UDC 537.32

Siberian Journal of Science and Technology. 2018, Vol. 19, No. 1, P. 17–21

CALCULATION OF CHARACTERISTICS OF THERMOELECTRIC COOLING SYSTEM OF HEAT-LOADED ELEMENTS OF RADIO ELECTRONIC EQUIPMENT

E. N. Vasil'ev

Krasnoyarsk Science Centre SB RAS, Institute of Computational Modelling SB RAS
50/44, Akademgorodok, Krasnoyarsk, 660036, Russian Federation
E-mail: ven@icm.krasn.ru

Modern technologies make it possible to construct electronic devices that combine small sizes and high energy consumption, which requires the optimization of thermal modes. A promising direction to improve cooling intensity of the heat-loaded element (HLE) and precision of temperature control is applying thermoelectric modules (TEMs), which endow the heat release system with a cooling function, i. e., allow to reach temperatures of the HLE below ambient temperature. In the present paper, the processes of heat transfer in thermoelectric system of cooling and temperature control (TESCTC) are comprehensively considered. The temperature field in the capacity of heat-distributing plate (HDP), and influence of the heat flux inhomogeneity on the HLE temperature increase have been defined. The results of operating modes calculations, taking into account the heat-power release of HLE, performance of TEM, parameters of HDP and cooler, and magnitude of thermal resistance of thermal contacts have been presented. The calculation method allows to determine the temperature of HLE and to optimize TESCTC modes to achieve maximum cooling efficiency and lower energy consumption. It has been found that the optimal power supply current of TEM, corresponding to the modes with the maximum efficiency of cooling, depends on the thermal resistance of the heat sink system and the power of the heat load.

Keywords: thermoelectric module, heat mode, heat-loaded element, cooling system, thermal resistance.

Сибирский журнал науки и технологий. 2018. Т. 19, № 1. С. 17–21

РАСЧЕТ ХАРАКТЕРИСТИК ТЕРМОЭЛЕКТРИЧЕСКОЙ СИСТЕМЫ ОХЛАЖДЕНИЯ ТЕПЛОНАГРУЖЕННЫХ ЭЛЕМЕНТОВ РАДИОЭЛЕКТРОННОЙ АППАРАТУРЫ

Е. Н. Васильев

Красноярский научный центр СО РАН, Институт вычислительного моделирования СО РАН
Российская Федерация, 660036, г. Красноярск, Академгородок, 50/44
E-mail: ven@icm.krasn.ru

Современные технологии позволяют производить радиоэлектронные устройства, сочетающие малые размеры и высокое энергопотребление, что обостряет проблему обеспечения оптимальных тепловых режимов. Перспективным направлением для повышения интенсивности охлаждения теплонагруженного элемента (ТНЭ) и точности терморегулирования является применение термоэлектрических модулей (ТЭМ), которые наделяют теплоотводящую систему функцией охлаждения, т. е. дают возможность достигать температуры ТНЭ ниже значения внешней среды. Комплексно рассмотрены процессы теплообмена в термоэлектрической системе охлаждения и терморегулирования (ТЭСОТ). Определено температурное поле в объеме теплораспределяющей пластины (ТРП) и влияние неоднородности теплового потока на увеличение температуры ТНЭ. Представлены результаты расчета режимов работы с учетом мощности тепловыделения ТНЭ, рабочих характеристик ТЭМ, параметров ТРП и кулера, величины термических сопротивлений тепловых контактов. Расчетная методика позволяет определять температуру ТНЭ и проводить оптимизацию режимов ТЭСОТ с целью достижения максимальной эффективности охлаждения и снижения энергозатрат. Установлено, что оптимальная сила тока питания ТЭМ, соответствующая режимам с максимальной эффективностью охлаждения, зависит от термического сопротивления системы теплоотвода и мощности тепловой нагрузки.

Ключевые слова: термоэлектрический модуль, тепловой режим, теплонагруженный элемент, система охлаждения, термическое сопротивление.

Introduction. The resource, operational stability and operating characteristics of the heat-loaded elements (HLE) of radio-electronic equipment significantly depend on their temperature condition, so in case of increase in working temperatures from 20 to 60 °C equipment failure rates increase more than twice [1]. The perspective direction for cooling and temperature control of HLE is the use of thermoelectric modules (TEMs). Thermoelectric system of cooling and temperature control (TESCTC) possess a list of advantages in comparison with other cooling systems, namely: possibility of smooth temperature control in rather broad range by changing of value and direction of supply current TEM; minor thermal inertness; high reliability; absence of moving parts; compactness and small weight; quietness of operation. TESCTC are effectively used for cooling of both miniature objects and large volume refrigerators [2–6].

