https://doi.org/10.46813/2025-159-120

UDC 629.7.036

APPLICATION OF CARBON-CARBON COMPOSITE MATERIALS FOR HEAT FLUX DENSITY SENSOR

V.Ye. Ovcharenko[1], I.Sh. Nevlyudov[1], O.V. Tokarieva[1], I.V. Gurin[2]
[1]Kharkiv National University of Radio Electronics, Kharkiv, Ukraine
E-mail: vitalii.ovcharenko@nure.ua, igor.nevliudov@nure.ua, olena.tokarieva@nure.ua;
[2]National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine
E-mail: igor@kipt.kharkov.ua

The study examines the design principles of an uncooled, casingless heat flux transducer based on carbon-carbon composite material (CCCM), considered promising for use in advanced nuclear installations, high-temperature diffusion furnaces and similar applications. The electrical properties of CCCM were investigated during heat flux density measurements under conditions of high-intensity heat transfer at temperatures up to 2500 °C. Recommendations for the development of an electronic measurement system for the bolometer have been formulated.

The development and advancement of next-generation nuclear power systems – particularly high-temperature gas-cooled reactors (HTGR, VHTR), nuclear process control systems based on small modular reactors (SMRs), as well as progress in controlled thermonuclear fusion technologies – are accompanied by increasingly stringent requirements for diagnostics, monitoring and control of energy parameters within zones directly exposed to radiation and thermal fluxes. Of particular importance are technologies for measuring the integral thermal load in reactor components where other methods are either inapplicable or face significant operational limitations.

In this context, bolometric sensors – devices that measure absorbed radiation energy through temperature change – are of special interest. Unlike local thermocouples, pyrometers or infrared thermography systems, bolometers are capable of integrating the total thermal impact over extended periods, which is particularly valuable for diagnosing irradiation conditions of materials, especially in cases where direct temperature measurement is not feasible due to radiation or geometrical constraints.

The application of bolometric systems in physical experiments has a long history, primarily in fields such as astronomy, studies of the cosmic microwave background, spectroscopy [1] and neutrino physics [2]. In the nuclear energy sector, the use of bolometers is currently sporadic. Some specific experiments in the field of nuclear fusion (e.g., ITER, JET, Wendelstein 7-X) include bolometric modules for diagnosing plasma heat losses [3, 4].

At the same time, under high-temperature and intense radiation conditions, typical of Generation IV reactors, such devices are practically not used.

Classical bolometers used in astronomy, plasma physics or neutrino research are typically cryogenic and highly sensitive to minimal energy fluxes. However, in the context of nuclear energy, there is a growing demand for high-temperature bolometers capable of operating at temperatures up to 1500…2000 °C and withstanding intense neutron and gamma radiation. This requires the use of new thermally and radiation-resistant materials for both the sensing element and the sensor housing.

In this context, ultrahigh-temperature composite materials are of particular interest – such as carbon–carbon composite materials (CCCM), carbon–silicon carbide composites (C/SiC), as well as materials based on HfC, ZrC, and TaC – which exhibit a unique combination of properties: operational stability at temperatures exceeding 2000 °C; low thermal conductivity in a defined direction; structural stability under radiation exposure; and the ability to adapt geometry to specific reactor assembly requirements.

In the scientific literature ultrahigh-temperature composite materials (UHTCMs) are typically studied as thermal protection or structural materials, but there is a notable lack of research addressing their use as the active element in bolometer-type sensing devices.

The application of carbon-carbon composites (CCC) as the thermosensitive or shielding component of a bolometer enables the development of passive or semi-passive sensors that can be integrated directly into the structural elements of a nuclear installation. Such a sensor, for example, can be positioned both within the reactor core and in peripheral zones to register the cumulative thermal energy absorbed by a component over the course of a campaign. This opens the possibility for long-term wireless monitoring, where the signal can be retrieved either via an embedded fiber-optic channel or after removal from the reactor core.

