Information-measuring technologies in the metrological support of heat flux measurements

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Abstract. Heat flux measurements are importance for energy, construction, space research, medicine, etc. The range of measured values is from several units to hundreds of thousands W/m^2. The use of appropriate heat flux sensors makes it possible to determine heat flux local in space and time, to measure the components of the heat flow and coefficient of heat exchange and coefficient of heat transfer during complex heat exchange. For their correct application and obtaining reliable measurement results, it is necessary to provide periodically monitoring of metrological characteristics of heat flux sensors.

This paper considers the information-measuring technology of metrological support of heat flux measuring, which allows you to adapt the basic principles of metrology of thermal quantities to specific spatial and temporal arguments of the implementation of the heat flux measuring process. The concept of modular construction of the metrological complex is proposed, the features of which are the separation of the measurement range into parts using various methods of generating and transmitting thermal energy and a single module for recording and processing measurement information. Such an approach made it possible to expand boundaries of the measurement range while ensuring the established uncertainty values of the measurement results. The information-measuring system for implement this concept is proposed. It consists of structurally completed modules of thermal blocks, in which a certain principle of thermal energy generation is implemented, and a set of standard devices for maintaining and monitoring the parameters of the given system operation modes. The software module of the developed system allows you to register and process measurement information.

The created system allows studies of the conversion coefficient of heat flux sensors with varying temperature values. The experimental results of the temperature dependences of the conversion coefficient of a series of heat flux sensors with different sensitivity are also presenting in paper.

Keywords: heat flux density, heat flux sensor, metrological provision, measurement, information-measuring technology.

1 Introduction

The informative parameters that are recorded in the research and modernization of energy-intensive technologies, and the introduction of new energy-efficient materials are temperature and heat flow. The second characterizes the process of thermal energy propagation in the object of study, its heat exchange with the environment or other objects, as well as the intensity of the processes that take place.

In particular, in the construction industry, the quality of building materials is monitored by measuring the surface heat flux, control of local and transmission heat losses of enclosing structures of buildings[1…5]; in medicine – diagnostics of various diseases in traumatology, oncology, etc., determining the thermal comfort of the body [6, 7]; in space research determines the thermal state of objects [8]; in thermal power engineering - control of local heat losses and determining the quality of thermal insulation, control of integral heat losses of energy objects during operation, etc. [9…11].

For solve the problems of the building industry and medicine, it is important to measure small values of the heat flux density in the range (1 ÷ 1 000) W/m^2, in aero space research (100 ÷ 20 000) W/m^2, for control of energy facilities is actual to measure of the heat flux up to 200 000 W/m^2. In all these cases, the value of the surface heat flux is an informative characteristic, which is measured using appropriate sensors in control and diagnostics systems and as a sensitive element of thermophysical devices.

At present, the issue of ensuring the uniformity of measurements of surface heat flux at the state level is being addressed in several countries of wold. The metrological provision of heat flux in the United States deals the National Institute of Standards and Technology (NIST). Calibration of measuring instruments for heat flux is by radiation method with determination of the unit of measurement by the Stefan-Boltzmann law [12, 13]. The National Organization of the Netherlands TNO is carried out of calibration of heat flux measuring instruments by the conductive method with determination of the unit of measurement according to the Fourier law [14]. The reproduction of a unit of measurement in Russia is carried out by the conductive method of determining the heat flux density by the Fourier law [15]. In Ukraine the metrological provision of heat flux is based on the radiation method with determining the unit of measure by the Stefan-Boltzmann law [16]. In sum, unit size reproduction in the world is implemented in the range of values from 10 to 100 thousand W/m^2.

Therefore, it should be noted that today metrology is provided for measuring the surface density of the heat flux in the range, the boundaries of which are orders of magnitude narrower than required. In addition, the high-intensity heat flux is reproduced mainly by models of black body, the structures of which today have a diameter of the output diaphragm of the order of 20…80 mm [17…19]. This places restrictions on the calibration of heat flow sensors larger than the diameter of the power source diaphragm. In this regard, the issue of ensuring the unity of measurements of heat flux is becoming a priority.

The aim of the work is to improve metrological support for heat flux measurements. Important here is the realization of the possibility of carrying out calibrations of measuring instruments of different types, expanding the range of measurements and minimizing resource costs.

2 Theoretical basis and Methodology of surface heat flux measurement

Unlike classical aproach, which is mainly focused on static measurements, increasing their sensitivity and precision by improving the elemental base and developing physical and technical principles of measurement, trends in the modern metrology require an increase in the measurement automation, which means is to provide not only the measurement of physical quantities, but also their physical principles, carrying out the necessary calculations, displaying the obtained results in the required form and ting them to destination or storage.

In the modern realization of measurements to the first place comes information-measuring technologies, which are a set of measurement methods, hardware and software, integrated for the purpose of collecting, processing, storing, displaying and using measurement information in the form of measurement results with a certain level of uncertainty for the benefit of consumers.

