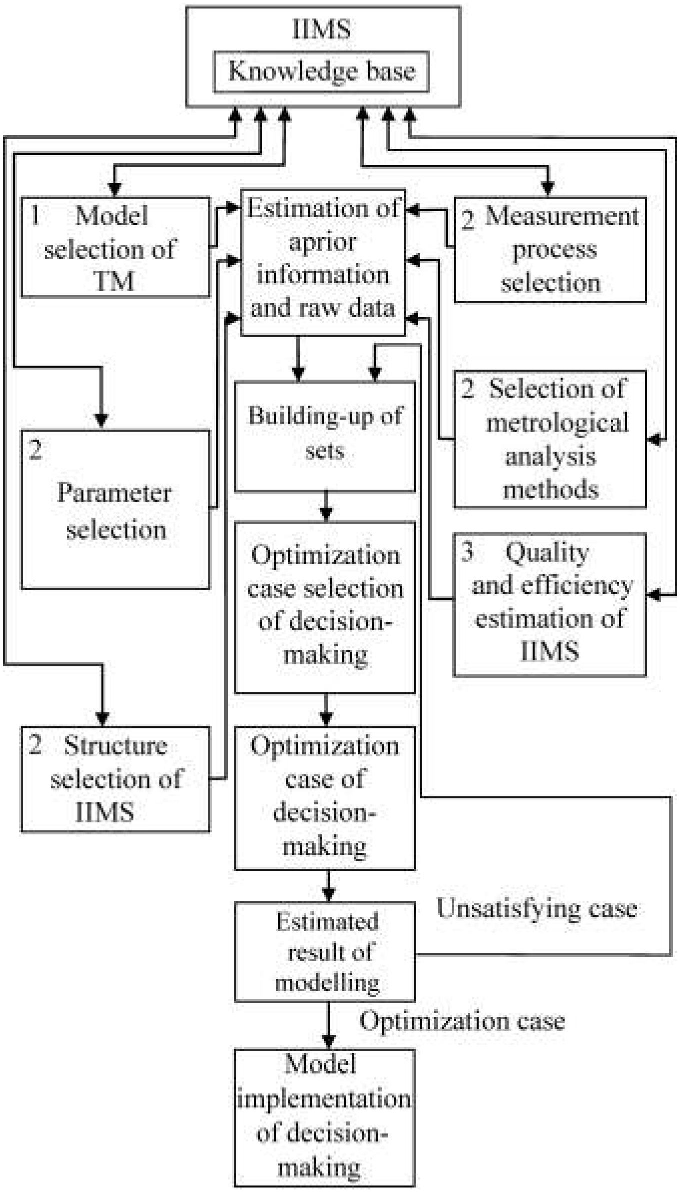

Figure 2. The block diagram of decision-making in IIMS to control the thermophysical properties of materials and products.

A mathematical model of decision-making in the system is used to assess the performance factor of IIMS based on the analysis of the properties of tested materials and products, the conditions and methods of conducting thermophysical measurements, the structures of the intelligent system, estimation test of thermophysical properties of tested materials and products.

As a result of making a decision in the measuring system the optimal algorithm of operating of IIMS and measuring procedures of thermophysical measurements are determined.

The effectiveness of IIMS is assessed as a result of a number of decisions: in accordance with the permissible ranges of measurement error of the thermophysical properties, checking the adequacy of the classification of tested materials as a result of monitoring the loss of inaccurate classification; loss of accuracy D_{ac} and efficiency D_{eff} when conducting thermophysical measurements based on the optimization of the optimality criterion taking into account the complex D_{ac} and D_{eff} ; the results of confidence estimation using the Dempster-Schafer method.

The estimation of efficiency of the developed mathematical signal models from the measuring probe is identified. Transformations of the signal mathematical models in the IIMS measuring channel are implemented to assess the accuracy of determining of thermophysical properties during non-destructive testing of IIMS using loss of accuracy in the process of determining of thermal properties of tested materials:

$$Q = P(N, M_s, M_c, \delta_{tpp}, \delta_t),$$

where N – set of tested materials; M_s – mathematical model of measuring probe signal; M_c – mathematical model of measuring channel in IIMS; δ_{tpp} – fractional error of the parameters of the thermophysical properties; δ_t – methodical error.

Conclusions

Here is the formalized state of IIMS concerning TPM of materials and products during functioning under uncertainty which allows to find informational and measuring situations for any functional mode in IIMS decision making.

Mathematical pattern has been made for making decisions in the system of uncertainty that allows to choose a functional situation for every functional mode.

Modeling of IIMS in Mathcad software has been carried out using mathematical patterns of the measuring channel, transferring measured information into IIMS, noise models that are different from those made in thermophysical measurements.

IIMS structural scheme has been made for TPM of materials and products that is unique in finding an optimal solution in uncertainty conditions; it allows to determine the parameters of thermophysical properties of materials promptly and with a relative error of no more than 5%.

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