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DESIGN OF A THERMOELECTRIC COOLING MODULE FOR AN X-RAY DETECTOR

The paper presents the results of designing a thermoelectric multistage thermoelectric cooling module for X-ray detectors. The structure of a thermoelectric cooler as part of an X-ray detector is developed and the possibilities of its practical use are analyzed. Bibl. 12, Fig. 2.

Key words: computer design, thermoelectric cooling, X-ray detector.

Introduction

General characterization of the problem. X-ray methods are widely used for non-destructive microanalytical studies of the structure and composition of materials with high spatial resolution [1]. The current state of nuclear microanalysis methods using focused beams of MeV energy ions with high monoenergeticity ($\Delta E/E=10^{-5}$) allows spatial resolution on the surface of up to 100 nanometers and up to 10 nanometers in the sample thickness. Further enhancement of the resolution substantially depends on the improvement of the analytical characteristics of semiconductor detectors, as well as on the use of wide-aperture position-sensitive radiation detectors of new types [2].

To increase the resolution of x-ray detectors, it is important to solve the problem of ensuring the optimal temperature of their operation [3-9].

It is solved by using semiconductor thermoelectric cooling modules [5-9] to provide the required cooling depth in the minimum working volume of the detector. Thus, single-stage thermoelectric modules are used for shallow cooling (to 250 K). Two-stage thermoelectric cooling modules are used for cooling sensors to operating temperature of 230 K, three-stage modules - to temperature of 210 K, four and five-stage modules – to temperatures below 190 K [10].

Therefore, the purpose of this work is to analyze the capabilities of thermoelectricity for cooling X-ray detectors and to design a multi-stage thermoelectric cooler for X-ray detectors.

Physical model

For the calculations, we used the physical model of a thermoelectric cooler as part of an X-ray detector presented in Fig. 1. It consists of a housing 2 with a beryllium window 1 through which radiation enters the X-ray detector 3. The required temperature and thermal conditions on the surface of the X-ray detector are provided by a multi-stage thermoelectric cooler with an electric power *W* consisting of n- and p-type thermoelectric material legs 8, electrically conductive interconnect plates 9, ceramic electrical insulation plates 7. A vacuum is created inside the detector housing 4 to reduce heat loss. The heat flow is removed from the thermoelectric cooler through the base of detector housing 5 and its fixture 6.

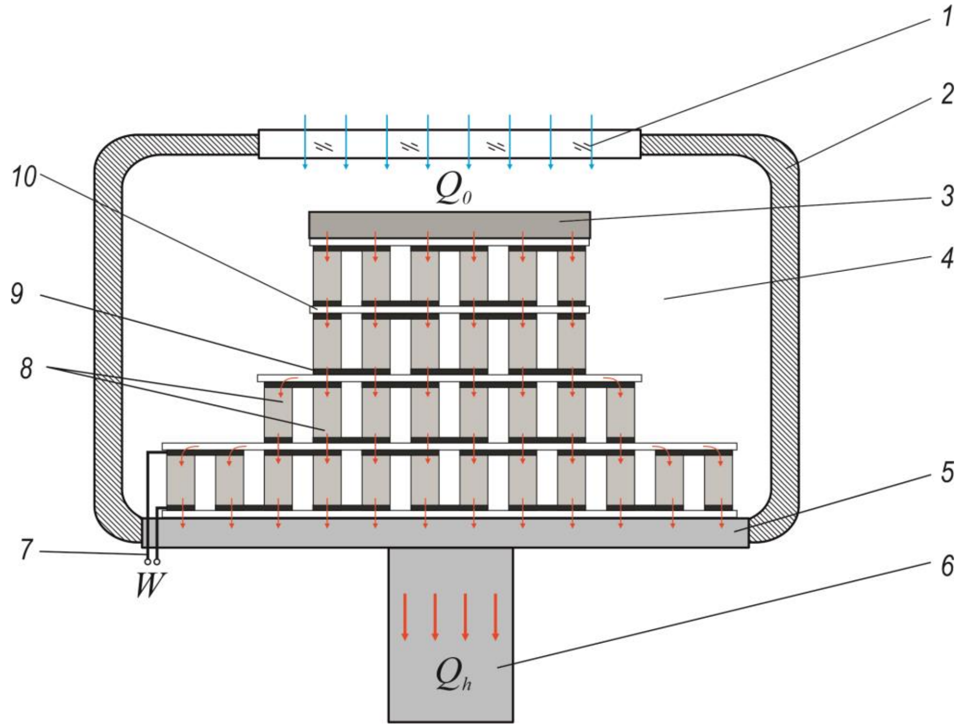

Fig. 1. Physical model of a thermoelectric multi-stage cooler as part of an X-ray radiation detector: 1 - beryllium window; 2 – device housing; 3 – X-ray radiation detector; 4 – internal space of device where vacuum is created; 5 – device housing base; 6 – device fixture;7 – electrical leads; 8 – legs of n- and p-type thermoelectric material, 9 – electrical interconnect plates, 10 – ceramic electrical insulating plates .

