Information support of the measuring device for choosing a thermophysical experiment data processing algorithm

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Abstract: This paper addresses the problem of constructing a subsystem of informational decision-making support for choosing the optimal method and algorithm for calculating the thermophysical properties of polymer composites, which allows minimizing the error in determining properties under given experimental conditions. The subsystem is based on a modified hierarchy analysis method. It is built on the alternative use of four algorithms for the calculation of thermophysical properties and is included as a module in the application software of an intelligent data-measuring device for studying the curing process of polymer composites. Using simulation modeling, an assessment of the possibility of using algorithms for calculating thermophysical properties under various combinations of experimental conditions was made. The structure, composition, principles of construction, purpose, capabilities and parameters of the main modules of the applied software of the data-measuring device are described.

1. Introduction
At the present stage of technological development the polymer composites (PC) are promising structural materials and are used in many industries, i.e. from the chemical industry to aeronautical and space technology. They are a combination of a polymer matrix (resin) and reinforcing fiber (glass, carbon or synthetic fiber, fabric or roving) and possess a set of unique physicochemical properties. The quality of polymer composite products and their properties are determined mainly by the properties of the ingredients and the temperature-time curing cycle. Therefore, the calculation of the optimal technological curing cycles of PC products is an important task [1-6]. Methods for calculating and optimizing PC cure cycles involve the use of mathematical models and the identification of the parameters of these models. One of the important parameters of the PC curing model is its thermophysical properties (TPP), both in the curing process and cured PCs. At the same time, the accuracy of determining TPP PC has a significant impact on the further use of the studied characteristics when calculating the optimal curing cycle for PC products [5-7].

The thermophysical properties of the polymer composites, i.e. volume heat capacity \( C(T, \beta, \gamma) \) and thermal conductivity \( \lambda(T, \beta, \gamma) \) are nonlinear functions of the degree of cure \( \beta \), temperature \( T \), and resin content \( \gamma \). The TPP of composites in the cured state, as well as other materials, can be determined in any conditions, by any method suitable for use. On the contrary, when determining TPP PC during the curing process, it is required to reproduce the temperature-time conditions corresponding to the curing cycle. Therefore, taking into account the specificity of the PC, it is necessary to conduct their research in conditions close to production, starting the study from the initial state of the PC - the prepreg to its...
final cured state - the composite [4-10]. In this case, these properties become in a certain sense effective, taking into account all the features of the curing process.

At present, many devices and methods have been developed for determining TPP, which have various features of their use, advantages and disadvantages. However, while there is no universal method and device for determining TPP, which gives equally good results in the study of any materials, in a wide range of temperatures and under any experimental conditions, including the curing process. Therefore, the definition and calculation of TPP in the curing process and cured PC will be based on the solution of the inverse heat conduction problem (IHCP) [11]. According to this, four methods were developed and, accordingly, four algorithms for processing experimental data and calculating thermophysical properties. However, each method and algorithm has individual features and limitations on the application. In addition, the accuracy of the results obtained and the stability of the computations of each algorithm differ with varying experimental conditions. For this reason, it is impossible to find a universal algorithm that would provide the minimum error in the calculation of TPP PC regardless of the experimental conditions. Therefore, when determining TPP, it is necessary to conduct numerical processing of the experimental results according to the available algorithms, compare the calculation results and select one of them. The task is nontrivial, since the comparison of the results of the algorithms requires the presence of an expert who is able to assess the compliance of the calculated TPPs with real values. In addition, this process can be lengthy. These arguments make it necessary to automate the decision-making process for choosing an algorithm that provides the minimum error in the calculation of TPP PC.

Therefore, an urgent task and goal of this work is the development of mathematical and algorithmic software built on the basis of various methods for determining TPP PC during heating and curing, and capable, analyzing the input conditions, to give the user recommendations on choosing the optimal TPP method with the minimum error.

2. Experimental equipment
To determine the TPP PC and study the curing process as a whole, a data-measuring device (DMD) was developed, a detailed description of which and the stages of its development are given in [5, 12].

The developed DMD for the study of PC properties provides the following functions: communication of the measuring system with the object of study; registration and conversion of information; numerical processing of experimental data (primary data processing, that is, preliminary processing of the initial experimental data, and secondary processing, that is, the calculation of the desired parameters of the material under study based on the solution of inverse problems); visual presentation and preservation of the initial conditions of the experiment and the results of processing; regulation and maintenance of the specified research conditions, experiment planning, management of the experiment; documenting the results; computer simulation of the experiment; verification of the adequacy of the experimentally studied parameters of the applied mathematical model.

