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Novel thermal method for the recognition and supporting the identification of solids and their thermal parameters

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Abstract

This article proposes a concept of new method for supporting the identification of solids and their thermal parameters. This concept is based on the idea of implementation of metrological methods and solutions known from hot-wire anemometry in applications for supporting the thermal identification of solids. The idea of the method is based on the fact that measuring head of the probe, comprising a resistance – temperature transducer heated by electric current, is continuously maintained in a stable thermal contact with the tested material, while the temperature of the resistance – temperature transducer is controlled by the constant – temperature controlled system. The characteristic parameters of the head – material system are determined based on measurement of the flux of heat transferred from the head in its various states of heating. These parameters are compared to parameters obtained for different materials used as standards during the system calibration process, which allows for a measured parameters to be correlated with calibration ones, classifying ultimately the tested material into specific class of materials. Selected methods of artificial intelligence can be applied here. In complex solutions it is possible to use measuring heads comprising higher number of resistance – temperature transducers, both passive and active ones, an array of measuring heads, complex algorithms of thermal excitations and interpretation of measured signals or the analysis of thermal waves propagation in a tested material.

Keywords: metrology, identification, thermal parameters, solids, measurement algorithms, thermodynamics

1. Introduction

Main objective of this scientific paper is to develop structures of systems and measurement algorithms and to conduct basic research and investigation of the novel thermal method for the recognition and supporting the identification of solids and their thermal parameters.

The problem of identification of materials and their physical parameters is one of the fundamental issues of metrology, covering many areas of basic and technical sciences. Applied research methods are based on various physical phenomena, the course of which allows for identification of parameters characteristic of the material. In general, the research process is based on measurement and interpretation of selected measurable physical parameters. This process can either be passive or an active one, associated with employment of artificially introduced external influences.

Spectrometry, based on generation and subsequent analysis of spectra, is one of the basic analytical methods for the identification of materials, which utilizes an electromagnetic radiation, mechanical waves as well as interaction between molecules and elementary particles [1]. A large class of analytical methods for identification of materials involves chemical methods based on characteristic reactions [2]. Among frequently used methods for identification of materials, several methods based on measurement of their physical characteristics, such as their mechanical, electrical, magnetic or optical properties as well as several other physical parameters, can also be found [3]. Thermal methods allowing for materials to be identified by measuring their thermal properties such as thermal conductivity or specific heat belong also to this group of methods [4].

A large group of the hereby presented methods require a sample of the material to be collected in order to determine its parameters and perform the identification. Moreover, some of these methods require the employment of advanced and complex measuring equipment, which prevents their practical utilization under other but laboratory conditions. Finally, in order to correctly identify the materials it is preferable to use several mutually complementary methods. Development and improvement of new methods presents thus a crucial aspect of basic research.

The author of this article proposes a concept of new method for supporting the identification of solids and their thermal parameters. This concept is based on the idea of implementation of metrological methods and solutions known from hot-wire anemometry in applications for supporting the thermal identification of solids. Hot-wire anemometry is a measurement method widely used in flow metrology [5]. It is based on introduction of heated measuring probe into the flow and subsequent determination of flow parameters based on analysis of the heat flux transferred by the flow. The quantities measured in this method include predominantly the flow rate and closely related derived quantities associated with temporal and spatial analysis, but also the temperature, composition and pressure of the flowing medium. Similar methodology and measuring equipment is used also in other areas of metrology, such as bolometry, gas concentration measurements or fluidized bed measurements [6].

2. The main idea of the novel method

The idea of the presented method is based on the fact that measuring head of the probe, comprising a resistance – temperature transducer heated by electric current, is continuously maintained in a stable thermal contact with the tested material, while the temperature of the resistance – temperature transducer is controlled by the constant – temperature controlled system [7]. The parameters characteristic of the head – material system are determined based on measurement of the flux of heat transferred from the head in its various states of heating. These parameters are compared to parameters obtained for different materials used as standards during the system calibration process, which allows for a measured parameters to be correlated with calibration ones, classifying ultimately the tested material into specific class of materials. Selected methods of artificial intelligence can be applied here. In complex solutions it is possible to use measuring heads comprising higher number of resistance – temperature transducers, both passive and active ones, an array of measuring heads, complex algorithms of thermal excitations and interpretation of measured signals or the analysis of thermal waves propagation in a tested material.

The proposed concept of thermal method for supporting the identification of solids and their thermal parameters, together with the research hypothesis, will be presented on the basis of a description of the basic solution shown in Figure 1. This solution is a subject of pending patent application submitted by the authors of the proposal [8].