Construction and characteristics of the cooling system. HLE *1* is considered to be a TESCTC widespread type applied to cooling, construction with heat distributing plate (HDP) *2*, TEM *3* and a cooler *4* (fig. 1). HDP is necessary for alignment of thermal power distribution arriving from HLE on TEM surface. At the same time TEM performs the function of a thermal pump transferring heat from the cold side to the hot. The cooler removes the total thermal power produced by both HLE and TEM to the external environment. These elements of the system have thermal contacts on the boundaries. On the areas of contact surface A the cooler removes heat to the external environment having temperature T_0. The boundary of B corresponds to the contact surface of the cooler with the hot side of HLE which temperature is described by average value of T_2. The cold side of HLE (B surface) has average temperature of T_1. HLE seat (D surface) is characterized by average value of temperature T_e. In case of HLE suspension from the considered construction, the normal heat-eliminating system, which is widely applied to HLE cooling, for example, in the computer equipment, is widely used.

Typical options of temperature distributions which can be implemented in TESCTC are given in fig. 2. Ambient temperature T_0 is the original value directly influencing HLE seat temperature. For the normal heat-eliminating system temperature value T_e of HLE seat certainly exceeds T_0 value, increase in temperature is assured due to the temperature fluctuations caused by thermal resistance of HLE and cooler (line *4*). The negative temperature drop made by HLE allows to reduce temperature T_e, which in this case can either exceed value of T_0 (line *2*), or be lower than this value (line *1*). Under certain conditions influence of own heat release of HLE can on the contrary lead to its additional heating (line *3*), not cooling. When analyzing efficiency of HLE cooling, basic operating characteristics of HLE are used; they can be calculated [7] or received from the vendor. In the present research the influence of HDP thermal resistance, cooler and thermal contacts on characteristics of thermoelectric cooling and HLE temperature are studied. HLE temperature is determined by the ambient temperature and the sum of temperature drops of all construction elements. During calculations temperature drops were calculated gradually at first in configuration "TEM-cooler", then in HDP in terms of thermal influence of HLE and TEM. The analysis of TESCTC characteristics is carried out on the example of serial TEM of NPO "Kristall".

Temperature calculation of the heat-loaded element. Values and temperature drop ratio depend on operating characteristics and parameters of all TESCTC construction elements and their cross impact [8–11]. In TESCTC in case of heat exchange of TEM with an external environment from its hot side, it is necessary to remove the total thermal power developed by HLE and TEM, which is, as a rule, considerably higher than HLE power due to rather low refrigerating coefficient of TEM. It causes the corresponding growth of temperature drop on thermal contacts and the cooler, which, as a result, leads to lowering of cooling efficiency. The difference of temperatures ΔT_0 between the cold side of TEM and the environment is determined from expression [11]

$$\Delta T_0 = T_1 - T_0 = R_s(Q+W) - \Delta T_{\text{TEM}} = \\ = R_s Q + R_s U(I,Q)I - \Delta T_{\text{TEM}}(I,Q),$$

here T_1, T_0 – temperature values of the hot side TEM and environment; R_s – total thermal resistance of the cooler and its thermal contact with TEM; Q, W – heat release capacities of HLE and natural energy consumption of TEM; $\Delta T_{\text{TEM}} = T_2 - T_1$ – temperature drop between the cold and hot sides of TEM; U, I – power and current intensity of power supply of TEM. Operating characteristics of TEM from the manufacturer $Q(\Delta T_{\text{TEM}})$ and $U(\Delta T_{\text{TEM}})$ are basic data for dependences determination $U(I, Q)$ and $\Delta T_{\text{TEM}}(I, Q)$ and further calculation ΔT. The method of dependences calculation is presented in [10; 11].