The structure of the providing DMD subsystems for studying the properties of PCs, their components and interrelations between them is presented in figure 1 and includes:

- technical support is a set of technical means;
- software is a collection of all software procedures, system and application software (AS);
- information support are methods of information display and storage of data on the state of the object under study for further use in the system and the central part of the information support is the database;
- mathematical support is a set of mathematical models, methods and algorithms;
- organizational and methodological support is a set of documents establishing the composition of the DMD, operating rules, etc.

The DMD software for determining TPP PC includes system software and application software.

Application software is a set of software modules that form the basis of DMD for determining TPP PC. Delphi 7 was chosen as the AS creation tool. It provides rapid development of various software applications, the convenience of which lies in the presence of many built-in ready-to-use components
for various programming areas and user-friendly interface. The block diagram of the application software is presented in figure 2.

Figure 1. The structure and interconnections of the DMD supporting subsystems.

Application software includes five modules:

- control module, it provides input in the dialogue cycle of information on the experiment, the management of the experiment, the collection and preservation of experimental and calculated information in the database;
- calculation module of TPP PC, it performs calculations based on the initial data received from the control module of experiment [5, 12];
- information visualization module, it provides a graphical representation of experimental and calculated data;
- simulation module, it performs model simulation experiments on testing algorithms for calculating the thermophysical properties of PC;
- decision support module (DSM) for choosing the optimal calculation method, based on the data on the results of the experiment, it allows you to choose the best method and algorithm for calculating the TPP, which provides the minimum methodological error.

According to this goal, a mathematical apparatus was developed for DMD, including four methods for determining TPP, on the basis of which we proposed:

- algorithm for calculating TPP as a function of time using temperature inside the sample;
- algorithm for calculating TPP as a function of time using temperature on the sample surfaces;
- algorithm for calculating TPP as a function of temperature based on the integral transformation of the inverse problem of heat conduction in the form of solving an integro-functional equation using temperatures inside the sample [11];
- algorithm for calculating TPP as a function of time based on Kalman filter.

Based on the algorithmic support the DMD, the application software has been developed, which is part of the thermophysical properties calculation module.
Figure 2. The block diagram of the DMD application software.

The choice of the best TPP calculation algorithm is made by the decision support module, which significantly helps the DMD user to correctly process the experimental data. After selecting the algorithm, the TPP is calculated and visualized in the form of graphs and tables [13]. The calculation of TPP by all algorithms is also provided. The visualization of the calculations will be displayed on a single graph to be able to compare the results.

3. Subsystem of support for decision-making

The basis of the subsystem of information support for decision-making on the choice of the optimal algorithm for calculating TPP is a modified hierarchy analysis method designed to solve multicriteria problems with a finite set of possible solutions [14]. The fundamental complexity of the problems of choice in many criteria lies in the impossibility of a priori determination of the best solution. To build a decision-making model for choosing the TPP calculation method, we will present it in the form of a hierarchical structure: the target is placed on the first level, the criteria composition is placed on the second level, and many alternatives are placed on the third level. Therefore, the essence of the method is to use a matrix of pairwise comparisons, built on the basis of expert data on the relative importance of the criteria.

The purpose of the subsystem is to calculate the TPP with the minimum methodological error under the specified conditions of the experiment. The goal can be achieved by choosing one of the alternatives - one of the TPP calculation methods. The choice of the most successful of the alternatives is made on the basis of their comparison with each other by criteria. In our case, as criteria, it is rational to use the list of experimental conditions and evaluate the actual operability of the algorithm and the error depending on the criterion.

On the basis of multiple numerical experiments on simulation using the DMD simulation module, matrices of method estimates are built according to the criteria. Having obtained the experimentally specific values of the criteria from the matrices, the actual operability and error of the method are
evaluated for each criterion. It is necessary to evaluate the criteria by degree of importance in order to obtain a total assessment of the alternative for all criteria. For this reason, a matrix of pairwise comparisons is constructed. Thus, we obtain an analytical model of the decision support process on the choice of the optimal calculation method:

$$MDS =< Z, Al, Kr, Kz, Sm, Sak, Wk, Kk >,$$

(1)

where $Z$ – purpose of building DSM; $Al = \{al_{jk}\}, \ jk = 1,...,\nu$ – alternative vector, $\nu$ is number of alternatives; $Kr = \{kr_{ik}\}, \ ik = 1,...,\mu$ – criteria name vector, $\mu$ – number of criteria; $Kz = \{kz_{ik}\}, \ ik = 1,...,\mu$ – criteria value vector; $Sm = \{sm_{jk}\}, \ jk = 1,...,\nu$ – vector of the overall assessment of each of the alternatives according to all the criteria; $Sak = \{sak_{ik,jk}\}, \ ik = 1,\mu, \ jk = 1,...,\nu$ – assessment matrix of alternatives for each criterion; $Wk = \{wk_{ik}\}, \ ik = 1,...,\mu$ – criteria weight vector; $Kk = \{kk_{ik,jk}\}, \ ik = 1,...,\mu, \ jk = 1,...,\mu$ – matrix of pairwise comparisons criteria.