The information-measuring technology of surface heat flux measurements metrological support, the constituent elements of which is presented in Fig. 1. Technology based on the justified use of different physical principles of reproducing a unit of surface heat flux density and transmitting its size in different parts of the extended dynamic range while providing a set level of uncertainty of the measurement results.

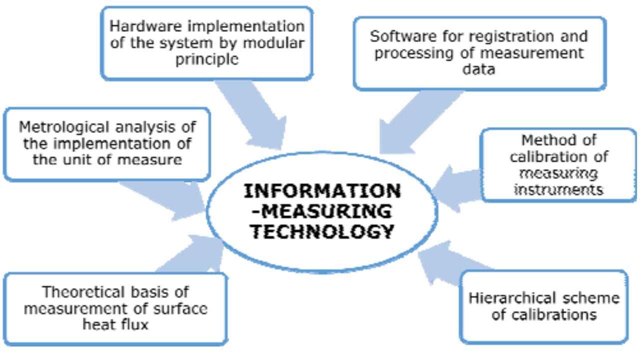

Fig. 1. Components of information-measuring technology for metrological support for measurements of surface heat flux

The theoretical basis of surface heat flux measurements in a wide range is based on the development of the basic elements of metrology of thermal quantities, in particular, the theoretical substantiation of methods and means of reproduction and transmission of the measurement unit, improvement of the hardware base for measuring instruments calibration and development of appropriate methodological tools. Fig. 2 are shown proposed methodology for ensuring the unity of measurements of the surface heat flux, which allows us to formulate the main perspective directions for the development of metrological support.

The methodology is based on three directions of development of scientific and applied foundations of ensuring uniformity of measurements, namely: theoretical, hardware and software and methodological support. Each of these directions involves solving a number of specific problems that take into account the peculiarities of the subject area of application of the measurements of the surface heat flux density, the methods and means of applied measurement, their characteristics.

In the process of reproduction and transmission of the unit of the heat flux on the surface of the test instrument, the field of the heat flux induced by the heat source is formed. The mechanism of formation of the field of heat flux is determined by the following main phenomena of heat transfer: thermal conductivity, radiation and convection, which describe the way of transfer of kinetic energy of particles (molecules, atoms, electrons, photons, etc.) during their thermal motion. The intensity and direction of energy transfer are determined by the heat flux vector.

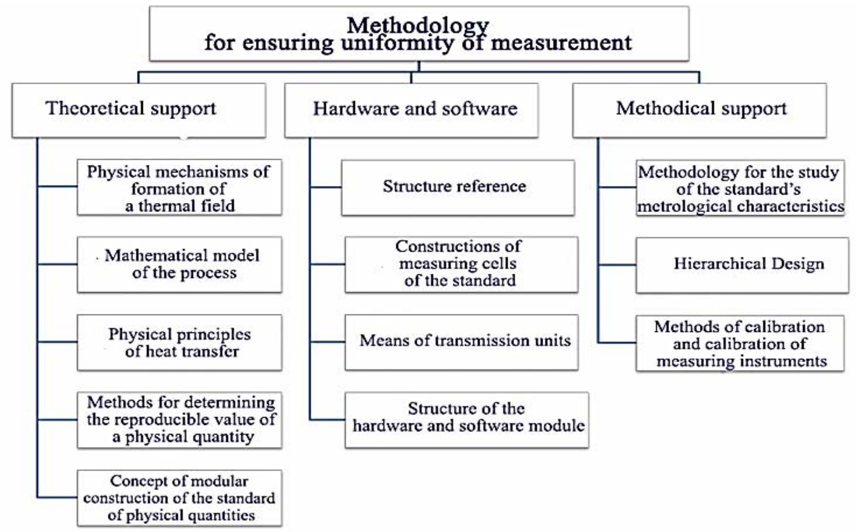

Fig. 2. Methodology for ensuring unity of heat flux measurement

Surface heat flux density is an energy flow that is transferred in the process of heat exchange through a unit of isothermal surface area over a period of time dt, and, irrespective of the method of forming thermal energy, in the general form can be determined by:

$$q(\mathbf{r},\gamma_i,\tau) = F^{-1} \cdot \frac{dQ(\mathbf{r},\gamma_i,\tau)}{dt} + \xi(\mathbf{r},\gamma_i,\tau,F,Q)\,, \tag{1}$$

where F – surface area of heat exchange; Q – heat flow through a unit of surface area of heat transfer; γ – input values to be measured to determine the magnitude of the surface heat flux density; $\xi(\mathbf{r},\gamma_i,\tau,F,Q)$ – a random field that determines the effect of a set of factors on the formation of a unit of measure.

Equation (1) determines the method of obtaining the value of the surface heat flux, taking into account the action of various factors of influence, each member of which determines a set of input quantities and the physical effects that accompany the measurement process.