An additional promising application of such bolometers lies in materials science research aimed at evaluating the thermoradiation resistance of novel structural and functional materials – particularly in the testing of composites, coatings or ceramics used within the reactor core or at phase boundaries. High-precision bolometric analysis enables the assessment of thermal degradation, thermal emission and absorption as functions of time and irradiation exposure.

Thus, there is a clear research gap at the intersection of bolometry and high-temperature composites in the context of nuclear energy and the development of CCC-based bolometers may become a key component of future diagnostic systems in the nuclear power industry.

A well-known method for measuring surface heat flux density involves placing a resistive heat flux transducer (HFT) in the path of radiative-convective emission. By detecting the change in electrical resistance caused by the temperature rise due to incident radiation, the resulting resistance – which is proportional to the heat flux – can be determined [5]. A device that operates on this measurement principle is referred to as a resistive bolometer. Resistive bolometers are characterized by low noise levels, structural simplicity, and low manufacturing costs. The key performance characteristics of uncooled resistive bolometers are determined by the material properties and the design of the heat flux transducer [6].

The main challenge in measuring such heat fluxes lies in selecting a suitable material for the HFT that can operate reliably for extended periods at temperatures up to 2800 °C. Its sensitivity to thermal flux must remain stable across a wide spectral range.

Structurally, a resistive bolometer consists of two parts: the sensor element, located inside the chamber and referred to as the heat flux transducer (or absorber), and the electronic unit for signal processing, which is located outside the chamber. Heat flux absorbers are characterized by a sufficient measurement range, compatibility with the physicochemical properties of the target environment, required measurement accuracy and other specific requirements, and they differ primarily in the materials used for their sensitive elements.

The material of the sensing element must possess high physicochemical stability, strong parameter consistency, radiation resistance, and the capability to operate at elevated temperatures of up to 2800 °C.

Considering that the HFT of a high-temperature resistive bolometer is located inside a vacuum chamber exposed to radiative heat fluxes, it must function as a non-contact and uncooled measuring device. The feasibility of its application is primarily determined by the heat resistance and mechanical strength of the material from which it is made.

A review of the scientific and technical literature shows that known bolometers employing metallic resistive alloys of various compositions and configurations as sensing elements can be used at temperatures up to 1250 °C [6, 7].

The aim of this work is to investigate the functional capabilities of CCC materials for the development of a novel technical solution: a contactless, uncooled HFT. Additionally, the study evaluates the feasibility of integrating the HFT into electronic systems for measurement, real-time monitoring and regulation of heat flux density within a measurement range of $10^3 \ldots 10^5$ W/m².

The research was based on the following objectives:

- Investigation of the electrical characteristics of an HFT fabricated from two-dimensionally reinforced carbon–carbon composite material and its applicability in a vacuum system without cooling;
- Assessment of the feasibility of using an uncooled, casingless HFT within a high-power radiation system;
- Development of recommendations for the design of a bolometer electronic measurement system.

The characteristics of CCC are well documented in the scientific and technical literature, as well as in applicable national and interstate standards [6–14]. Key advantages of two-dimensional reinforced CCC products are: low specific weight (1.35…1.85 g/cm³), high radiation resistance, stable mechanical performance over a wide temperature range, low heat capacity, high thermal conductivity and resistance to thermal shocks (elastic modulus, Poisson's ratio). These materials are able to maintain their shape and geometrical stability during thermal cycling in vacuum or inert atmospheres at furnace temperatures up to 2500 °C. The experimental investigations were carried out using high-temperature gas-phase furnaces at NSC KIPT.

The experimental basis for the theoretical and practical justification of heat flux density measurements inside the gas-phase furnace chamber includes:

– a prototype of a specialized caseless resistive radiation heat flux sensor, manufactured from two-dimensional reinforced CCC;

– a vacuum furnace for producing carbon–carbon composite materials using the thermogradient technology;

– a reactive gas supply system. Methane in gaseous form (precursor) is used as the reactive gas and is delivered into the furnace chamber through a filter;

– an automatic furnace temperature monitoring and control system;

– temperature sensors, a microammeter with a measurement range up to 300 μA, accuracy class not lower than 1;

– a non-contact optical pyrometer "Promin" with an error not exceeding 3%.