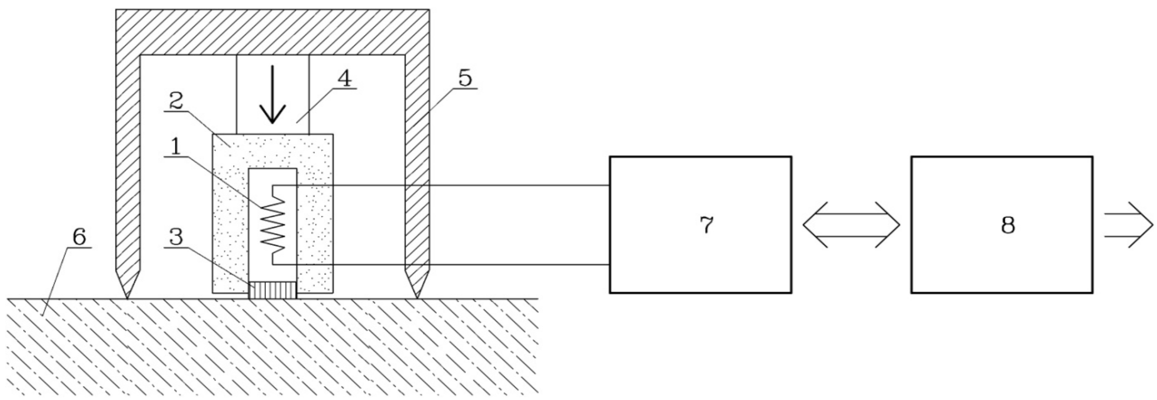

Fig. 1. Basic system for supporting the identification of solids and their thermal parameters

The system for supporting the identification of solids consists of a measuring head comprising the resistance – temperature transducer 1, thermally isolated by the sheath 2. Thermal contact between the resistance – temperature transducer 1 and tested material 6 is realized through the contact layer 3 made of highly thermally conductive material. Stable thermal contact with the tested material is ensured by the locking system 4 together with the housing of the head 5, also in touch with the surface of tested material. In the case of identification of powdery materials, it is preferred to introduce the resistance – thermal transducer deep into the tested material. The resistance – temperature transducer 1 is electrically connected by a two- or four-wire line to a constant – temperature controlled circuit 7. This circuit supplies the resistance – temperature transducer 1 with a current, the intensity of which ensures that the transducer's temperature is maintained at a given fixed value irrespective of the conditions of heat transfer, above the temperature of the tested material. The measurement process is controlled by the data processing unit 8, the main goal of which is to set the fixed temperature of the transducer, measure the intensity of current flowing through it and determine the heat flux. Besides that, it ensures the reference data storage and implementation of measurement algorithm and generates the output measurement signal.

A simplified description of the method for supporting the identification of solids is based on the following measurement algorithm. In the steady state, the process of heat exchange between the measuring head and the tested material can be described by means of the approximate equation:

$$I^2 R = kA(T - T_0) \tag{1}$$

where:

- I – the current heating the resistance – temperature transducer, the measured parameter
- R – the resistance of heated transducer, the remotely set parameter
- k – the sensor characteristic parameter, the constant
- A – the parameter of identification of tested material, the measured parameter
- T – the temperature of heated transducer, the remotely set parameter
- T_0 – the temperature of tested material, eliminated parameter.

For two distinct transducer heating levels T_1 and T_2, we obtain the following two relationships describing the steady state:

$$I_1^2 R_1 = kA(T_1 - T_0) \tag{2}$$

$$I_2^2 R_2 = kA(T_2 - T_0) \tag{3}$$

Subtracting these equations side by side and determining the value of A, we obtain an identification parameter of the tested material, eliminating the unknown temperature of the material T_0 at the same time:

$$A = \frac{I_2^2 R_2 - I_1^2 R_1}{k(T_2 - T_1)} \tag{4}$$

Comparing the value of parameter A used for identification of the material obtained during the measurement process with the values obtained for reference materials during the calibration process, the tested material can easily be classified into given class of materials. In complex measurement algorithms, it is possible to use many different levels of heating of the transducer as well as to record the temporal changes of heat flux, what subsequently enables the determination of large amount of various identification parameters. In order to compare these parameters with the reference database, artificial intelligence methods, such as the methods of fuzzy logic, can be used.

The herein described simplified system for supporting the identification of solids allows for obtainment of information supporting the identification of tested material, whereas the testing is performed *in situ* rendering no need to collect the sample of the material. Moreover, the testing isn't considerably invasive nor destructive and the measuring head is equipped with cheap single measuring transducer. The presented method for identification of materials allows for elimination of the temperature of tested material from the measurement algorithm. Both solid as well as powder materials can be subject to identification.