It is required to choose one of the elements of the vector of alternatives $al^* \in Al$, which corresponds to the minimum overall score for all criteria:

$$al^* \rightarrow sm^* = \min(sm_{jk}), \ jk = 1,...,\nu.$$  

(2)

The vector of the total assessment of alternatives is calculated as:

$$sm_{jk} = \sum_{ik=1}^{\mu} sak_{ik,jk} \cdot wk_{ik}.$$  

(3)

To obtain a matrix for evaluating methods according to several criteria, we perform simulation experiments, having previously determined the list of criteria $Kr$:

- thickness of sample ($kr_1$);
- temperature difference across the thickness of sample ($kr_2$);
- experiment time ($kr_3$);
- number of measuring thermocouples located along the sample thickness ($kr_4$);
- temperature measurement error ($kr_5$).

Simulation modeling is carried out on the basis of a sequential enumeration of various predictable situations that arise during the measurements of TPP, by changing the values of one criterion with the same values of other criteria and obtaining calculation errors for all methods. After completion of calculations with a change in the value of one criterion, it is necessary to proceed to the next and so on. As a result, we obtain a set of value ranges for each criterion and a corresponding set of TPP error values calculated by each of the methods. The obtained data are recorded in the form of a set of rules of the knowledge base in the format:

$$If \ \ k_{\mu} = [d_{k_{\mu}}^{i_1}, ...], \ h_k = 1...\chi_{ik} \ \ Then \ \ e_{i_hk}^{d_{i_hk}},$$

$$...$$

$$If \ \ k_{\mu} = [d_{k_{\mu}}^{i_1}, ...], \ h_k = 1...\chi_{ik} \ \ Then \ \ e_{i_hk}^{d_{i_hk}},$$

$$...$$

where $[d_{k_{\mu}}^{i_1}, ...], \ h_k = 1...\chi_{ik}, \ ik = 1,...,\mu$ – ranges of possible values for each criterion; $e_{i_hk}^{d_{i_hk}}$ – error values in the calculation of TPP by each of the algorithms in different ranges of criteria values; $\chi_{ik}$ – number of value ranges for criterion $kr_{ik}$.
Using the rules of the knowledge base (4) for specific experimental conditions, a matrix is built for evaluating TPP calculation methods according to the formulated criteria $K_r$.

The weight vector of criteria $W$ is determined by constructing a matrix of pairwise comparisons, which is obtained on the basis of expert estimates. One of the criteria is selected, with which it is most convenient to compare all the others. Then the expert determines how many times the weight of the first criterion is greater than the weight of the second. Next, the first criterion is compared with the third, and so on, sequentially. After such comparisons, the numbers $k_{11}, k_{12}, \ldots, k_{1\mu}$ will be obtained. The remaining elements of the matrix of pairwise comparisons are determined by the formula:

$$k_{ik,jk} = \frac{k_{i1,jk}}{k_{i1,ik}}, \quad ik = 1, \ldots, \mu, \quad jk = 1, \ldots, \mu.$$  \hfill (5)

At the next stage, weights are calculated based on the constructed matrix of pair comparisons (5), which characterize the relative importance of the criteria:

$$w_{ik} = \frac{k_{i1,ik}}{k_{i1,jk}}, \quad ik = 1, \ldots, \mu - 1, \quad w_{i\mu} = 1.$$  \hfill (6)

Finally, weights (6) are normalized and used to calculate the total estimate of alternatives (3) by the formula:

$$w_{ik} = \frac{w_{ik}}{\sum_{jk=1}^{\mu} w_{jk}}, \quad ik = 1, \ldots, \mu.$$  \hfill (7)

After that, the optimal method and algorithm for calculating the thermophysical properties of polymer composites is selected by the DSM.