For the study of the electrical characteristics of the CCC-based heat flux sensor (HFS), a prototype was developed. A CCC heat flux sensor can be manufactured in virtually any shape – flat, rod-shaped, or tubular – depending on the design features of the device. Depending on the intended application, the electrical resistance of an HFS may range from a few ohms to several tens of ohms.

Taking into account mechanical constraints, the position of the heat source, and the spatio-temporal integral characteristics of heat fluxes, a tubular configuration was proposed. A similar cylindrical design was previously used in studies of anisotropic transverse-type semiconductor HFSs made of ceramic materials with a thick-film resistive spiral applied. The thermal resistance of such HFSs could not exceed 500 °C.

Therefore, for the study of surface heat fluxes, a caseless cylindrical tubular resistive HFS made of CCC was fabricated and installed directly in the furnace.

The HFS, whose design layout is shown in Fig. 1, is a caseless monolithic structure in the form of a spiral, with two enlarged end zones for mounting in the seating location inside the furnace. The outer diameter of the sensitive element of the HFS prototype was 12 mm, the inner diameter 8 mm, with a working zone length of 51 mm; the spiral pitch of the HFS was 4 mm; and its thermal conductivity coefficient was 1.5 W/(m·K). The surface area was 3200 mm², while the specific electrical resistivity of the CCC was 40 (Ω·mm²)/m. The current leads for the HFS, used to measure its electrical resistance, were made of two CCC rods, which simultaneously served as its mounting elements and, through hermetic feedthroughs in the furnace housing, were electrically connected to the measurement system.

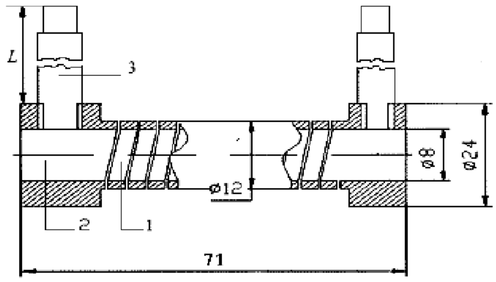

Fig. 1. Design of the HFS:
1 – cylindrical resistive section; 2 – mounting zone;
3 – rods for mounting and current connection

The studies have shown that, regardless of the initial velocity distribution of the reactive gas supplied into the furnace, after flowing along the furnace walls the velocities within the heat flux equalize and acquire a stable distribution. The length of the stabilization zone required to reach the isothermal state is approximately half of the furnace height.

To register the integral heat flux from the heater – which includes the reflected radiation from the chamber walls and the convective – radiative heat exchange with the gas flow – the HFS is recommended to be positioned along the height at the center of the inner wall of the vacuum furnace, midway between the chamber wall and the surface of the preform zone.

The advantages of the HFS design using CCC are as follows:

– the ability to register the spatio-temporal integral characteristics of radiation heat fluxes, both direct from the source and reflected from the chamber walls, due to the tubular form of the design;

– sensitivity to convective heat transfer effects, in particular to mass transfer parameters of the reactive gas between the furnace walls and the preform, achieved through the large surface area of the resistive element;

– elimination of the need for a separate housing and insulators for the HFS, which reduces the overall weight of the device.

As a drawback, the presence of two CCC rods used for mounting should be noted, since their resistance must be taken into account in the corresponding calculations.

To analyze the proposed HFS design (see Fig. 1) by calorimetric methods, the feasibility of measuring non-stationary heat fluxes over extended periods using a bolometer was investigated. A non-stationary heat flux measured with a resistive bolometer is understood as a time-varying flux absorbed by the HFS that causes a change in its electrical resistance. Measurements performed in a gas-filled environment under the influence of an intensively circulating reactive gas and variations in the surface roughness of the preform create significant challenges for modeling the temperature distribution on the surface.

Considering these difficulties, in practice it is advisable to use an experimental approach to obtain information about the surface heat flux, based on the application of specialized primary measuring devices. When using relatively simple measurement procedures, this allows accurate data to be obtained during temperature monitoring and control by the electrothermal method in real time.