Mathematical and computer descriptions of the model

The system of equations for the description of coefficient of performance of a thermoelectric cooler depending on the parameters of physical model is determined from thermal balance equations:

$$Q_c = \chi_1 (T_c^{(1)} - T_c), \tag{1}$$

$$\begin{cases} Q_h = \chi_3 (T_h^{(2)} - T_h^{(1)}) \\ Q_h = \chi_4 (T_h^{(1)} - T_h) \end{cases}, \tag{2}$$

$$Q_h = Q_c + W_{TE}. \tag{3}$$

Here, $T_c^{(1)}$ is detector surface temperature, T_c is thermoelectric module cold side temperature, χ_1 is thermal contact resistance, $T_h^{(2)}$ is thermoelectric module hot side temperature, $T_h^{(1)}$ is detector base temperature; T_h is temperature of surface to which heat is removed, χ_2 is thermal contact resistance, χ_3 is thermal resistance of heat exchanger on the “hot side” of thermoelectric converter, Q_0 is refrigerating capacity, Q_h is heating capacity.

With regard to (1) – (3), the expression for the coefficient of performance of thermoelectric cooler will be written in the form:

$$\varepsilon_r = \frac{Q_0}{W + W_1} = \frac{\alpha I (T_c + Q_0 N_1) - 0.5 I^2 R - \lambda (T_h - T_c - (Q_h N_2 + Q_0 N_1))}{W + W_1}, \tag{4}$$

where α is differential Seebeck coefficient of material, I is current strength, R is electrical resistance of thermoelectric module, λ is average thermal conductivity of thermoelectric module legs, W_1 is power consumed to provide heat exchange,

$$N_1 = \frac{(\chi_1 + \chi_2)}{\chi_1 \chi_2},\ N_2 = \frac{(\chi_3 + \chi_4)}{\chi_3 \chi_4}. \quad (5)$$

To design the thermoelectric cooler, the COMSOL Multiphysics software package was used [11]. For this purpose, the equations of the physical model must be presented in a certain form, as will be shown below.

To describe heat and electricity flows, we use the laws of conservation of energy

$$div\vec{E} = 0 \quad (6)$$

and electrical charge

$$div\vec{j} = 0, \quad (7)$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \quad (8)$$

$$\vec{q} = \kappa\nabla T + \alpha T\vec{j}, \quad (9)$$

$$\vec{j} = -\sigma\nabla U - \sigma\alpha\nabla T. \quad (10)$$

Here, $\vec{E}$ is energy flux density, $\vec{q}$ is thermal flux density, $\vec{j}$ is electric current density, U is electric potential, T is temperature, α, σ, κ are the Seebeck coefficient, electrical conductivity and thermal conductivity.

With regard to (8) – (10), one can obtain

$$\vec{E} = -(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T - (\alpha\sigma T + U\sigma)\nabla U. \quad (11)$$

Then the laws of conservation (5), (6) will take on the form:

$$-\nabla\left[(\kappa + \alpha^2\sigma T + \alpha U\sigma)\nabla T\right] - \nabla\left[(\alpha\sigma T + U\sigma)\nabla U\right] = 0, \quad (12)$$

$$-\nabla(\sigma\alpha\nabla T) - \nabla(\sigma\nabla U) = 0. \quad (13)$$

The second-order nonlinear differential equations in partial derivatives (12) and (13) determine the distribution of temperature T and potential U in the thermoelectric cooler.

Solving these equations with the use of technology of object-oriented computer simulation [11] and optimal control theory [12] allows finding optimal design of thermoelectric converter and the dependences of its characteristics.

Computer design results

As a result of computer simulation, the structure of a thermoelectric multistage module (Fig. 2) was designed, which provides the possibility of its use to ensure the temperature conditions of the X-ray detector (Table 1).

