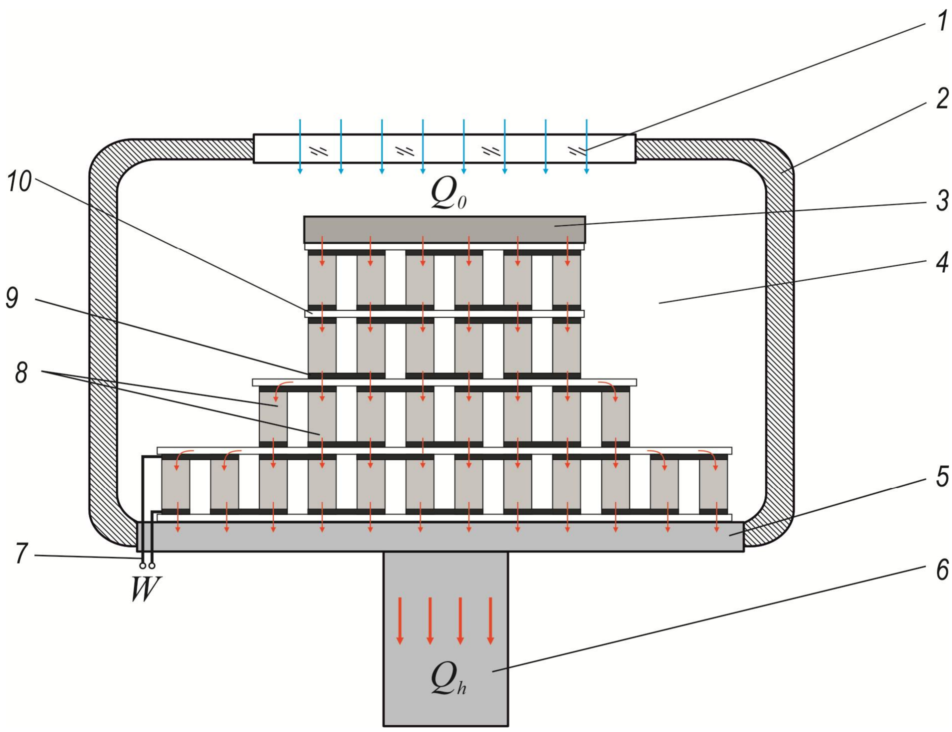

Fig. 1. Physical model of a thermoelectric multi-stage cooler as part of an X-ray radiation detector:
1 - beryllium window; 2 – device housing; 3 – X-ray radiation detector;
4 – internal space of device where vacuum is created; 5 – device housing base;
6 – device fixture;7 – electrical leads; 8 – legs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

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

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

$$div\vec{E} = 0 \tag{6}$$

and electrical charge

$$div\vec{j} = 0, \tag{7}$$

where

$$\vec{E} = \vec{q} + U\vec{j}, \tag{8}$$

$$\vec{q} = \kappa \nabla T + \alpha T \vec{j}, \tag{9}$$

$$\vec{j} = -\sigma \nabla U - \sigma \alpha \nabla T. \tag{10}$$

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

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

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

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

$$-\nabla(\sigma \alpha \nabla T) - \nabla(\sigma \nabla U) = 0. \tag{13}$$

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.

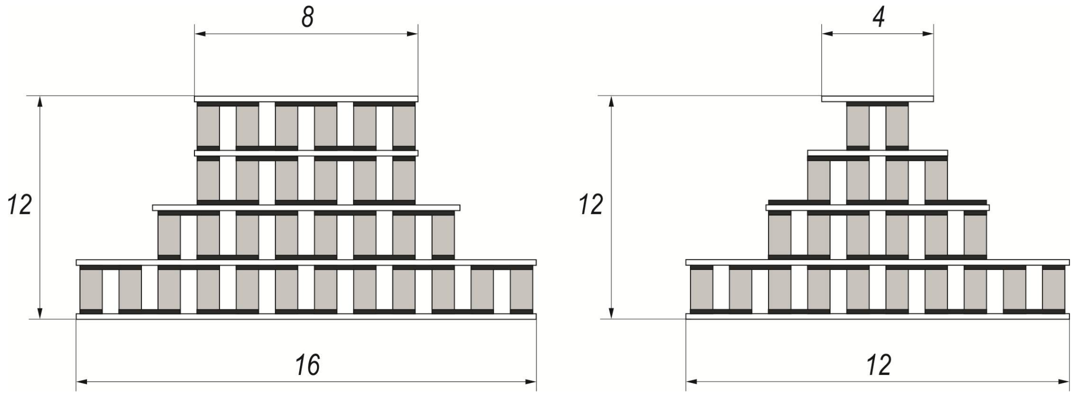

Fig.2. Schematic design of a thermoelectric cooler for an X-ray radiation detector

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 $\varepsilon = 0.02$ 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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