The electrothermal method is based on Joule-Lenz's law of heat released in a conductor during the passage of a direct current. The heat flux or its density for electric heating devices is determined from the measurement of the amount of energy consumed by the heater.

The physical quantity that characterizes the energy flux transferred during heat exchange across a body surface per unit time is the heat flux (Φ). It is numerically equal to the ratio of the amount of heat (dQ) to the time interval ($d\tau$) during which the transfer occurred [9]:

$$\Phi = dQ/d\tau.$$

The ratio of the heat flux passing through a surface oriented perpendicular to the direction of heat transfer to the area (A) of this surface is defined as the surface heat flux density (q) [9]:

$$q = \Phi/A.$$

This value can be determined using a wattmeter or by measuring the current (I) and the voltage drop (ΔU) over a specified time interval with an ammeter and a voltmeter, respectively. In this case, the heat flux is calculated using the following formula:

$$\Phi = I \cdot \Delta U.$$

For accurate measurements of heat flux values, the potentiometric method is used with the application of a reference resistance coil connected into the electrical circuit beyond the heating zone, in series with the main heater. By measuring with a potentiometer the voltage drop across the reference resistor (coil) (ΔU_0) and across the heater (ΔU), the heat flux is calculated according to the following formula:

$$\Phi = \Delta U \cdot \Delta U_0/R_0,$$

where R_0 is the electrical resistance of the reference coil.

Recording the result of the corresponding electrical measurement provides information about the desired heat flux of the integral radiation.

The sensitivity of the bolometer is defined as the ratio of the change in the voltage drop across the sensitive element of the bolometer, caused by the change in its electrical resistance, to the amount of heat released during the absorption of thermal radiation. It is calculated according to the following formula:

$$S = \Delta U/(\varepsilon \cdot \Phi),$$

where ε is the emissivity of the HFS.

It follows that the sensitivity of the bolometer can be increased within wide limits by raising the current. However, this is restricted by the fact that, at high current levels, the self-heating of the bolometer affects its sensitivity, which requires special compensation methods.

As the “reference resistance” value, the actual temperature dependence of the electrical resistance of the CCC-based HFS specimen under study was used.

Fig. 2 shows the temperature dependence of the electrical resistance of the CCC-based HFS specimen, obtained in a vacuum chamber by passing electric current through the HFS. It should be noted that the conductivity of CCC increases with temperature, similar to semiconductors.

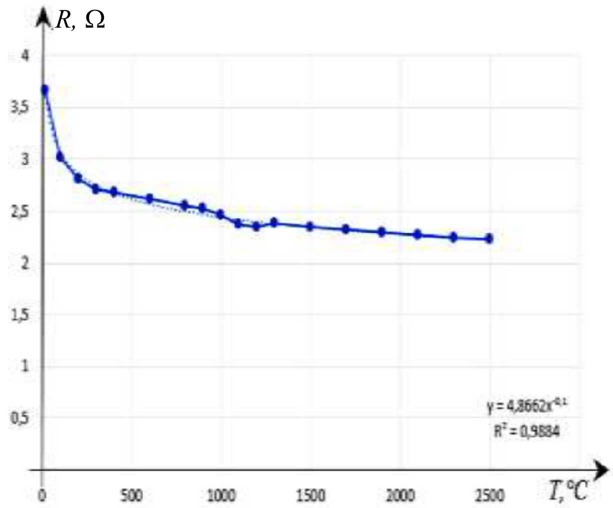

Fig. 2. Temperature dependence of the electrical resistance of the CCC-based HFS specimen under study

In the course of the experiment, the dependence of the electric current on temperature at a supply voltage from a stabilized 24 V source was also obtained (Fig. 3).