Thus, a thermoelectric cooler contains 4 stages - 6, 12, 27 and 65 pairs of thermoelectric material legs, its overall dimensions are 12 x 16 x 12 mm, while providing a cooling area of 4 x 8 mm. The dimensions of legs of thermoelectric material based on n- and p-type bismuth telluride (Bi_2Te_3) are 0.6 x 0.6 x 1.8 mm. Insulating plates of aluminum oxide (Al_2O_3) are 0.5 mm thick, electrical interconnects of copper (*Cu*) with an anti-diffusion layer of nickel (*Ni*) are 0.1 mm thick.

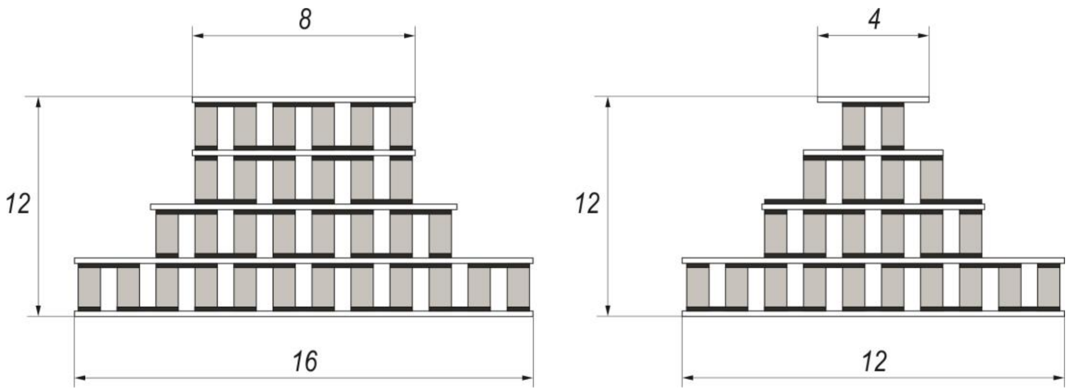

Fig.2. Schematic design of a thermoelectric cooler for an X-ray radiation detector

The estimated cooling capacity of the thermoelectric converter is Q_0 = 57 mW (3 mW - thermal load from the detector plus 54 mW - leakage through radiation). Provided the temperature at the detector $T_c^{(1)}$ = - 70 °C and at the heat sink temperature T_h = +20 °C, the coefficient of performance of the thermoelectric cooler is ε = 0.02. Therefore, the electrical power that will be consumed by this converter is W = 2.85 W.

The results obtained prove the possibilities of using thermoelectric coolers for assuring temperature and thermal conditions for X-ray radiation detectors and outperform the well-known world analogs [10].

Conclusions

1. Computer-aided design of a thermoelectric cooler for X-ray detectors was conducted.
2. The structure and characteristics of a thermoelectric cooler (as part of an X-ray detector) were designed. Thus, the thermoelectric cooler contains 4 stages of Bi_2Te_3 based thermoelectric material with the overall dimensions of 12x16x12 mm while providing a cooling area of 4x8 mm.
3. The electric power of a thermoelectric converter $W = 2.85$ W was determined, which with the coefficient of performance ε = 0.02 provides for the temperature of detector housing base $T_c^{(1)}$ = -70 °C and ΔT = 90 K.

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ПРОЕКТУВАННЯ ТЕРМОЕЛЕКТРИЧНОГО МОДУЛЯ ОХОЛОДЖЕННЯ ДЕТЕКТОРА РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ

У роботі наведено результати проектування термоелектричного багатокаскадного термоелектричного модуля охолодження рентгенівських детекторів. Розроблено конструкцію термоелектричного охолоджувача у складі детектора рентгенівського випромінювання та проаналізовано можливості його практичного використання. Бібл. 12, рис. 2 .
Ключові слова: комп'ютерне проектування, термоелектричне охолодження, рентгенівський детектор.

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ПРОЕКТИРОВАНИЯ ТЕРМОЭЛЕКТРИЧЕСКОГО МОДУЛЯ ОХЛАЖДЕНИЯ ДЕТЕКТОРА РЕНТГЕНОВСКОГО ИЗЛУЧЕНИЯ

В работе приведены результаты проектирования термоэлектрического многокаскадного термоэлектрического модуля охлаждения рентгеновских детекторов. Разработана конструкция термоэлектрического охладителя в составе детектора рентгеновского излучения и проанализированы возможности его практического использования. Библ. 12, рис. 2.

Ключевые слова: компьютерное проектирование, термоэлектрическое охлаждение, рентгеновский детектор.

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