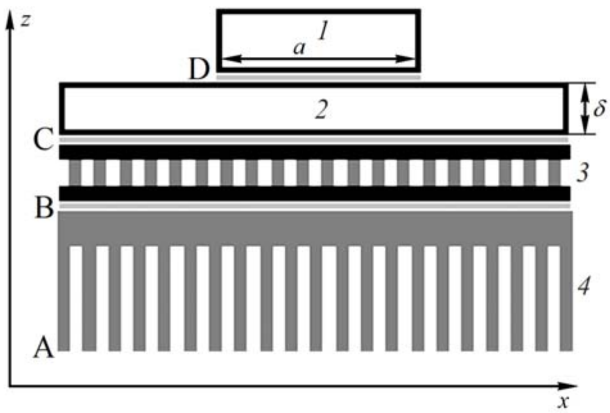

Fig. 1. Thermoelectric cooling system

Рис. 1. Схема термоэлектрической системы охлаждения

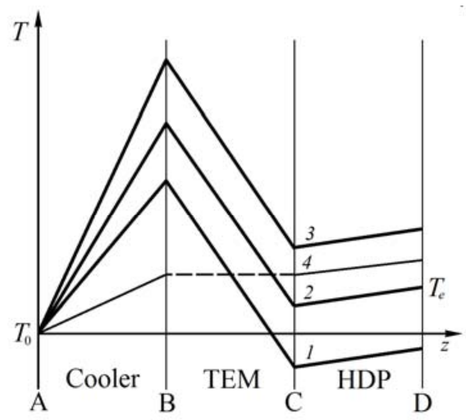

Fig. 2 Temperature distribution in the cooling system

Рис. 2. Распределение температуры в системе охлаждения

Dependences of the cold side temperature drops of TEM and the environment on the power consumption under Q = 40 W and R_s = 0.1, 0.3 and 0.5 K/W are presented in fig. 3 for TEM "S–127–14–11" (solid lines) and "S–199–14–11" (broken lines), having maximum refrigerating values 79.3 and 124.2 W. Negative values ΔT_0 correspond to the modes, in which cold side temperatures of TEM are lower than ambient temperature. Temperature drop values ΔT_0 considerably depend on R_s, variation interval of values ΔT_0 for the fixed W within the range of R_s = 0–0.5 K/W averages at about 55–60 °C. For the given dependencies presence of least values is typical. This least values correlate with the best values of energy consumption W, under which the maximum cooling of HLE can be achieved. When increasing R_s from 0.1 to 0.5 K/W these values W fall from 103 W to 38 W for TEM "S–127–14–11" and from 120 W to 37 W for TEM "S–199–14–11".

For temperature drop losses in HDP measurement mathematical model based on numerical solution of the three-dimensional equation of heat conduction is used with regard to the load characteristic of TEM:

$$c_v \rho \frac{\partial T}{\partial t} = \lambda \left(\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} \right),$$

where c, ρ, λ – specific heat capacity, density and heat conduction coefficient of material; T – temperature; t – time; x, y, z – spatial coordinates. Values c, ρ and λ in all estimated area had constant values corresponding to copper. HDP sizes were equal in cross x and y directions were equal to TEM 40×40 мм^2 overall dimensions, in z direction its thickness δ varied. The HLE seat was set in the center of HDP's upper surface in the form of a square with side a. On the upper and lower boundaries of HDP inhomogenuity of heat fluxes, caused by influence of HLE and TEM was considered. To solve this equation the method of total approximation with splitting of the task into spatial coordinates [12] was applied.

Based on calculations distributions of temperature HDP with different values of its thickness δ and HLE size a were obtained. The integral parameter characterizing heat-transmitting ability of HDP is the thermal resistance of R. Quantitative thermal resistance is calculated as the relation of average temperatures of HLE seat difference and the bottom surface of HDP to the transferred thermal power, where time value R depends both on heat conduction of HDP material and HLE and HLE sizes. Dependences R on thickness of copper HDP are shown in fig. 4 for different values a, curves *1*, *2*, *3*, *4* and *5* correspond to values 22.5, 17.5, 12.5, 7.5 and 2.5 of mm. Based on values of thermal resistance R and power of heat release of HLE, Q value of temperature drop on HDP is defined by the expression $\Delta T_{\text{HDP}} = RQ$. The figure shows that the range of best values δ makes approximately from 3 mm where a = 22.5 mm up to 5 mm where a = 2.5 mm. Optimization of HDP parameters allows to minimize temperature drop and as a result to reduce HLE temperature. Besides, calculations proved that inhomogenuity of the temperature field of TEM cold side leads to essential increase in thermal resistance of HDP compared to the case of isothermal heat-eliminating surface [13; 14]. This increase R is explained by the increase in average length of heat transmission in HDP capacity, caused by lower values of temperature on TEM edges. Lowering thermal resistance value and losses of HDP temperature drop can be assured by applying materials with higher coefficient of heat conduction or hyper heat-conducting plates (plane thermal pipes) in which high effective heat conduction is reached due to phase transformations of the heat carrier in case of movement in the porous environment [15; 16].