The implementation of the measurement unit depends on the precision of the measurement of the input quantities and the intensity of the action of a set of factors, each of which is characterized by such an indicator of accuracy as uncertainty. Given that each input value and each impact factor contains a certain uncertainty, the uncertainties of their totality have an effect on the total uncertainty of the results of the reproduction of the unit of surface heat flux density.

The summary measurement uncertainty is formed from the standard uncertainties of the components included in the equation for determining the surface flux density (1), and assuming that all the components of the uncertainty in (2) are uncorrelated, defined as:

$$u(q) = \sqrt{\sum_{i=1}^{\mathrm{n}} k_i^2 u(\gamma_i)^2} \ , \qquad (2)$$

where $u(q)$ – the total uncertainty of the implementation of the unit of measurement over a wide range; k_i – the coefficients of influence of the *i*-th component of determining the surface heat flux density; $u(\gamma_i)$ – the standard uncertainty of the individual components of determining the surface flux density.

The analysis of the world experience of the measurement unit realization [20…25] of the surface heat flux with the formation of heat energy by both radiation and conductive method is established that there is no single method of formation of thermal energy that would allow to reproduce the unit of measurement in a wide dynamic range without deterioration of such indices as uncernuty of measurement result .

For this reason it was proposed to divide the dynamic range by the heat flux density into parts, in each of which the reproduction of a unit of measurement occurs using different physical principles. Based on this, the concept of constructing a surface heat density standard on a modular principle was developed.

Therefore, to ensure the uniformity of measurements in the present conditions, the standard of surface heat flux should be implemented in the form of information-measuring system [26], which is a set of functionally-integrated measuring, control, computing and other auxiliary technical means formed to obtain measurement information, its transformation, processing, visualization and documentation. This principle ensures the technical and information-interoperability of the modules, simplifies maintenance, improves the accuracy and reliability of the system and allows to extend the functionality.

3 Implementation of conceptual model

The implementation of the proposed conceptual model of the standard of surface heat flux density involves different physical principles for the generation and transmission of thermal energy. To ensure uniformity of measurements across the range 1…50 W/m^2. It is proposed to use the model of absolutely black body as a source of thermal energy and to transmit the unit of measurement to the heat flux sensors in a radiation way. Determining the value of the surface heat flux reproduced in this way is carried out based on the Stefan-Boltzmann law.

Implementation of the unit of measurement in the range $2 \cdot 10^1 \dots 2 \cdot 10^4$ W/m^2 made by the method of hot guarded plate by forming a heat flow using an electric heater, while the transfer of the unit size is carried out in a conductive way and the use of heat flux sensors. Determination of the magnitude of the reproduced value of the surface heat flux density is based on the Joule-Lenz law.

In the range $1 \cdot 10^4 \dots 2 \cdot 10^5$ W/m^2 the formation of heat flow is proposed to be carried out by means of an emitter, whereby the unit size is transmitted in a radiation way. Both heat flux sensors and thermal radiation receivers can serve as transmitters.

The modular principle of construction of the information-measuring system allows to form a standard of surface heat flux density in a form structurally completed modules of thermal blocks in which the certain principle of formation of thermal energy is realized, and a set of standard devices for maintaining and controlling the parameters of the given modes of operation of the system. In Fig. 3 presented a scheme for constructing a standard modular principle.

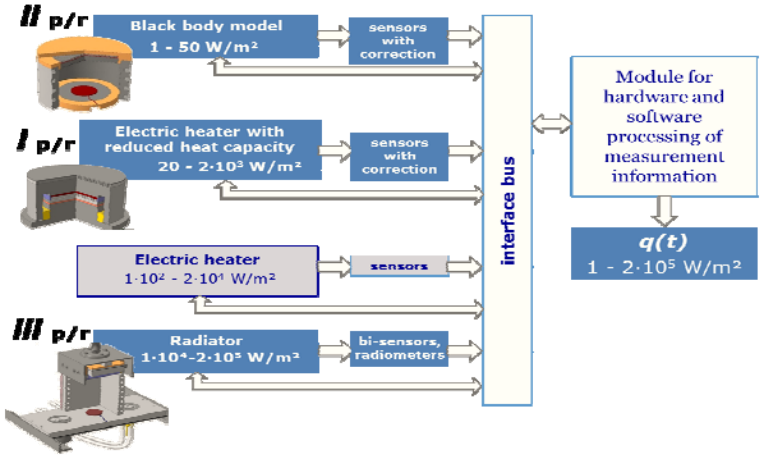

Fig. 3. Scheme of modular construction of the standard

According to this scheme, thermal blocks are developed in each part of the range, which creates conditions for reproducing the unit of surface heat flux density and transmitting its size to the appropriate measuring instruments.

I part of range. The thermal block contains an isothermal source of thermal energy to create first-order boundary conditions on the surface of the measuring instrument (the heat flux sensor under test). The measurement unit is transmitted using only conductive method. In this case, the heat flux sensor has the same geometric dimensions in the radial direction as the working surface of the heat source.

