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INVESTIGATION OF ELECTRICAL THERMAL NOISE OF C/C COMPOSITES IN A HIGH-TEMPERATURE VACUUM CHAMBER

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The electrical thermal noise properties of carbon-carbon composite materials have been investigated. The results of studying the effect of thermal influence on the magnitude of Johnson thermal noise in a 10-Ω resistor made of carbon-carbon composite material in the frequency range up to 1 MHz at temperatures up to 3000 K in a thermal vacuum chamber are presented. Recommendations are provided regarding the application of noise thermometry in nuclear reactors.

The analysis of the influence of temperature on the noise properties of carbon-carbon composite materials (C/C composites) plays a key role in the development and improvement of high-performance electronic components and sensor devices that operate under high-temperature and extreme environmental conditions. The study of thermal noise in C/C composites is a less common research direction compared to the study of the noise characteristics of metals and semiconductors, which emphasizes the relevance of further scientific research in this field.

Previous studies focused on investigating the thermal effect on the resistive properties of C/C composites. In particular, connecting a resistor made of C/C composites to a measuring current source with subsequent voltage measurement makes it possible to calculate its bulk electrical resistance, specific volume resistance, surface resistance, and other parameters. The results of the studies demonstrated the semiconductor-like dependence of the resistor's electrical resistance on temperature. However, despite this feature, C/C composites cannot be classified as a classical semiconductor material. They are neither a metal nor a semiconductor but belong to the class of composites with a predominance of carbon bonds [1]. The temperature-dependent behavior of current-voltage characteristics when applying electrical current has been thoroughly studied and confirmed in many scientific works and validated by practical developments [2].

At the same time, it was observed that even in the absence of a power source connected to a resistor made of C/C composites, a potential difference is recorded at its terminals. Fig. 1 presents an oscillogram of the noise signal in relative units, illustrating the dependence of instantaneous values of fluctuation voltage on time. The analysis of the oscillogram obtained from the resistor made of C/C composites showed the irregular nature of random voltage fluctuations with amplitudes in the range of tens of microvolts, which vary randomly over wide ranges depending on resistance and temperature values and do not depend on the initial reference point or the duration of observation. The results obtained require further investigation of thermal noise in C/C composites and their potential application in modern electronic thermometric devices capable of operating under extreme conditions

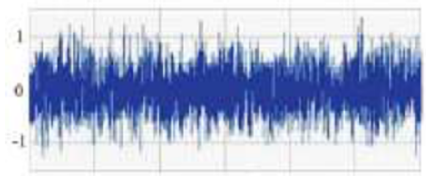

Fig. 1. Oscillogram of the noise signal

In electronic devices, similar fluctuations are observed in all elements with active resistance at temperatures above absolute zero, even without the application of an electrical voltage. At room temperature (300 K), the noise signal spectrum remains uniform up to frequencies on the order of 6 THz, and it is known as thermal (or white) electrical noise. Thermal noise is usually modeled as noise with a uniform power spectral density at frequencies up to 1 MHz [3].

The study of the temperature dependence of the electrical characteristics of thermal noise in carbon-carbon composite materials opens up possibilities for their targeted use in various technical applications. Thermal noise is caused by microscopic fluctuations in the crystal lattice induced by temperature effects and by macroscopic dissipative phenomena arising from the chaotic thermal motion of charge carriers, atoms, or molecules. As a result, a fluctuating potential difference appears at the ends of the conductor. The thermal motion of free electrons generates random microcurrents, which are accompanied by random voltages with instantaneous values different from zero. The higher the conductor's temperature, the more it "noises." According to the classification, such noise belongs to the natural type, since it is determined by the fundamental physical properties of materials [4]. According to the classification of the National Institute of Standards and Technology (NIST, USA), this type of noise is defined as Johnson noise (JNT) [5].

The main characteristic of this noise is the root mean square (RMS) value of the voltage, conventionally defined as the noise power across an electrical resistance, which depends on the resistance temperature, bandwidth, and frequency. According to the well-known Nyquist formula, the RMS voltage value that determines the noise power generated by a resistance R can be calculated with high accuracy. For temperatures above 25 K in the frequency range below 1 MHz, the noise power can be approximated with a relative error of less than $1{\cdot}10^{-6}$. This feature makes it possible to use thermal noise voltage as a thermometric parameter for accurate temperature measurement of various materials.