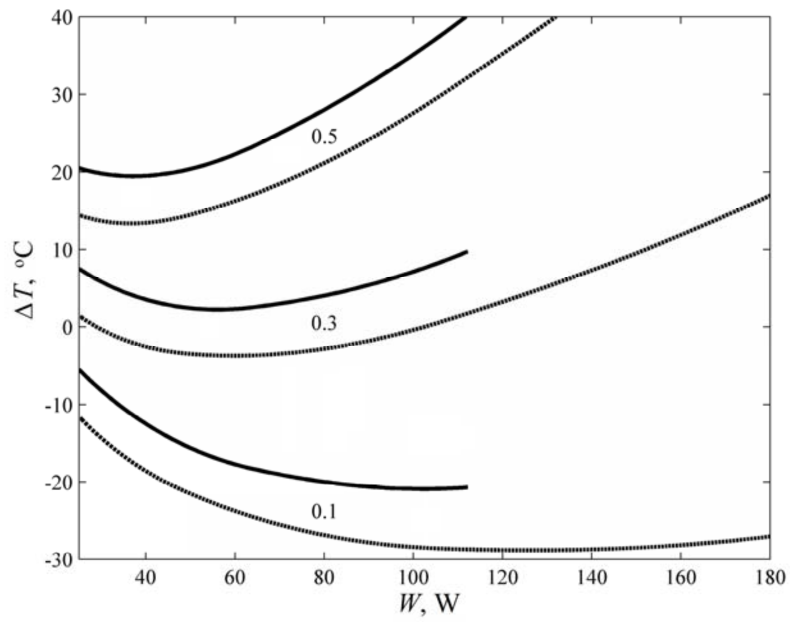

Fig. 3. Dependences of the TEM cold side temperature drops and the environment on the power consumption under Q = 40 W and various values of R_s

Рис. 3. Зависимости разности температур холодной стороны ТЭМ и окружающей среды от потребляемой мощности при Q = 40 W и различных значениях R_s

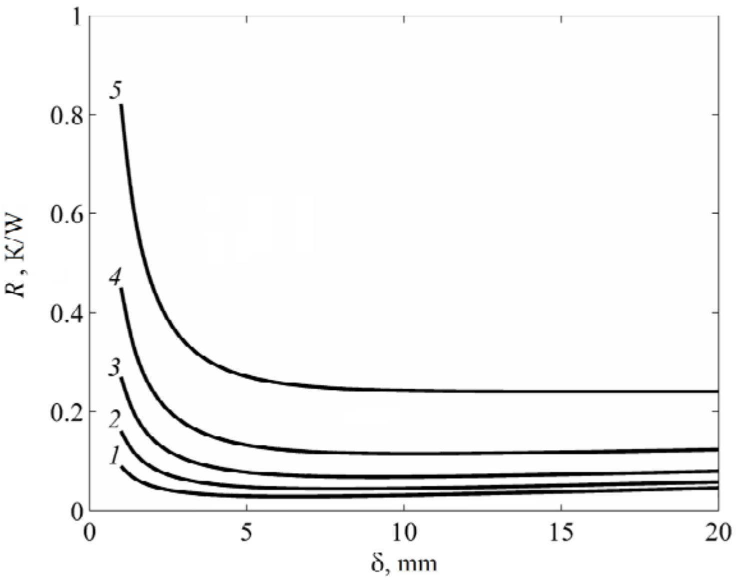

Fig. 4. Dependencies $R(\delta)$ for the cooper HDP, curves *1*, *2*, *3*, *4* and *5* correspond to a = 22.5, 17.5, 12.5, 7.5 and 2.5 mm

Рис. 4. Зависимости $R(\delta)$ для медной ТРП, кривые *1*, *2*, *3*, *4* и *5* соответствуют a = 22.5, 17.5, 12.5, 7.5 и 2.5 мм

Thus, the considered two-step algorithm allows to calculate HLE temperature. At the first stage temperature of the TEM cold side is determined by calculation of total temperature drop in the "cooler – TEM" system with regard to the HLE thermal power, operating characteristics of TEM, cooler thermal resistance and thermal contacts, ambient temperature. Then temperature drop in HDP is calculated and based on HDP temperature distribution on the upper boundary of HDP with regard to the thermal resistance of heat contact on its seat, foundation temperature is determined. Final expression for average temperature of HLE seat calculation has the following appearance

$$T_e = T_0 + \Delta T_0 + RQ.$$

Under the known internal thermal resistance of HLE (information of the vendor) its influence is considered the same way, herewith the temperature of the semiconductor crystal, located in the HLE case, will be defined.