The conductive method of using an electric heater is a significant advantage of reproducing a unit of surface heat flux density and transmitting its size. The most significant of these are the high accuracy of the task and the maintenance at a certain level of electrical quantities involved in the formation of heat flow, and the possibility of implementing the unit of measurement over a wide temperature range. The heat flux is formed on the main heater due to the Joule effect when passing electric current through it. Electric current is supplied from the power supply unit. To determine the value of the input power of the heater included consistently unambiguous measure of electrical resistance. Thus, power is determined by measuring the voltage at the contacts of the primary heater and at the potential terminals of a single measure of electrical resistance.

Structural model of formation of measurement results uncertainty by the conductive method in Fig. 4 is presented as a cause and effect Isikawa diagram.

The elements of the diagram are the input factors and quantities that directly measure to determine the surface heat flux density, as well as the physical effects that have an impact on the end result - the accuracy of the unit size reproduction.

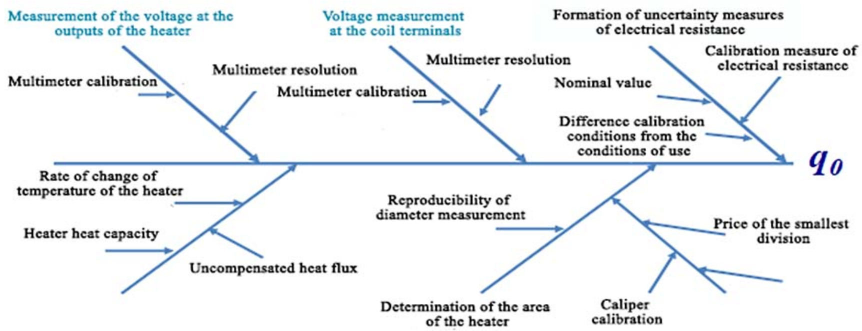

Fig. 4. Scheme of the formation of heat flux measurement results uncertainty by conductive method

It is established that the main sources of uncertainty of the measurement result are:

Measurement of voltage at the inputs of the heater by voltmeter; calibration of the voltmeter in the range of measured values of voltage; digit voltmeter; measuring the voltage at the inputs of a measure of electrical resistance by a voltmeter; calibration of the voltmeter in the range of measured voltage values at the terminals of the measure of electrical resistance; calibration of the measure of electrical resistance (when determining the thermal power of the electric current supplied to the heater).

Measuring the diameter of the heater with a caliper; calibration of the caliper (when determining the heater area). The heat losses are caused by temperature drift, heat capacity of the heater and uncompensated heat flow as additional sources.

The components of the heat flux reproduction uncertainty have been estimated. Calculations based on the results of the study of metrological characteristics of the standard heat flux sensors and passport data on the standard devices. The estimation results for the three values of the surface heat flux density are presented in Table 1. To compare the calculated results, the estimates are given as a percentage of the contribution of each component of uncertainty from the action of the respective source to the total uncertainty of the measurement results taken as 100%.

As we can see, with the decrease in the value of the reproduced value of the surface density of the heat flux, the influence of the heat capacity of the main heater increases, and already by the values $q = 10$ W/m^2 has a dominant influence.

Table 1. Estimates of the constituent sources contribution of uncertainty to the summary uncertainty

Sources of uncertainty	Percentage in summary uncertainty		
	10 W/m^2	100 W/m^2	$2{\cdot}10^4$ W/m^2
Measuring the diameter of the main heater	3	9	20
Measurement of voltage at the inputs of the main heater	1	4	11
Measuring the voltage at the inputs of the resistance coil	1	8	18
Calibration of the measure of electrical resistance	3	14	30
Uncompensated heat flow	6	23	2
Thermal losses due to the heat capacity of the main heater	86	41	18

Reducing the heat capacity of the main heater can be achieved by changing its thickness. However, this method is limited by the technological processes of manufacturing the heater and its finite size.

II part of range. Another way to reduce this effect is to avoid direct contact between the surfaces of the heat source and the sensor being tested, which is possible when using the radiation method of heat flow formation. Therefore, the second part of the range requires the creation of a thermal block with a low-intensity thermal radiation source. This source can be a model of a completely black body. The most productive and versatile for the reproduction of the surface heat flux density by the radiation method is a scheme for the construction of a thermal block with the use of a measuring cell formed by the flat designs of the heat source and heat sink on which the sensor under study is mounted and a side screen [27].

The scheme that implements the radiation method of reproducing the normalized value of thermal energy, assumes the presence in the device of a closed space formed by two diffusely radiating surfaces.

Determination of the surface heat flux density in the radiation method of supplying thermal energy is carried out on the basis of the Stefan-Boltzmann law. Therefore, the formation of heat flux occurs by maintaining the temperature difference between the heat source and the heat sink, taking into account the energy emitted by the heat transfer surfaces, their relative location and the thermo-radiation characteristics.

