A.V. Prybyla

A.V. Prybyla, *cand. phys.– math. sciences* [1,2]

[1]Institute of Thermoelectricity of the NAS and MES of Ukraine,
1 Nauky str., Chernivtsi, 58029, Ukraine;
[2]Yuriy Fedkovych Chernivtsi National University
2 Kotsiubynskyi str., 58000, Ukraine

EFFICIENCY INCREASE OF THERMOELECTRIC COOLING MODULE FOR X-RAY DETECTOR

The paper presents the results of designing a multi-stage thermoelectric cooling module for X-ray detectors. The design of a thermoelectric cooler as a part of X-ray detector is developed and the technique of increase of its energy efficiency is offered. Bibl. 11, Fig. 1.

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

Introduction

General characterization of the problem. Thermoelectric coolers are widely used to ensure optimal operating modes of various radiation detectors [1, 2]. Their use with semiconductor X-ray detectors is especially relevant, which significantly increases their resolution [3-9].

In [3], the results of computer design of a thermoelectric multi-stage cooler for X-ray detector are presented. The optimal geometric dimensions and operating modes of the cooler were determined, which provide the best operating conditions for X-ray detector. However, the analysis of the thermal circuit of a thermoelectric cooler for X-ray detector showed the presence of heat loss, which leads to a decrease in its energy efficiency.

Therefore, the purpose of the work is to analyze the possibilities of increasing the efficiency of a thermoelectric cooler for X-ray detector.

Physical model

For the calculations, we have used the physical model of a thermoelectric cooler as part of X-ray detector presented in Fig. 1. It consists of a housing 2 with a beryllium window 1 through which radiation enters X-ray detector 3. The required temperature and thermal conditions on the surface of 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 9, electrically conductive interconnect plates10, ceramic electrical insulation plates 11 and electrical leads 8. A vacuum is created inside the detector housing 5 to reduce heat losses. The heat flow is removed from the thermoelectric cooler through the base of detector housing 6 and its fixture 7.

Analysis of the thermal circuit of X-ray detector showed that the source of the greatest losses of efficiency of the thermoelectric cooling module (which also leads to a decrease in the maximum temperature difference) are thermal inleaks to the thermoelectric legs of the module cascades due to radiation. In order to reduce these losses, it was proposed to improve the design of the thermoelectric module by introducing additional radiation shields 4 in Fig.1.