Conclusion. In the present paper heat exchanging processes in TESCTC are considered; the algorithm allowing to carry out calculation of HLE temperature and TESCTC modes optimization to increase cooling efficiency of HLE and lowering of TEM energy consumption are provided. It is stated that the value of effective power consumption of TEM corresponding to the modes with maximum cooling efficiency depends on the thermal resistance of the cooler and power of HLE heat release.

Acknowledgments. This study was supported by the Russian Foundation for Basic Research, administration of the Krasnoyarsk Territory, and Krasnoyarsk Territory foundation supporting scientific research activity (project No. 16-41-242104).

Благодарности. Исследование выполнено при финансовой поддержке Российского фонда фундаментальных исследований, Правительства Красноярского края, Красноярского краевого фонда поддержки научной и научно-технической деятельности в рамках научного проекта № 16-41-242104.

References

1. Nenashev A. P. *Konstruirovanie radioelektronnykh sredstv* [Designing of radio-electronic means]. Moscow, Vysshaya Shkola Publ., 1990, 432 p. (In Russ.).

2. Chang Y. W., Chang C. C., Ke M. T., Chen S. L. Thermoelectric air-cooling module for electronic devices. *Applied Thermal Engineering*. 2009, Vol. 29, No. 13, P. 2731–2737.

3. Huang H. S., Weng Y. C., Chang C. C., Chen S. L., Ke M. T. Thermoelectric water-cooling device applied to electronic equipment *International Communications in Heat and Mass Transfer*. 2010, Vol. 37, No. 2, P. 140–146.

4. Zhu L., Tan H., Yu J. Analysis on optimal heat exchanger size of thermoelectric cooler for electronic cooling applications. *Energy conversion and management*. 2013, Vol. 76, P. 685–690.

5. Gladushchenko V. N., Derevyanko V. A., Vasil'ev E. N. et al. [Thermoelectricity in engineering problems of the modern technology of cooling]. *Elektronnye i elektromekhanicheskie sistemy i ustroistva* [Electronic and electromechanical systems and devices]. Tomsk, AO NPC Polus Publ., 2016, P. 177–183 (In Russ.).

6. Derevyanko V. A., Gladushchenko V. N., Vasil'ev E. N. et al. *Termoelektricheskiy blok okhlazhdeniya* [Thermoelectric cooling module]. Patent RF, no. 2511922, 2014.

7. Vasil'ev E. N. [Mathematical Model for the Calculation of the Characteristics of the Cooling Thermoelectric Modules]. *Journal of Siberian Federal University. Engineering & Technologies.* 2015, Vol. 8, No. 8, P. 1017–1023 (In Russ.).

8. Vasil'ev E. N., Derevyanko V. A. [Calculation of thermoelectric modules efficiency for radio electronic components cooling]. *Materialy XX Mezhdunar. nauch. konf. "Reshetnevskie chteniya*" [Materials XVII Intern. Scientific. Conf "Reshetnev reading"]. Krasnoyarsk, 2013, P. 211–213 (In Russ.).

9. Vasil'ev E. N., Derevyanko V. A. [Analysis of thermoelectric modules efficiency in cooling systems]. *Vestnik SibGAU*. 2013, No. 4(50), P. 9–13 (In Russ.).

10. Vasil'ev E. N. Calculation and Optimization of Thermoelectric Cooling Modes of Thermally Loaded Elements. *Technical Physics*. 2017, Vol. 62, No. 1, P. 90–96.

11. Vasil'ev E. N. Optimization of Thermoelectric Cooling Regimes for Heat-Loaded Elements Taking into Account the Thermal Resistance of the Heat-Spreading System. *Technical Physics.* 2017, Vol. 62, No. 9, P. 1300–1306.

12. Samarskii A. A. *Teoriya raznostnykh skhem* [The theory of difference schemes]. Moscow, Nauka Publ., 1989, 616 p. (In Russ.).

13. Glinskii I. A., Zenchenko N. V. Computer simulation of the heat distribution element for high power microwave transistors. *Russian Microelectronics*. 2015, Vol. 44, No. 4, P. 236–240.