Fig. 5 shows a constructive model of the uncertainty formation of the result of surface heat density reproduction by the radiation method.

From Fig. 5 it follows that the main factors of influence on the uniform distribution of the heat flow field in the absolute method of measurement include:

- contribution of uncontrolled convective or convective-conductive components into the heat flow;
- the ratio between the dimensions of the cavity of the radiator: the diameter of the heat-sensing surface of the heat sink and the height of the screen;
- the nature of the distribution of local angular coefficients on the surface of the heat sink on which the sensor is located;
- the ratio of the values of the radiator temperature and the temperature control of the heat sink;
- thermo-radiation characteristics of heat exchange surfaces.

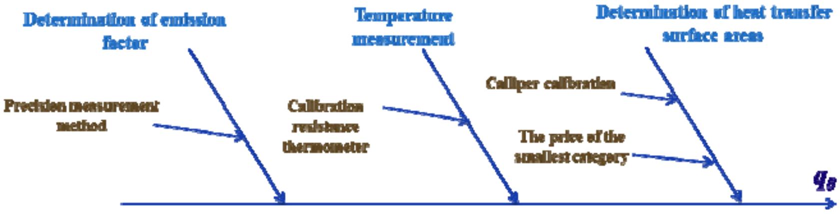

Fig. 5. Scheme of the formation of measurement results uncertainty by radiation method

The thermal energy source is made in the form of a flat model of a black body. A feature of this scheme is the use of a side black screen, thermostated at the same temperature as the heat sink. This allows to ensure almost complete absence of the convective component in the location of the investigated sensor, which contributes to the formation of a uniform field of flow of thermal radiation on the surface of the heat sink under conditions of low heat exchange. In this case, the design of the measuring cell of the heat block provides for the possibility of placing heat flow sensors in it without rigid requirements to the radial size of the means of transmitting the unit of measurement, but there are limitations regarding their inertia.

III part of range. The heat block should contain a source of high-intensity thermal energy, which causes certain structural features of the construction of the measuring cell. At high-intensity heat exchange, which is observed in the reproduction of heat flow in the range of values ($1 \cdot 10^3$-$2 \cdot 10^5$) W/m^2, the use of the conductive method is also limited. In this case, the limitation is the heat resistance of the measuring cell materials and the test instrument. Therefore, in accordance with the structure shown in Fig. 3, in the third part of the range, it is proposed to produce a high-intensity heat flux by radiation.

The formation of high-intensity heat flux is possible by using a heat source with a temperature on the surface of the radiation body of at least 650… 1100 K. This characteristic is possessed by high-temperature models of absolutely black body and incandescent lamps.

The main sources of uncertainty in this case are the uneven distribution of the heat flux density entering the heat sink, as well as the contribution of the convective component to the resulting heat flux. Comparison of the characteristics of thermal emitters

[28], taking into account the redistribution of energy transfer methods, revealed the advantages of quartz halogen incandescent lamps, which have the lowest percentage of convection heat transfer, which has a significant effect on the formation of a homogeneous heat flux field on the heat sensing. For this part of the range, it is possible to calibrate contact measuring instruments that have adequate thermal stability and thermally independent sensitivity.

Creating a module of the third part of the range, the thermal block of which is essentially a measuring comparator, opens the way to the implementation of verification of standard means of contact and contactless measurements.

4 Hardware and software module of Information-measuring system

Implementation of the hardware part of the heat flux density standard surface is presented on Fig. 6. It is a set of functionally integrated three thermal and electronic units, ancillary equipment and a personal computer with appropriate software.

SPECIFICATIONS

Measurement range, W/m^2:

I part of range $1 \div 50$;

II part of range $2 \cdot 10^1 \div 2 \cdot 10^3$;

III part of range $1 \cdot 10^4 \div 2 \cdot 10^5$

Extended uncertainty, %:

I part of range 0,6;

II part of range 0,6;

III part of range 0,7

Fig. 6. Implementation of the hardware part of the heat flux density standard

The thermal blocks provide the implementation of methods of reproduction and transmission of the unit of measurement of the surface heat flux density over a wide dynamic range. To convey the unit size in a specific part of the range, the heat flux sensors or thermal radiation receivers are placed in the appropriate measuring cell and provide the necessary fixed operating modes for temperature and surface heat flux density.

The regulation of the necessary modes of operation of the standard in terms of temperature and density of heat flow, registration, transmission, processing and archiving of measurement information is carried out using the hardware and software module of the system, the structure of which is presented in Fig. 7.

The hardware part of the hardware and software module of the system consists of task modules and maintenance of measurement modes and modules of primary data registration.

The measurement and maintenance modes module consists of four units that perform the functions of setting and controlling the thermal modes of the system and the corresponding boundary conditions.