The RMS voltage value of thermal noise is determined by the expression:

$$\overline{V_T^2} = 4kTRe(Z)\Delta f, \quad (1)$$

where $\overline{V_T^2}$ – root mean square (RMS) value of the thermal noise voltage, V; k – Boltzmann constant $k = 1.38{\cdot}10^{-23}$ J/K; T – temperature, K; Δf – bandwidth, Hz; Re (Z) – real part of the resistance of the generating resistor, Ω

From equation (1) it follows that by determining the root mean square value of the thermal noise voltage generated by the resistance of a resistor within a known frequency band Δf, and knowing the value of this resistance, it is possible to determine the temperature in any volume regardless of the specific physicochemical properties of the resistor material. This is possible because thermal noise depends exclusively on temperature and resistance, and not on the conductor's material. Thus, measuring thermal noise makes it possible to determine temperature accurately while accounting for the specific properties of the material.

This principle has formed the basis of new methods of passive pyrometry, in particular low-frequency noise spectroscopy, which provides high sensitivity and accuracy of temperature control compared to traditional electrical and optical methods [6, 7]. Such methods have found wide application in areas where conventional sensors lose stability due to extreme operating conditions, for example, in nuclear energy, where the sensitive element of the sensor is exposed to radiation and over time becomes unsuitable for recalibration [8]. Noise thermometry is also applied for high-precision temperature control in vacuum and diffusion furnaces, in high-temperature technological processes, particularly in vacuum-thermal refining of materials at temperatures up to 3000 K [9, 10].

In the aerospace field, noise thermometry methods play an important role in ensuring accurate temperature measurements of engines and other critical components, which is essential for flight safety and the reliability of aviation technology. In metallurgy, this method is used for temperature monitoring in furnaces and casting processes, contributing to production optimization and improving the quality of the final product [11].

Johnson noise thermometry (JNT) methods have also been successfully tested for temperature control during crystal growth experiments on the International Space Station [12]. Studies have demonstrated the potential of JNT for medium-term experiments (up to several months) at temperatures above 1500 °C with an accuracy of up to 0.1 °C. By comparison, experiments with tungsten–rhenium thermocouples under similar conditions showed temperature drifts of up to 100 °C after only 20 h of continuous operation.

Scientific studies devoted to Johnson noise thermometry using different sensors based on metals and semiconductor materials have been presented in numerous publications [11, 13]. High stability, the absence of calibration requirements, and resistance to external influences make this method promising for use under microgravity conditions, as well as in high-temperature and radiation-intensive environments.

In the study of the total noise power, the full noise level generated by the resistor was evaluated over a fairly wide frequency range – from a few hertz to several megahertz. This covers the mid- and near-infrared spectra of thermal radiation that may be present in the vacuum chamber. Review works in the field of physical electronics confirm that the infrared noise in the range up to 1 MHz has the greatest research value for this study. This frequency range is particularly important for high-precision temperature measurement, since infrared noise is directly related to thermal radiation, which depends on temperature. The application of noise thermometry methods in this range makes it possible to achieve high measurement accuracy and sensitivity, which is critically important in areas such as vacuum thermal refining, where precise temperature control is necessary to ensure the required physicochemical properties of materials. The study of infrared thermal noise in the range up to 1 MHz is a promising direction for the development of passive pyrometry methods to improve the accuracy of temperature measurement in various technological processes.

In the present work, an investigation of the electrical characteristics of thermal noise of a resistor made of carbon–carbon composite material was carried out. Numerical modeling of the root mean square value of the thermal noise voltage of a passive resistor in the infrared radiation range was performed at temperatures from 297 to 3000 K. Previously, similar studies of thermometry of high-temperature processes using the thermal noise characteristics of a C/C composite resistor in the temperature range up to 3000 K had not been published.

The object of the study is an original resistor made of carbon–carbon composite material with a specific electrical resistivity of 40 ($\Omega{\cdot}mm^2$)/m and a total resistance of 10 Ω, which was manufactured at the National Science Center "Kharkiv Institute of Physics and Technology." The current leads were also made of the same material, ensuring uniformity of electrical and thermal properties throughout the structure, as well as providing strong mechanical fastening to avoid the microphone effect.