3. Origin and application area of the method

The hereby presented conception, based on the idea of implementation of metrological methods and solutions known from hot-wire anemometry in applications for supporting the thermal identification of solids, is pioneering and innovative. The current state of the art in this scientific field may be considered in two main aspects:

- specialized methods and measurement systems developed for hot-wire anemometric applications,
- thermal methods allowing for identification of materials by measuring their thermal properties such as thermal conductivity or specific heat.

The hot-wire anemometric method is documented by rich and still growing literature evidence. A series of monographs related to basic and specialized research techniques has been published [5, 9]. Reported are the results of the latest studies aimed at improving the measurement methods, applications of new micro- and nanotechnologies [10] as well as measurement algorithms based on methods of artificial intelligence [11]. Author of this paper has considerable achievements in the field related to new measurement methods and systems, supported by scientific papers published in cutting-edge worldwide journals and patented solutions. Author's original solutions, including those listed below, may in particular prove themselves useful in realization of the proposed research:

- the non-bridge constant – temperature controlled circuit [7],
- the temperature compensation and correction techniques [12],
- the two-state hot-wire anemometer [13],
- the hot-wire anemometer with switched heating level [14],
- the use of algorithms of artificial intelligence [11],
- methods of temperature waves [15].

The literature evidence related to methods of determination of thermal parameters of materials allowing for their identification is also rich. In addition to standard methods for determination of thermal conductivity, specific heat or measurement of heat flux [4], other specialized and complex measurement systems such as differential scanning calorimeter (DSC) [16] or thermal scanning microscope (TSM) [17] must be mentioned here. The latter solution presents a particular example of how measurement methods and solutions known from hot-wire anemometry may successfully be employed in measurement techniques. This reflects the global trend towards constant development of measurement methods, which is possible especially thanks to advances in micro- and nanotechnologies [18] and development of information technologies.

Author of this paper believe that the hereby proposed measurement method would allow one to complement the portfolio of existing measurement methods with a new tool supporting the identification of solids and their thermal parameters. Such a tool may find its possible application in many areas of science and technology, in particular as a supporting sensor in robotics (robot's thermal finger), autonomic measuring probes, automation, diagnostics, flaw detection, identification of dangerous materials, in technological and production processes, exploitation and processing of raw materials, archaeology, as well as in exploration of the Solar system objects. The idea of extending the range of applicability of methods developed originally for the purposes of hot-wire anemometry to new research areas presents an innovative solution, requiring, however, a series of studies of a fundamental nature to be performed. Only following these studies it will be possible to evaluate the usefulness of this new method as well as possible areas of its applicability. Obviously, new technological and metrological problems related to the method itself, as well as new concepts of development of the construction and structure of the measuring system and employed algorithms for interpretation of measurements may emerge during the research. The basic solution, presented in the description of the proposed method is only preliminary and is based on very simplified model of a physical phenomenon. Planned research should, however, provide more detailed insight into specific properties and parameters of the method and its metrological potential. Results obtained as an effect of basic research will create the opportunity to implement the method in a specific class of research applications, affecting at the same time both the development of given scientific area as well as technological progress.

4. Proposals for further research and development of the method

The concept of thermal method for supporting the identification of solids and their thermal parameters was developed in 2015. So far, author has performed the analysis of literature related to this topic as well as preliminary research aimed at developing the basic concept of the measurement system [19], allowing for patent application to be submitted [8]. The future research will involve the theoretical and model analysis, development of equipment to be used in experimental research, the research process itself, data processing and analysis of the results. The theoretical and model analysis will be performed using the Matlab universal environment for scientific calculations and simulations. The measuring probes will be manufactured based on the concept shown in Figure 1, whereas single probes, probes consisting of a system of several resistance – temperature transducers as well as the probe arrays are planned to be constructed. An important issue is also the selection of appropriate construction materials. The probes will be optimized in order to maximally utilize the potential of the underlying measurement method. For the purpose of controlling the probes, an electronic system operating on the basis of the concept of the non-bridge constant – temperature controlled circuit will be developed.

The constant-temperature controlled circuit presents an electronic system supplying the resistance – temperature transducer with the current of such an intensity, that the resistance and indirectly the temperature of heated probe is maintained at a given preset level, irrespectively of external conditions of heat exchange. The value of the resistance is set by means of the digital signal supplied to a multiplying digital-analogue converter with the *R – 2R* ladder. Voltage signals proportional to intensity of current and voltage of the sensor present the output signals of the system. They allow to calculate the heat flux. A block diagram of the non-bridge constant-temperature controlled circuit with four-point supply system of the measuring probe is presented in Figure 2.