The unit of reference and maintenance of the reference temperature is realized by means of the temperature controller of the reference couplings of the thermocouples, which controls the thermostat. The scheme is implemented with a pre-amplifier signal of the resistance thermometer and regulator-meter.

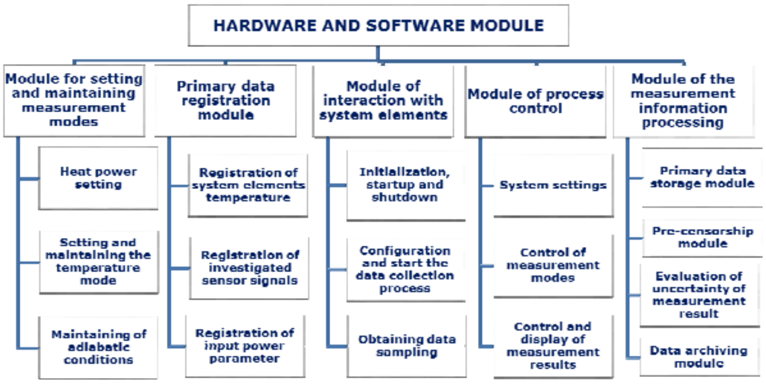

Fig. 7. Hardware software module of the system

The unit for maintaining adiabatic conditions is built on a controller that is designed to control the power supply to the guard heater. Due to the possibility of regulating the power of the guard heater in two ways in the control system is a two-position signal switch and two pre signal amplifiers, respectively, differential thermocouple and auxiliary sensor thermocouple.To set and maintain the temperature, a heat sink temperature controller and a protective screen temperature controller are used.

The heat sink temperature controller is used to control the heat output of the heat sink assembly according to the resistance thermometer.

The protective screen temperature controller is designed to regulate the temperature of the thermal screen according to the readings of the resistance thermometer built into the screen.

To regulate the temperature of the couplings of thermocouples, the heater, the heat sink and the protective screen, four standard RT-0102 model regulators are used, and Pt1000 thermocouples are used as resistance thermometers.

The thermal power task unit is implemented based on a standardized stable voltage source.

The module of registration of primary data consists of blocks of registration of temperature of elements of system, registration of parameters of power, registration of signals of the investigated sensors. ICP DAS I-7018 modules have been used to provide temperature recording of system elements and to register the signals of the sensors under study:

- 8-channel ADC with a bit rate of 16 bits and a conversion frequency of 10 Hz;
- dynamic range adjustment and calibration;

- support for RS-485 industrial trunk interface and addressing, which makes it possible to create a measuring network.

The power parameter recording unit is based on the Picotest precision digital multimeter M3500A model with a relative measurement error of 0.0015 / 0.0004, in%, in the voltage range from 0 V to 10 V and 0.002/ 0.0006, in %, in the range from 10 V to 100V, Fluke 8846A digital multimeter with an error of 0.0037/0.0035 within ± 100 mV in voltage measurement mode and uniquely measured electrical resistance P310 of 0.1 Ohm class of 0.01.

The system software is made in a modular structure, which made it possible to connect and integrate into the main program code of previously created dynamic libraries.

The developed software includes modules that are functionally divided into three groups: module of interaction with system elements, module of process control, module of the measurement information processing.

The system interaction module provides software coordination and data exchange with hardware by sequentially calling functions that meet different tasks:

- initial setup and initialization of the interface

search for ID and initialization of individual I-7018 modules in the RS-485 network;

- adjusting the dynamic range and frequency of the I-7018 ADC module polls;

- Setting the poll cycle time, response timeout, data type, measurement channel poll queue that can be saved and downloaded from configuration files.

The resulting data sets are transmitted to the software modules that implement the control and processing functions of the measurement information - these are the modules for controlling the process of the system operation and processing of the measurement information.

The measurement information processing unit consists of a pre-censorship module of the measurement data samples, a primary data storage module, and a data archive module.

The pre-censorship module of measurement data is intended to avoid cases of storage of data with errors as a result of transmission through RS-232/485 and exclusion of measurement data with excess errors. The first problem is solved by converting the received ANSI string to a number, if at this stage an error occurs, the request is transmitted to the process control module. To solve the second problem, statistical criteria are used, which allow us to calculate marginal sample values.

The primary data storage module stores the input values of the signals used for further processing in the form of matrices, which allows to improve the processing efficiency of the data and the system as a whole, as well as normalize the input data to bring it to a predetermined range of values.

The data-archiving module is responsible for storing input values of signals which allows to not lose data in case of hardware or software failure. In addition to archiving, the operator commands automatic storage of data.

The process control module of the system provides general control of the modes of operation, including in the interactive mode, displaying the results of measurements using 2D graphs and tables

5 Experimental studies

With the use of the information-measuring system, experimental studies of the temperature dependence of the sensitivity of a number of heat flux sensors, thermocouples of which are made of copel and chromel thermoelectrode wires with nickel coating, with the variation of the ratio of the cross-sectional area temperature (30 ÷ 200) °C. In Fig. 8 the results of the experimental studies in the form of a dependence of the conversion factor of a series of heat flow sensors are presented.