The geometric parameters of the resistor were determined taking into account technological limitations during manufacturing and the requirements for electrical connection in the laboratory setup. The resistor design has the form of a spiral made of a monolithic cylindrical rod of C/C composite (Fig. 2, item 1). At both ends of the resistor (item 2), zones 10 mm long were provided for connecting two current leads (item 3). This design ensures reliable electrical connection and promotes efficient heat dissipation, which is critically important for accurate measurements under laboratory conditions.

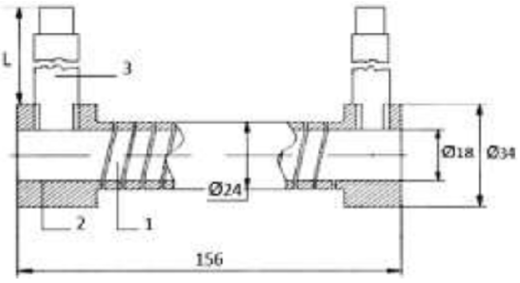

Fig. 2. Design of the C/C composite resistor

The design makes it possible to study the electrical characteristics of the thermal noise of the C/C composite resistor, to carry out their identification, and it has a number of unique advantages and features that should be taken into account when measuring specific values of thermal noise:

- ✓ C/C composites are characterized by high thermal resistance, mechanical strength, and dimensional stability at temperatures up to 2500 °C, which makes them ideal for use under high-temperature conditions;
- ✓ stability of linear dimensions in vacuum at temperatures up to 3000 K: C/C composites maintain their geometric parameters even under extreme temperatures, ensuring measurement accuracy. The coefficient of thermal linear expansion for such materials is about $3.0\cdot10^{-6}$ K^{-1};
- ✓ high structural stability and radiation resistance: resistors made of C/C composites demonstrate significantly higher resistance to radiation compared to traditional metals and semiconductors;
- ✓ possibility of creating a monolithic, compact, frameless design: the absence of the need to apply coatings on the resistor eliminates dielectric losses in its reactive components;
- ✓ absence of ferromagnetic properties: the resistor and its leads have no ferromagnetic properties, which prevents the induction of voltage or current in the measuring circuit;
- ✓ absence of hysteresis in the thermal current–voltage characteristic: C/C composite resistors do not exhibit hysteresis phenomena, which ensures the stability of their characteristics;
- ✓ low level of flicker (1/f) noise: due to the absence of a potential barrier between the material of the current leads and the resistor;
- ✓ resistance to aggressive environments;
- ✓ dependence of resistor resistance on temperature, which makes it possible to use it for thermometric measurements.

At a resistor resistance of 10 Ω and a temperature of 290 K, the length of the resistive element is calculated by the expression $= \frac{R\cdot S}{\rho}$, where In the study of the total noise power, the full noise level generated by the resistor was evaluated over a fairly wide frequency range – from a few hertz to several megahertz R – electrical resistance of the resistor, Ω; ρ – specific electrical resistivity, (Ω·mm²)/m; S – cross-sectional area of the resistor, mm².

For the given parameters we obtain:

$$l = \frac{10\cdot 9}{40} = 2250\ mm.$$

Taking into account the spiral diameter, the number of turns is approximately 34, and the total length of the resistor is 156 mm. After manufacturing and mechanical adjustment, the exact resistance value of the resistor was 10.0021 Ω.

To determine the root mean square value of the thermal noise voltage generated by the resistor, the dependence of the resistor resistance on temperature was preliminarily obtained in a vacuum furnace (Fig. 3).

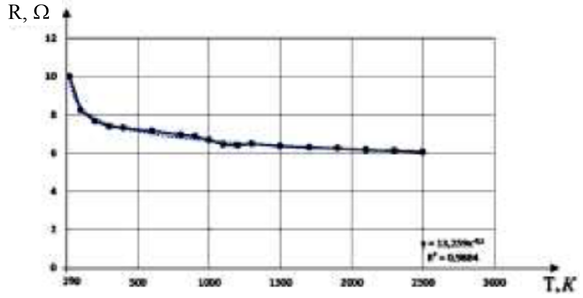

Fig. 3. Temperature dependence of the resistance of the C/C composite resistor

The origin of thermal noise in the C/C composite resistor is caused by random fluctuations of quantum-mechanical collisions within the material. The root mean square value of the thermal noise voltage in the resistor is always proportional to its resistance in the absence of inertial elements and other types of noise. The results of numerical modeling of the root mean square value of the thermal noise voltage of the resistor at frequencies up to 1 MHz, given the known temperature dependence of its resistance, are presented in Fig. 4.