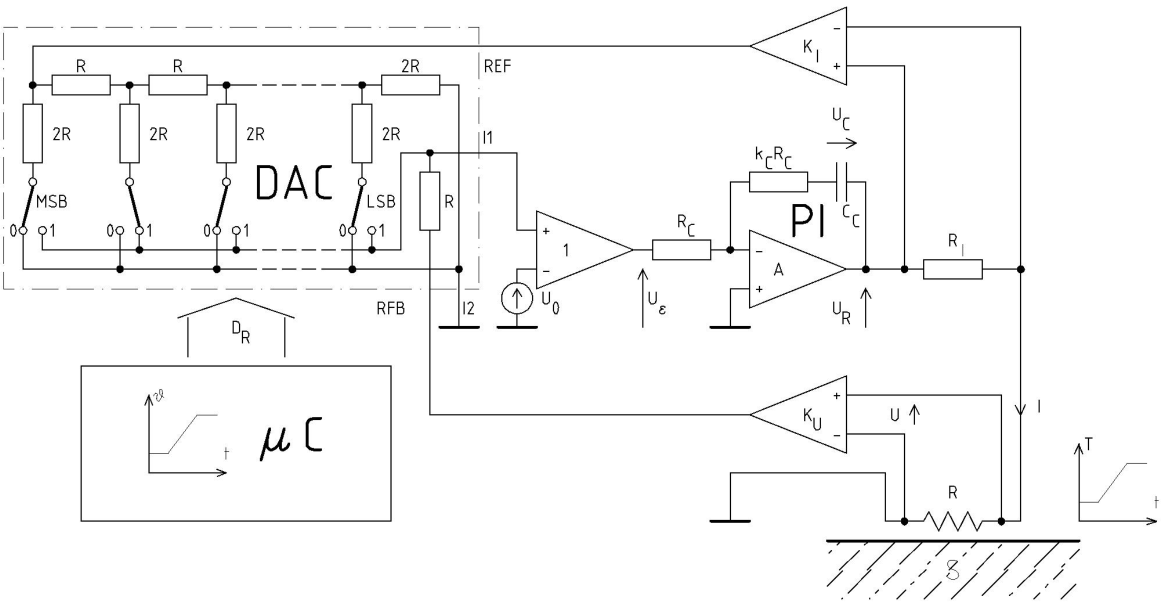

Fig. 2. Block diagram of the constant-temperature controlled circuit

The probe *R* (resistance – temperature transducer) is connected to the circuit by means of the four-line cable with the current and voltage signals being kept separately. The signal proportional to the current through resistor R_I is amplified by a differential amplifier with the gain K_I and brought to input *REF* of a *N*-bit digital-analogue converter *DAC*. This converter acts as a comparator of two analogue signals, in which the value of one of these signals is multiplied by the factor proportional to the digital control signal D_R. From output of the amplifier K_U, a signal proportional to the voltage of the probe *R* is supplied to input R_{FB} of the converter. The converter is controlled by a digital control signal D_R. The output I_I is connected with inverting input of the controller *PI*. Its task is to supply the sensor with a current such that the error voltage U_e could be reduced down to zero. In the steady state, the following relationship will hold true:

$$R = \frac{R_I K_I D_R}{K_U 2^N} \tag{5}$$

Therefore, the probe resistance is directly proportional to the value of the digital control signal D_R from control system m*C*. The voltage proportional to the preset current of the probe available at the amplifier K_I output and the voltage proportional to the preset voltage of the probe at the amplifier K_U output present the output signals of the system. In this solution, according to equation (5), the resistance of the probe depends on the digital control signal, ratio of gains of the sensor current and voltage amplifiers as well as on the value of the only reference resistor R_I incorporated in the circuit. Assuming linear temperature dependence on probe resistance system allows for control of probe temperature in time and measuring the heat flux.

The constant – temperature controlled circuit will allow for precise time-dependent profile of temperature to be entered and for time-dependent measurements of heat flux to be conducted. This system will cooperate with the module for acquisition and processing of experimental data and with computer system. A set of selected measurement standards will be prepared, whereas the standards are planned to be diversified in terms of materials they are made of and dimensions. The research will be conducted under controlled laboratory conditions using the scientific apparatuses and instruments which are at the disposal of authors of the proposal. The measurement algorithms based on measurement of the heat flux and its variability in time, developed within the framework of this concept, will be implemented. Employment of forced excitation, both constant and variable in time, is also expected. Employment of the analysis of the propagation of temperature waves in tested material is also under consideration. In order to visualize the undergoing processes, an infrared medium resolution camera will be used. The results obtained in this research will be processed using Matlab, an environment for scientific calculations and simulations.