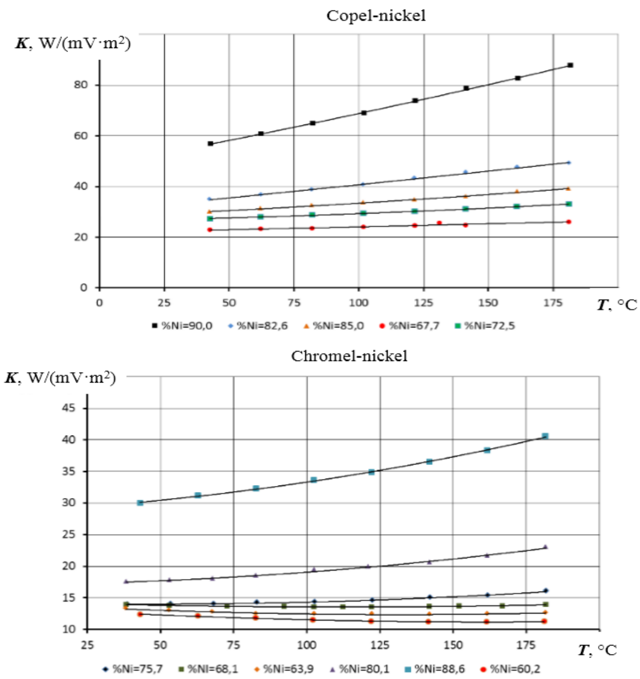

Fig. 8. Temperature dependences of the conversion factor of heat flow sensors with variation of the reduced cross-sectional area of the thermoelectrode

At each point in the range, five series repeated measurements were conducted. Expanded uncertainty of measurement results is less then 1.8 % at a coverage coefficient 2. As a result of such studies, it becomes possible not only to determine the metrological characteristics of the heat flux sensors, but also to select heat flux sensors whose characteristics will be optimal for the conditions of their subsequent operation.

6 Conclusions

The proposed information and measurement technology combines theoretical basis, software, proposed hardware for the implementation of the standard modular principle, its metrological analysis and the scheme of transferring the size of the unit of measurement, techniques for the study of metrological characteristics of the measuring instruments, and allows to adapt the main provisions of metrology specific spatial and temporal arguments for the implementation of the process of measuring the surface heat flux density.

A mathematical model is proposed that illustrates the relationship between the reproduction unit of the unit of measurement and individual components of the uncertainty that affects the accuracy of forming the unit of measurement for different heat transfer processes. The uncertainty of the measurement of the surface density of the heat flux and the main factors of influence has been studied using a cause and effect Isikawa diagram.

On the basis of the conducted researches the perspective directions of development of metrological support of measurements of heat flow are substantiated, in particular, realization of the conceptual model of the standard of surface heat flux density were applied the different physical principles of generation and transmission of thermal energy. It allows to provide measurement of in a wide range of heat flux values.

Hardware and software are presented that implement the concept of modular construction of the surface heat flux density standard in the range of values from 1 W/m^2 to 200 000 W/m^2

References

1. Biddulph, P., Gori, V., Elwell, C. A., Scott, C., Rye, C., Lowe, R., Oreszczyn, T.: Inferring the thermal resistance and effective thermal mass of a wall using frequent temperature and heat flux measurements. Energy and Buildings. Vol. 78: pp. 10–16 (2014). doi:10.1016/j.enbuild.2014.04.004
2. Ricciu, R., Galatioto, A., Besalduch, L. A., Desogus, G., Di Pilla, L.: Building wall heat capacity measurement through flux sensors. J. sustain. dev. energy water environ syst., 7(1) pp. 44-56 (2019). doi:10.13044/j.sdewes.d6.0234.
3. EN 12667: Thermal performance of building materials and products – Determination of thermal resistance by means of guarded hot plate and heat flow meter methods – Products of high and medium thermal resistance. (2001).
4. Dekusha, L., Kovtun, S., & Dekusha, O.: Heat Flux Control in Non-Stationary Conditions for Industry Applications. Proceedings of 2nd Ukraine Conference on Electrical and Computer Engineering (UKRCON), Lviv, July 2019, IEEE: pp. 601-605 (2019). doi: 10.1109/UKRCON.2019.8879847
5. Babak, V., Dekusha, O., Kovtun, S., Ivanov, S.: Information-measuring system for monitoring thermal resistance. CEUR Workshop Proceedings, Vol. 2387: pp. 102-110 (2019). http://ceur-ws.org/Vol-2387/20190102.pdf
6. Liu, J., Xu, L.X.: Boundary information based diagnostics on the thermal state of the biological bodies. Int. Journal Heat MassTransfer. Vol. 43, pp. 2827-2839 (2000).
7. Miyakawa, M., Bolomey, J.C.: Non-invasive thermometry of the human body. CRC Press Inc. (1996)
8. Lin, T.C.: Influence of Laminar Boundary-Layer Transition on Entry Vehicle Designs. Journal of Spacecraft and Rockets. Vol. 45 (2), pp. 165-175 (2008).
9. Pontt, J.: Diagnostics of Insulation Condition and Risk Evaluation of Electrical Machines Employed in Mining Application. IEEE Industry Applications Society Annual Meeting. IEEE Conferences IAS 2009: 1-3 (2009)