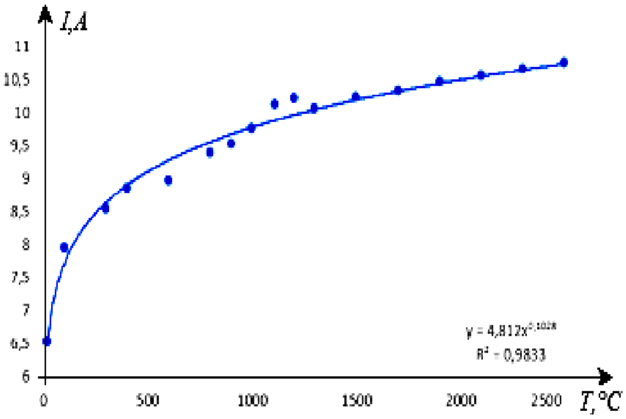

Fig. 3. Temperature dependence of the electric current of the CCC-based HFS specimen under study

Any complex technical object under development requires thorough experimental elaboration and verification of design solutions and calculations. In this work, the main attention is focused on issues related to the organization of analog electrical signal acquisition from the HFS. The primary parameter carrying information about the heat flux is the electrical resistance value of the HFS resistor.

The current level of development of measurement technology and information technologies imposes strict requirements on the operation of real-time control systems. Improving the accuracy and simplifying the operation of an uncooled bolometer with a caseless HFS is achieved by enhancing the precision of analog signal measurement and by implementing structural methods of signal processing in the processor of the bolometer’s electronic section.

The high requirements for the accuracy of digital signal processing necessitate the use of an analog-to-digital converter (ADC) with a resolution of at least 12 bits. During the conversion of the absorbed heat flux into an electrical signal proportional to the temperature change, this same input effect is also converted into an electrical signal proportional to the derivative, followed by further signal processing [5].

Thus, the efficiency of the uncooled bolometer depends on the accuracy of analog signal measurement and the use of appropriate methods for its real-time processing.

Designing the input stage circuitry of the instruments based on bridge measurement schemes makes it possible to significantly increase the accuracy of measuring the thermophysical properties of materials. This is achieved by reducing the errors that occur during the measurement of absolute temperature values and their differences, heat fluxes passing through the samples, as well as from the influence of the temperature of the heat source and receiver and other factors [12, 15].

In view of this, the creation of a software module based on a microcontroller was proposed to generate signals for heat flux measurements. As a “compensation bolometer”, its digital model with modulation and measurement of the alternating component of the signal was used. The operating mode selection, settings, and input of the HFS conversion coefficient into the microprocessor are performed by the operator.

The measurement of heat flux density in the furnace is carried out when the temperature of the resistive element of the HFS lies within the practically linear section of the temperature dependence of the specific resistance of the material, namely from 500 to 2500 °C. Under these conditions, the HFS is in thermodynamic equilibrium with the surrounding working medium, and its electrical resistance corresponds to the values shown in Fig. 2.

A widely used input stage for measuring small signals is a resistive bridge, in which one arm is connected to the HFS resistor. The other arms of the bridge include constant resistors whose resistance values are equal to the resistance of the HFS resistor at the initial measurement point. Such a balanced bridge circuit provides the highest sensitivity [5]. When the heat flux in the furnace changes, the resistance of the HFS resistor varies, disturbing the balance of the bridge. The magnitude of the voltage imbalance across the bridge diagonal makes it possible to determine the value of the surface radiation heat flux, which is recorded at a frequency of 1…0.1 Hz, taking into account the pre-obtained dependence (see Fig. 3).

Based on the known overall dimensions and the pre-determined surface area, the surface heat flux density is calculated. It should be noted that the resistance change of the bolometer HFS under the influence of thermal radiation in the temperature range of 500…2500 °C is about 0.02 Ω for each 100 °C temperature increment. Signal generation of the heat flux is carried out using specialized circuit solutions.

One of the methods for solving this task is to expand the dynamic range and improve the quality of conversion by discretizing the signal in time and quantizing it by level. This makes it possible to obtain accurate readings by amplifying the difference between the current value of the input analog signal and the reconstructed signal from the digital sequence. The obtained signal is added to the input signal for further processing. The block diagram of the input stage of the bolometer's electronic circuit that performs such processing is shown in Fig. 4.