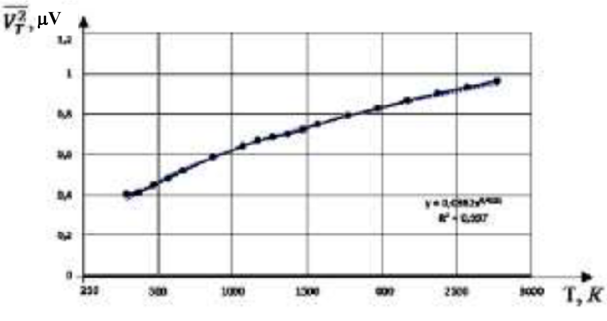

Fig. 4. Temperature dependence of the thermal noise voltage (μV) of the C/C composite resistor

From Fig. 3 it can be seen that the electrical resistance of the resistor decreases sharply with increasing temperature up to 500 K, after which it decreases smoothly and uniformly up to 3000 K. At the same time, as shown in Fig. 4, with increasing temperature, the root mean square value of the thermal noise voltage increases from 0.4022 to 0.9641 μV. The temperature dependence of the root mean square value of the thermal noise voltage is almost linear, indicating a uniform distribution of noise power across the entire frequency range. For the obtained values, an approximating polynomial describing this dependence has been constructed:

$$\overline{V_T^2} = 0.0362\mathrm{T}^{0.4121}.$$

If a conductor has only an active resistance RRR, its noise power spectral density does not depend on frequency, which characterizes it as “white” noise with a constant spectral density within the measured frequency range.

From expression (1), it is possible to determine a number of parameters that characterize the thermal noise of the C/C composite resistor and that can be used for the selection and design of an electrical measuring circuit.

The most common method of measuring noise voltage is based on its comparison with a reference value, which is generated by a standard noise generator integrated into the amplifier, or with a voltage whose level is predetermined. To ensure measurement accuracy, it is necessary to preliminarily obtain the noise voltage characteristic of the C/C composite resistor and guarantee its stability both in the switched-on and switched-off operating modes of the device. In addition, it is important to minimize the influence of parameter variations of different primary sensor specimens that serve as noise sources, in order to improve the accuracy and reproducibility of measurement results.

The temperature is determined by analyzing the ratio of the measured noise powers, which, ideally, does not depend on the amplifier gain factor or the bandwidth. For this purpose, two measurements are usually performed: one for the resistor at an unknown temperature, and another for a reference noise source, which is usually a resistor with a precisely known temperature.

$$T = T_{ref}\frac{\overline{V_T^2}}{\overline{V_{ref}^2}}\frac{R_{ref}}{R_T},$$

where T_{ref}, R_{ref}, $\overline{V_{ref}^2}$ – respectively, the temperature, resistance and average noise power of the reference resistor; R_T, $\overline{V_T^2}$ – the resistance and average noise power of the resistor at an unknown temperature.

For measuring the thermal noise voltage in order to regulate temperature in vacuum, highly sensitive electronic equipment is required, capable of ensuring accurate signal registration, while the recorded signal must contain exclusively components of thermal origin. Modern methods that combine software and hardware solutions make it possible to perform high-precision measurements of small signals in real time and to obtain their instantaneous values in digital format [13]. This enables the creation of an automated system for monitoring and controlling the temperature regime in the range up to 3000 K.

Noise thermometry is not a widely accepted method of temperature control for general use due to its high sensitivity to weak signals and the complexity of their accurate measurement. However, this approach gains particular importance in nuclear ground-based and space reactors, where traditional methods may be less effective or unsuitable. The main difficulty of noise thermometry lies in the need to amplify the signal by a factor of 10 or more, as well as in its effective filtering and rectification with minimal distortion.