10. Jussila H.K., Mityakov, A.V., Sapozhnikov, S.Z., Mityakov, V.Y., Pyrhönen, J.: Local Heat Flux Measurement in a Permanent Magnet Motor at No Load. Transactions on Industrial Electronics. Vol. 60 (11), IEEE: pp. 4852 – 4860 (2013).
11. Howey, D.A., Childs, P.R. N., Holmes, A.S.: Air-gap convection in rotating electrical machines. Transactions on Industrial Electronics. Vol. 59 (3), IEEE: pp. 1367–1375 (2012).
12. Tsai, B.K., Gibson, C.E., Murthy, A.V. & others: NIST MEASUREMENT SERVICES: Heat-Flux Sensor Calibration. NIST Special Publication 250-65 (2004).
13. Heat Flux Meters: Calibration. Nordtest method. NT FIRE 050. NORTEST, Helsinki (1995).
14. Cherepanov, V.Ya.: Gosudarstvennyiy pervichnyiy etalon edinitsyi poverhnostnoy plotnosti teplovogo potoka. Doklad Federalnomu Agentstvu po tehnicheskomu regulirovaniyu i metrologii (FGUP «SNIIM»), Novosibirsk (2007).
15. ASTM C1130-07:2012. Standard Practice for Calibrating Thin Heat Flux Transducers. ASTM International (2012).
16. Nazarenko, L.A., Polevoi, V.I., Bondarenko, L.I.: Derzhavnii spetsIalnii etalon odinitsi energetichnoyi osvitlenosti nekogerentnym vyprominyuvannyam. Ukrainskii metrologichnii jurnal. Vol. 1: pp. 31–36 (1995).
17. Zarr, R., Carvajal, S., & Filliben, J.: Sensitivity Analysis of Factors Affecting the Calibration of Heat-Flow-Meter Apparatus. Journal of Testing and Evaluation. V. 47: 20170588 (2019). doi:10.1520/JTE20170588.
18. Murthy, A.V., Tsai, B.K., Saunders, R.D.: Facility for calibrating heat flux sensors at NIST: an overview. Proc. ASME Heat Transfer Division, New York: ASME, Vol. 3: pp. 159-164 (1997).
19. Olsson, S.: Calibration of Radiant Heat Flux Meters-The Development of Water Cooled Aperture for Use with Black Body Cavities. SP Report 1991:58, Nordtest Project 873-90, Swedish National Testing and Research Institute, Sweden (1991).
20. Turzó-András, E., Magyarlaki, T., Németh, S., Kovács, T.: Intercomparison of heat flux sensors. Report of EUROMET Project No 426, Hungarian Trade Licensing Office, Thermometry Department (2010).
21. Turzo-Andras, E., Blokland, H., Hammerschmidt, U. et al.: Round-Robin Test of Heat Flux Sensors. International Journal of Thermophysics. Vol. 32: pp. 2708–2715 (2011). doi:10.1007/s10765-011-1078-8.
22. Hammerschmidt, U.: Guarded Hot Plate (GHP) Method: Uncertainty Assessment. International Journal of Thermophysics, Vol. 23 (6), (2002).
23. Anderson, P., Wetterlund, I.: Uncertainty in Heat Flux Calibrations performed according to NT FIRE 050. Nordtest Project № 1525-01, SP Swedich National Testing and Research Institute. SP Report 2001:34.
24. Murthy, A.V., Tsai, B.K., Saunders R.D.: Radiative Calibration of Heat-Flux Sensors at NIST: Facilities and Techniques. Journal of Research of the National Institute of Standards and Technology. Vol. 105 (2), pp. 293-305 (2000).
25. Osadchy, S.M., Potapov, B.G.: The state standard of the unit of density of the radiation heat flux in the range from 5 to 2500 kW/m^2. Almanac of Modern Metrology, Vol. 12: pp 65-72 (2017).
26. Babak, V., Babak, S., Yeremenko, V.: Teoretichni osnovy informatsiyno-vimiryuvalnyh system: Pidruchnyk, NAU, Kyiv (2017).
27. Kovtun, S., Dekusha, L., & Vorobiov, L.: Features of reproduction the heat flux density unit of measurement by radiation method. The scientific heritage, P.1 (22): pp 51-55 (2018).
28. Ayzenberg Yu.: Spravochnaya kniga po svetotehnike, Znak, Moscou (2006).