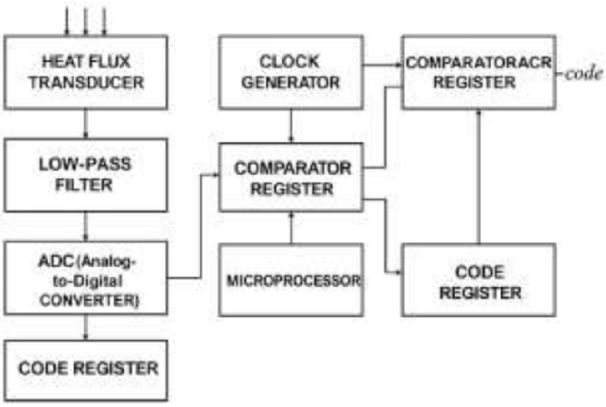

Fig. 4. Block diagram of the input stage of the bolometer electronic circuit

The input signal from the HFS passes to the ADC through a low-pass filter (LPF), which cuts off unwanted noise and interference, ensuring the purity of the input signal. The cutoff frequency of the LPF is adjusted to cover the main frequency band characteristic of the measured signal while effectively reducing the influence of high-frequency noise.

Digitization of the input signal from the bolometer HFS is carried out using a high-precision ADC. Given the high accuracy requirements, the resolution of the ADC must be at least 12 bits. This ensures sufficient precision when measuring small changes in the electrical resistance of the HFS that occur due to variations in the heat flux.

After digitization, the signal is processed further. At the first stage, the processor compares the current value of the signal with the previous one, which makes it possible to determine deviations from the baseline. If necessary, the signal is corrected by multiplying by a constant coefficient, which is configured for specific measurement conditions. This is required to accurately compensate for any errors associated with temperature variations or other external factors.

Since the bolometer HFS is sensitive to temperature, accurate determination of device parameters requires calibration at least at two temperature values. This makes it possible to account for the nonlinearity in the behavior of the HFS material, ensuring more accurate measurements over the entire operating temperature range

The conversion of the input signal includes discretization in time, quantization by level, and digital encoding. The noise level of uncooled bolometers with resistive elements of less than 5 Ω should be determined according to the characteristics of the selected component base of the amplification stage [16]. It should be noted that during the study the stability of the electrical characteristics of the HFS resistor during heating and cooling across the entire investigated temperature range was confirmed.

Thus, new functional capabilities of using CCC for the development of a HFS as part of non-contact, uncooled bolometers have been confirmed.

CONCLUSIONS

On the experimental prototype of a resistive HFS based on CCC, the feasibility of measuring and controlling the integral heat flux density in the infrared range at high temperatures up to 2500 °C was experimentally confirmed, both in vacuum and in an inert gas environment.

After digital signal processing, it was established that a caseless, uncooled bolometer with a CCC-based resistive element of up to 5 Ω demonstrates sufficient sensitivity over long periods of operation.

As a result of the conducted studies, new data were obtained that may serve as the scientific and technical basis for the development of high-sensitivity bolometers with a measurement dynamic range within 600…2500 °C. This opens the possibility for detailed investigation of thermal balance and measurement of integral thermal loads in units of advanced prospective nuclear facilities, high-temperature diffusion furnaces, and other applications.

REFERENCES

1. J.N. Ullom and D.A. Bennett. Review of superconducting transition-edge sensors for x-ray and gamma-ray spectroscopy // *Superconductor Science and Technology*. 2015, v. 28(8), p. 084003; DOI: 10.1088/0953-2048/28/8/084003

2. A. D'Addabbo, C. Alduino, K. Alfonso, et al. The CUORE and CUORE-0 experiments at LNGS // *EPJ Web of Conferences*. 2017, v. 164, p. 07047; DOI: 10.1051/epjconf/201716407047

3. H. Meister, M. Bernert, W. Biel, et al. Bolometer developments in diagnostics for magnetic confinement fusion // *J. Instrum.* 2019, v. 14(10), C10004; doi:10.1088/1748-0221/14/10/C10004

5. І.С. Васильківський, Я.П. Юсик. Температурометричні мостові схеми для вимірювання теплофізичних характеристик // *Вісник Національного університету «Львівська політехніка». Теплоенергетика. Інженерія довкілля. Автоматизація.* 2008, №617, с. 108-117.