4. Simulation results and discussion

The presence in the software of the simulation module allows us to conduct numerical experiments to compare the developed methods and algorithms, to assess the stability and the possibility of applying these algorithms to calculate TPP for different values of each of the input experiment parameters. The simulation study began with the selection of a list of experimental conditions, the change in the values of which is largely reflected in the TPP calculation. The choice of such parameters is made empirically based on knowledge about the passage of a real experiment. The main input conditions of the experiment, selected for further analysis, were taken: the number of thermocouples for measuring the temperature over the sample thickness, the temperature differential over the sample thickness and the type of TPP functions. The type of TPP dependence on temperature was set as constants, as functions linearly increasing and decreasing in two times, as well as a function with an extremum, imitating the process of curing the composite. The initial data for simulation was the calculated temperature field, on which white noise was applied with amplitude of 0.1 K.

As a result of the analysis of the conducted simulation experiments, a summary table 1 was obtained, which characterizes the relationship between the input experiment conditions at heating and curing of the PC and the ability to use one of the four algorithm for calculating TPP: as a function of time using temperature inside the sample, as a function of time using the temperature on the sample surfaces, as a function of temperature based on the integral transformation of IPHC and as a function of time based on Kalman filter. For each algorithm, we obtain an estimate of the possibility of using it is 1 or 0. In the table, sign 1 indicates that the algorithm is acceptable, stable for this data and will allow calculating the TPP with a minimal error, sign 0 means that the algorithm is not acceptable for the calculation based on these data.

The data presented in the table confirm the statement about the absence of a TPP calculation algorithm that is universal for various combinations of experimental input conditions and indicates the
presence of limitations in the application of each of the proposed algorithms. However, for solving a practical problem of increasing the accuracy of calculating the TPP, the choice of the calculation algorithm plays a key role. In addition, the table takes into account the effects of only three basic conditions of the experiment on the possibility of using algorithms. The inclusion of additional parameters in the analysis leads to its substantial complication and the impossibility of forming the final conclusions in the form of a table. Thus, the developed algorithms complement each other’s capabilities and expand the area of experimental conditions.

The generalized and structured results of simulation studies of the applicability and accuracy of the TPP calculation algorithms were used in the development of the decision support module. The module automatically selects one of the four TPP calculation algorithms that is stable and has a minimum error of less than 5% under the given experimental conditions, and recommends it to the DMD user for processing experimental data when calculating TPP [13].

**Table 1.** Estimates of the possibility of using the algorithms for calculating TPP under various combinations of experimental conditions.

| Experimental conditions | Temperature difference across the thickness of sample | Type of TPP function | Number of thermocouples |
|-------------------------|-----------------------------------------------------|-----------------------|-------------------------|
| ΔT < 5 K                | C = const, C(T);                                    | const or as a function of time using temperature inside the sample. |
| 5 K ≤ ΔT ≤ 25 K         | C = const, C(T);                                    | a function of temperature using the temperature of sample surfaces. |
| ΔT > 25 K               | C = const, C(T);                                    | a function of time based on the integral transformation of IPHC. |

| Algorithm for calculating TPP as an algorithm is applicable, 0 – not applicable. |
|----------------------------------|-------------------------------------------------|
| constant or as a function of time using temperature inside the sample. | 1 1 1 1 1 1 | 0 0 0 0 0 |
| a function of time using the temperature of sample surfaces. | 1 1 1 1 1 1 | 1 1 0 0 0 |
| a function of temperature based on the integral transformation of IPHC. | 0 1 1 0 0 0 | 0 1 1 0 1 |
| a function of time based on Kalman filter. | 1 1 1 1 1 1 | 1 1 0 0 0 |

5. Conclusion

The proposed subsystem of information support for decision-making on the choice of the optimal method and algorithm for calculating the TPP of polymer composites is part of the intelligent data-measuring device software for the study of the curing process of PC, based on the alternative use of four algorithms for calculating the TPP. The use of four algorithms has an undoubted advantage, since they complement each other’s capabilities and expand the field of experimental conditions.

The proposed decision support module for choosing the optimal TPP PC calculation algorithm allows us to reduce the errors in determining TPP. An additional advantage of using a subsystem in DMD is information support for users who do not have special knowledge about the principles of building and
operating of methods for determining and algorithms of the TPP calculation and optimal conditions for their use, which expands the capabilities of the DMD user interface.

All developed algorithms for calculating TPP in DMD and descriptions of their use in DSM are presented by separate independent procedures. Such an architecture for building DMD software makes it possible in the future to increase the number of algorithms, thereby increasing the accuracy of calculating TPP and expanding the functionality of DMD.

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