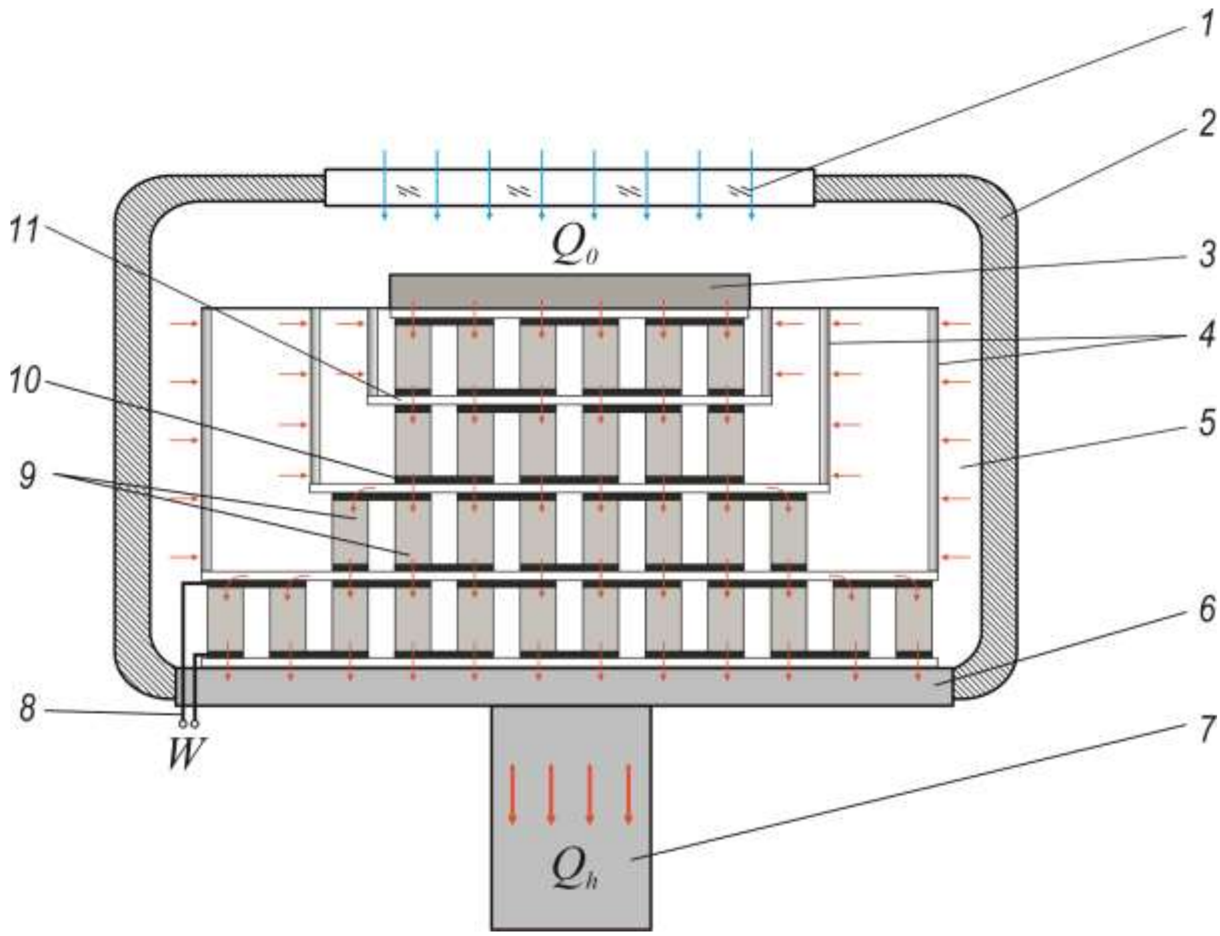

Fig. 1. Physical model of a thermoelectric multi-stage cooler as part of X-ray detector:
1 – beryllium window; 2 – device housing; 3 – X-ray detector;
4 – radiation shields; 5 – internal space of a device where vacuum is created;
6 – device housing base; 7 – device fixture;
8 – electrical leads; 9 – n- and p-type thermoelectric material legs,
10 – electrical interconnect plates, 11 – 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:

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

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

$$Q_h = Q_c + W_{TE}. \quad (3)$$

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 [10]. 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 [10] and optimal control theory [11] allows finding optimal design of thermoelectric converter and the dependences of its characteristics.

Computer design results

As a result of computer design of the improved model of the thermoelectric cooler (according to the physical model in Fig. 1), its energy characteristics were calculated and compared with the results of previous studies [2].

Thus, the thermoelectric cooler has 4 stages – each comprising 6, 12, 27 and 65 pairs of legs of thermoelectric material, with its overall dimensions - 12 x 16 x 12 mm while providing the cooled area 4 x 8 mm. The dimensions of thermoelectric material legs based on n- and p-type bismuth telluride (Bi_2Te_3) - 0.6 x 0.6 x 1.8 mm. Electrical insulating plates are made of alumina (Al_2O_3) 0.5 mm thick, electrical connections are made of copper (*Cu)* with anti-diffusion layer of nickel (Ni) 0.1 mm thick. In addition, the thermoelectric cooler contains radiation shields that have thermal contact with the surface of each stage and provide reduction of heat loss due to radiation.

Comparison of simulation results with previous studies [2] shows that the presence of radiation shields leads to a decrease in heat loss inside the thermoelectric multi-stage module by 30% (Q_0 = 31 mW).

When 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 = 0.023. Therefore, the electric power that will be consumed by such a converter is W ≈ 1.5 W.

Moreover, the use of radiation shields opens up opportunities to increase the maximum temperature difference of the thermoelectric module by 5 K, which is important to ensure optimal operating modes of X-ray detectors.

Conclusions

1. The possibility of increasing the energy efficiency of a thermoelectric cooler for X-ray detector by using radiation shields is revealed.
2. It is established that the presence of radiation shields leads to a decrease in heat loss inside the thermoelectric multi-stage module by 30%.
3. It is determined that when the temperature at the detector is provided $T_c^{(1)}$ = -70 °C and at the heat sink temperature T_h = +20 °C the coefficient of performance of the thermoelectric cooler is ε = 0.023. Therefore, the electric power that will be consumed by such a converter is W ≈ 1.5 W.

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Прибила А.В.[1,2]

[1]Інститут термоелектрики НАН і МОН України,
вул. Науки, 1, Чернівці, 58029, Україна;
[2]Чернівецький національний університет
ім. Юрія Федьковича, вул. Коцюбинського 2,
Чернівці, 58000, Україна

ПРО ПІДВИЩЕННЯ ЕФЕКТИВНОСТІ ТЕРМОЕЛЕКТРИЧНОГО МОДУЛЯ ОХОЛОДЖЕННЯ ДЕТЕКТОРА РЕНТГЕНІВСЬКОГО ВИПРОМІНЮВАННЯ

У роботі наведено результати проектування термоелектричного багатокаскадного термоелектричного модуля охолодження рентгенівських детекторів. Розроблено конструкцію термоелектричного холоджувача у складі детектора рентгенівського випромінювання та запропоновано методику підвищення його енергетичної ефективності. Бібл. 11, рис. 1.

Ключові слова: комп'ютерне проектування, термоелектричне охолодження, рентгенівський детектор.

Прибыла А.В.[1,2]

[1]Институт термоэлектричества НАН и МОН Украины,
ул. Науки, 1, Черновцы, 58029, Украина;
[2]Черновицкий национальный университет
им. Юрия Федьковича, ул. Коцюбинского 2,
Черновцы, 58000, Украина

О ПОВЫШЕНИИ ЭФФЕКТИВНОСТИ ТЕРМОЭЛЕКТРИЧЕСКИХ МОДУЛЕЙ 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 предложена методика повышения его энергетической эффективности. Библ. 11, рис. 1.
Ключевые слова: компьютерное проектирование, термоэлектрическое охлаждение, рентгеновский детектор.

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