6. ДСТУ ISO 8301:2007. *Теплоізоляція. Визначення теплового опору та пов'язаних із ним характеристик в усталеному режимі приладом із*

перетворювачем теплового потоку (ISO 8301:1991, IDT). К.: «Держспоживстандарт», 2009, 33 с.

7. ДСТУ 3756-98. *Енергозбереження. Перетворювачі теплового потоку термоелектричні загального призначення*: Загальні технічні умови. К.: «Держстандарт», 1999, 25 с.

8. В.А. Гурин, И.В. Гурин, Ю.Е. Мурин, С.Г. Фурсов, В.В. Колосенко, А.А. Корнеев, А.В. Григорьев, А.Н. Буколов. О некоторых возможностях газофазных методов для изготовления углерод-углеродных тепловых узлов для выращивания монокристаллов // *Вопросы атомной науки и техники.* 1998, №4(76), с. 46-55.

9. Т.Г. Грищенко, Л.В. Декуша, Л.И. Воробьев и др. *Теплометрия: теория, метрология, практика*: Монография в трех книгах / Под ред. Т.Г. Грищенко. К.: «Институт технической теплофизики НАН Украины», 2018, 433 с.

10. Yu.A. Gribanov, I.V. Gurin, V.V. Gujda, A.N. Bukolov, V.V. Kolosenko. Study on corrosion properties of carbon-carbon composites // *Problems of Atomic Science and Technology*. 2020, N 1(125), p. 154-160.

11. В.О. Скачков, В.І. Іванов, С.А. Воденніков, Ю.В. Мосейко. Масоперенесення під час ізотермічного ущільнення карбонізованих вуглепластиків // *Східно-Європейський журнал передових технологій.* 2012, №1(5), с. 8-11.

12. Vitalii Babak, Svitlana Kovtun. Ensuring the Reliability of Measuring Results of the Heat Flux Density at the Non-Destructive Testing Objects // *Bulgarian Society for NDT International Journal "NDT Days"*. 2018, v. 1, issue 3, p. 398-405.

13. V. Ovcharenko, O. Tokarieva. Consideration of the inertial characteristics of thermoresistive temperature transmitters in their design // *XIX International scientific and practical conference "Innovative approaches to solving scientific problems"*, May 16-19, 2023, Tokyo, Japan, p. 411-413.

14. Л.И. Грачева. Тепловое деформирование углерод-углеродных композиционных материалов с различными схемами армирования при термоциклировании // *Проблемы прочности*. 2007, №3, с. 118-133.

15. І.В. Гурін, І.Ш. Невлюдов, В.Є. Овчаренко, О.В. Токарєва. Система автоматичного управління з нейромережевими регуляторами для підвищення якості ВВКМ // *Інтегровані технології та енергозбереження.* 2024, №2, с. 104-116.

16. Mohinder S. Grewal, Angus Andrews. *Kalman filtering: theory and practice using MATLAB* / 3rd Edition. New Jersey: John Wiley & Sons, 2008.

Article received 12.09.2025

ЗАСТОСУВАННЯ ВУГЛЕЦЬ-ВУГЛЕЦЕВИХ КОМПОЗИЦІЙНИХ МАТЕРІАЛІВ ДЛЯ СЕНСОРА ВИМІРЮВАННЯ ГУСТИНИ ТЕПЛОВОГО ПОТОКУ В ДИФУЗІЙНІЙ ПЕЧІ

В.Є. Овчаренко, І.Ш. Невлюдов, О.В. Токарєва, І.В. Гурін

Розглянуто принципи побудови неохолоджуємого безкорпусного перетворювача теплового потоку з вуглець-вуглецевого композиційного матеріалу (ВВКМ) для застосування у дифузійній печі. Проведено дослідження електричних властивостей ВВКМ у процесі вимірювання густини теплового потоку в умовах високоінтенсивного теплообміну за температур до 2500 °С. Розроблено рекомендації щодо створення електронної вимірювальної системи болометра.