The analysis of problems related to the development of thermal noise sensors based on carbon–carbon composite material for measuring the temperature of the active zone and coolant of nuclear reactors focuses on ensuring their high reliability, long service life, and resistance to extreme temperature and radiation conditions. High temperatures, intense radiation exposure, and the aggressive environment of the reactor space require careful selection of materials and design solutions that guarantee the stability of sensor parameters throughout its service life.

In nuclear reactors, sensor elements are subjected to extreme conditions, including pressures above 20 MPa, temperatures up to 2200 °C, as well as intense irradiation by thermal neutrons, which cause material transmutation, and gamma radiation fluxes, which lead to crystallographic dislocations, embrittlement, and swelling of structural elements. For comparison, according to study [14], tungsten–rhenium thermocouples operating at a temperature of 1250 °C demonstrated a gradual drift at a rate of 1.5 °C per hour, leading to a total temperature shift of 130 °C over 1000 h of operation. At the same time, in the same reactor, a noise thermometer with a measurement error of about 10 °C showed no signs of drift, which indicates its high stability under severe test conditions.

The measurement of thermal noise in a resistor is a complex task that requires high precision in electrical assembly and the use of specialized equipment. Compliance with these conditions ensures the necessary stability and reliability of the results obtained, which is critically important for achieving the research objectives.

Modern noise-based temperature measurement devices in the infrared range are highly sensitive instruments that contain input and output RF paths as well as an automatic voltage meter. The input signal is the noise signal generated by the carbon–carbon composite resistor, and the output signal is formed by the amplifier for automatic control and temperature measurement.

Noise thermometry using a sensor based on carbon–carbon composite material can be applied in the temperature range up to 3000 K, which significantly exceeds the limits of traditional temperature sensors. Since the measurement of temperature is based on fundamental physical principles, the characteristics of such sensors are not subject to drift. Although the electronics used for measuring the required values may experience drift, the modern component base minimizes it.

The random nature of noise implies that the statistical uncertainty of temperature measurement decreases proportionally to the square root of the bandwidth and measurement time, especially when using a quadratic detector in the device. Therefore, for accurate and rapid measurements, preliminary research work is necessary to ensure optimal system configuration. The choice of measurement method is determined by the specific operating conditions and the required level of accuracy. A reliable analysis of the method's uncertainty is only possible at the design stage, when the relationship between the thermodynamic temperatures of the object is established based on the measured spectral power densities.

The high reliability of a temperature sensor in the form of a resistor made of carbon–carbon composite material for monitoring high temperatures, as well as its stability in nuclear installations on Earth and for space applications, confirms the feasibility of further work on the practical implementation of such a sensor. Future research will consider various solutions aimed at developing circuit design aspects and connecting the thermal noise sensor for registration, taking into account the modern component base and neural network technologies.

CONCLUSIONS

The study substantiates the feasibility of using carbon–carbon composites (C/C composites) for the registration of thermal noise and for the monitoring of high-temperature processes in nuclear reactors, diffusion vacuum furnaces, and other installations operating under extreme conditions. The investigations of the temperature dependence of the noise-related electrical characteristics of C/C composites confirm their ability to generate electrical thermal noise signals, opening up prospects for their application in highly sensitive temperature sensors.

Resistors based on C/C composites can effectively function as primary noise transducers of heat flux, ensuring high-precision and reliable control of working environment parameters under extreme temperature conditions. The amplitude of signals formed in the infrared temperature range is sufficient for reliable registration when modern methods of software–digital processing are employed.

The results obtained demonstrate the potential for further studies of thermal and other types of noise in C/C composites, which may contribute to the development of advanced high-temperature sensors for application in critically important technologies.

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ДОСЛІДЖЕННЯ ЕЛЕКТРИЧНОГО ТЕПЛОВОГО ШУМУ ВВКМ В УМОВАХ ВИСОКОТЕМПЕРАТУРНОЇ ВАКУУМНОЇ КАМЕРИ

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

Досліджено електричні теплові шумові властивості вуглець-вуглецевих композиційних матеріалів. Представлено результати дослідження дії теплового впливу на величину теплового шуму Джонсона в резисторі опором 10 Ом з вуглець-вуглецевого композиційного матеріалу в діапазоні частот до 1 МГц за температур до 3000 К у тепловій вакуумній камері. Надані рекомендації по застосуванню шумової термометрії в ядерних реакторах.