14. Semenyuk V. A., Bezverkhov D. B. Modeling and Minimization of Intercascade Thermal Resistance in Multi-Stage Thermoelectric Cooler. Proc. of the XVI Int. Conf. on Thermoelectrics. Dresden, Germany, 1997, IEEE, P. 701–704.

15. Vasil'ev E. N., Derevyanko V. A., Kosenko V. E. et al. [Computational modeling of heat exchange in thermoregulation systems of space vehicle]. *Vychislitel'nye tekhnologii*. 2009, Vol. 14, No. 6, P. 19–28. (In Russ.).

16. Vasil'ev E. N., Nikiforova E. S. [Mathematical model of heat exchange processes in honeycomb panels with heat pipes]. *Vestnik SibGAU*. 2005, No. 3, P. 23–26 (In Russ.).

Библиографические ссылки

1. Ненашев А. П. Конструирование радиоэлектронных средств. М. : Высш. школа, 1990. 432 с.

2. Thermoelectric air-cooling module for Chang electronic devices / Y. W. Chang [et al.] // *Applied Thermal Engineering*. 2009. Vol. 29, No. 13, P. 2731–2737.

3. Thermoelectric water-cooling device applied to electronic equipment / H. S. Huang [et al.] // *International Communications in Heat and Mass Transfer.* 2010. Vol. 37, No. 2. P. 140–146.

4. Zhu L., Tan H., Yu J. Analysis on optimal heat exchanger size of thermoelectric cooler for electronic cooling applications // *Energy conversion and management*. 2013. Vol. 76. P. 685–690.

5. Термоэлектричество в инженерных задачах современной техники охлаждения / В. М. Гладущенко [и др.] // Электронные и электромеханические системы и устройства. Томск : АО «НПЦ «Полюс». 2016. С. 177–183.

6. Пат. 2511922 Российская Федерация, МПК[7] F 25 B 21/02. Термоэлектрический блок охлаждения / Деревянко В. А., Гладущенко В. М., Васильев Е. Н. и др. № 2012142405/06 ; заявл. 04.10.2012 ; опубл. 10.04.2014, Бюл. № 10.

7. Васильев Е. Н. Математическая модель для расчета характеристик термоэлектрических модулей охлаждения // Журнал Сиб. федер. ун-та. Сер. «Техника и технология». 2015. Т. 8. № 8. С. 1017–1023.

8. Васильев Е. Н., Деревянко В. А. Расчет эффективности термоэлектрических модулей для охлаждения радиоэлектронных элементов // Решетневские чтения : материалы XVII Междунар. науч. конф. (12–14 нояб. 2013, г. Красноярск) / под общ. ред. Ю. Ю. Логинова ; Сиб. гос. аэрокосмич. ун-т. Красноярск, 2013. Т. 1. С. 211–213.

9. Васильев Е. Н., Деревянко В. А. Анализ эффективности применения термоэлектрических модулей в системах охлаждения радиоэлементов // Вестник СибГАУ. 2013. № 4(50). С. 9–13.

10. Васильев Е. Н. Расчет и оптимизация режимов термоэлектрического охлаждения теплонагруженных элементов // Журнал технической физики. 2017. Т. 87, № 1. С. 80–86.

11. Васильев Е. Н. Оптимизация режимов термоэлектрического охлаждения теплонагруженных элементов с учетом термического сопротивления теплоотводящей системы // Журнал технической физики. 2017. Т. 87, № 9. С. 1290–1296.

12. Самарский А. А. Теория разностных схем. М. : Наука, 1989. 616 с.

13. Глинский И. А., Зенченко Н. В. Расчет теплораспределяющего элемента конструкции для мощных СВЧ-транзисторов // Микроэлектроника. 2015. Т. 44, № 4. С. 269–274.

14. Semenyuk V. A., Bezverkhov D. B. Modeling and Minimization of Intercascade Thermal Resistance in Multi-Stage Thermoelectric Cooler // Proc. of the XVI Inter. Conf. on Thermoelectrics. Dresden, Germany, 1997, IEEE. P. 701–704.

15. Вычислительное моделирование процессов теплообмена в системах терморегулирования космических аппаратов / Е. Н. Васильев [и др.] // Вычислительные технологии. 2009. Т. 14, № 6. С. 19–28.

16. Васильев Е. Н., Никифорова Е. С. Математическое моделирование теплового режима гипертеплопроводного радиатора мощного радиоэлемента // Вестник СибГАУ. 2005. Вып. 3. С. 23–26.