5. Conclusions

Main objective of this scientific concept is to develop structures of systems and measurement algorithms and to investigate the novel thermal method for supporting the identification of solids and their thermal parameters. The problem of identification of materials and their physical parameters is one of the fundamental issues of metrology, covering many areas of basic and technical sciences. Applied research methods are based on various physical phenomena, the course of which allows for identification of characteristic parameters of the material.

A large group of the methods of identification require a sample of the material to be collected in order to determine its parameters and perform the identification. Moreover, some of these methods require the employment of advanced and complex measuring equipment, which prevents their practical utilization under other but laboratory conditions. Finally, in order to correctly identify the materials it is preferable to use several mutually complementary methods. Development and improvement of new methods presents thus a crucial aspect of basic research.

The author of this article propose a concept of new method for supporting the identification of solids and their thermal parameters. This concept is based on the idea of implementation of metrological methods and solutions known from hot-wire anemometry in applications for supporting the thermal identification of solids. The idea of the presented method is based on the fact that measuring head of the probe, comprising a resistance – temperature transducer heated by electric current, is continuously maintained in a stable thermal contact with the tested material, while the temperature of the resistance – temperature transducer is controlled by the constant – temperature controlled system. The characteristic parameters of the head – material system are determined based on measurement of the flux of heat transferred from the head in its various states of heating. These parameters are compared to parameters obtained for different materials used as standards during the system calibration process, which allows for a measured parameters to be correlated with calibration ones, classifying ultimately the tested material into specific class of materials.

The herein described system for supporting the identification of solids allows for obtainment of information supporting the identification of tested material, whereas the testing is performed *in situ* rendering no need to collect the sample of the material. Moreover, the testing isn't considerably invasive nor destructive and the measuring head is equipped with cheap single measuring converter. The presented method for identification of materials allows for elimination of the temperature of tested material from the measurement algorithm. Both solid as well as powder materials can be subject to identification.

Author of this paper believe that the hereby proposed measurement method would allow one to complement the portfolio of existing measurement methods with a new tool supporting the identification of solids and their thermal parameters. Such a tool may find its possible application in many areas of science and technology, in particular as a supporting sensor in robotics (robot's thermal finger), autonomic measuring probes, automation, diagnostics, flaw detection, identification of dangerous materials, in technological and production processes, exploitation and processing of raw materials, archaeology, as well as in exploration of the outer space objects.

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Nowa metoda termiczna do rozpoznawania i wspomagania identyfikacji substancji stałych i ich parametrów termicznych

Streszczenie

Autor pracy proponuje nową koncepcję metody wspomagania identyfikacji ciał stałych oraz ich parametrów cieplnych. Koncepcja ta oparta jest o ideę implementacji metod i rozwiązań metrologicznych znanych z termoanemometrii w zastosowaniach do wspomagania identyfikacji termicznej ciał stałych. Podstawowa idea proponowanej metody pomiarowej polega na tym, że głowica pomiarowa zawierająca nagrzewany prądem elektrycznym rezystancyjny przetwornik temperatury utrzymywana jest w stabilnym kontakcie termicznym z badaną substancją, a poziom temperatury rezystancyjnego przetwornika temperatury zadawany jest poprzez sterowany układ stałotemperaturowy. Na podstawie pomiaru strumienia ciepła odbieranego z głowicy w różnych stanach nagrzania wyznaczane są parametry charakterystyczne układu głowica – substancja. Parametry te porównywane są z parametrami uzyskanymi dla różnych substancji w procesie wzorcowania układu, co pozwala na określenie korelacji parametrów wzorcowych i mierzonych, a tym samym na zaklasyfikowanie badanej substancji do danej klasy materiałów. Korzystne może tu być zastosowanie metod sztucznej inteligencji. W rozbudowanych rozwiązaniach możliwe jest zastosowanie w głowicy większej ilości rezystancyjnych przetworników temperatury, zarówno pasywnych jak i aktywnych, stosowanie matrycy głowic, zastosowanie złożonych algorytmów wymuszeń termicznych i interpretacji sygnałów mierzonych, jak również badanie propagacji fal termicznych w badanej substancji.

Słowa kluczowe: metrologia, identyfikacja, parametry termiczne, ciała stałe, algorytmy pomiarowe, termodynamika