УДК 519.876.5

Improvement of Effectiveness of Cooling of Electronic Heat-Loaded Modules

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There has been developed, manufactured and researched by numerical and experimental methods an operating sample of a typical construction of a cooling system of electronic heat-loaded modules of dual application, which can be used in devices of both special and civil purposes. The main idea of organizing an effective cooling is to provide heat transfer from a heat-loaded module, located in conditions where it is impossible to provide the thermal regime necessary for trouble-free operation, to an area where it is possible to organize the dissipation of the transported heat flow through free convection. A gravity-assisted heat pipe with a threaded capillary structure was used as a heat transfer device. As heat-loaded modules there were used powerful volumetric electronic modules made in the form of a prism with flat side faces, on which powerful semiconductor electronic components were installed. Due to application of a highly efficient closed evaporation-condensation cycle of heat transfer occurred in heat pipes, it became possible to increase the power of the electronic module in almost two times while keeping its temperature within the specified limits, graphical dependences of the temperature of semiconductor electronic components on the consumed electric power in the range from 13 to 36 W were obtained by using a calculation method. The experimental data were compared with those obtained due to the calculation.

Key words: semiconductor electronic modules, LEDs, heat pipe, free convection, efficiency

DOI: 10.20535/RADAP.2020.81.47-55

Research objective

High-heat semiconductor electronic modules are widely used in devices of both special and civil purposes. For example, high-power microwave electronic modules are known to be used in antenna systems of radar engineering [1, 2], in energy-efficient LED lighting devices [3,4], etc. Considering that a small part of the electrical energy consumed by LED lighting devices is converted into net energy of emitted signals in the power amplifiers of antenna systems or into energy of optical radiation, the rest major part thereof, is converted into thermal energy and heats the semiconductor crystal of the electronic component. The increasement of temperature of the semiconductor crystal leads to decreasement of its operation reliability. It has been found that for every 2°C temperature rise, the reliability of a silicon chip will be decreased by about 10 % [5,6]. The major cause of an electronic chip failure is due to temperature rise (55 %) as against other factors which accounts 20 % vibration, 19 % humidity and 6 % dust [7]. To ensure reliable operation of electronic modules, the development of highly efficient cooling systems for heat-generating electronic components of the module is required. The objective of this study is the selection and study of the thermal characteristics of a typical cooling system of electronic heat-loaded modules of dual application, which could be used to ensure normal thermal regime of both special-purpose products and household lighting appliances.

1 Analysis of recent researches and publications

To ensure a given thermal regime of electronic heat-loaded modules now there are being used air cooling systems with the application of highly thermally conductive substrates [8,9], radiators [10,11], fans [12], thermoelectric coolers [13] and liquid cooling systems using heat exchangers with integrated minichannels [14,15] and microspray devices [16].

The simplest in design and the cheapest are air cooling systems, which, in turn, are divided into cooling systems with natural air convection and cooling systems with forced air convection. To increase the cooling efficiency, the heat-generating surfaces of powerful electronic components are equipped with developed heat-exchange surfaces in the form of radiators of any of those types. It is not always possible to place the radiator directly on the surface of the electronic component or in the immediate closeness thereto, because of certain structural or functional features of the device. To connect a heat-loaded electronic component with a radiator, in such cases thermally conductive devices are being used, the simplest of which are busbars made of thermally conductive material. The longer is the heat transfer element (busbars), the higher is the temperature difference along its length and the higher is the temperature of the electronic component.

There are two ways to reduce the temperature difference in the heat transfer element. The first way is to increase the thermal conductivity of the material from which it is made. However, this option is related to the necessity to use such materials as diamond as a heat transfer element, which is limited by its high cost and deficiency. The second way is to use a highly efficient heat transfer devices operating using a closed evaporation-condensation cycle of heat transfer inside the heat transfer element — the so-called heat pipes and thermosiphons [17–19], which have a higher equivalent thermal conductivity if to compare with metals.

Heat pipes and thermosiphons are now widely used for cooling powerful electronic modules of both special purposes (power amplifiers for radar and telecommunication systems) [20–22] and civil purposes (LED lighting devices) [23, 24]. During operation [20] to cool several power amplifiers of radar systems there is used a cooling block of six heat pipes, located at an angle of 85 degrees to the horizon, with horizontal fins installed on the upper sections of the heat pipes. During operation [21] to cool the power amplifier of telecommunication equipment there is used a radiator with radial flat vertical fins installed in the condensation zone of a thermosyphon, which allows to dissipate the heat flow of both forced and natural air convection (Fig. 1). A similar design of the cooling system of the electronic modules of the power amplifier is used in [22]. To cool electronic modules in household products, for example, in LED lighting devices, there are used heat pipes of both direct [23] and curved [24] shapes.

In general, the condensation zone of a heat pipe or thermosiphon is usually removed at a certain distance from the heat-loaded electronic component and is equipped with a radiator, allowing to dissipate the removed heat flow into the environment. The design and shape of the radiators are quite diverse and depend on the specific application conditions and design features of the cooled device. Thus, the characteristics of a radiator with partially cut lamellar fins, forming a system of minichannels on the base surface were studied in [25]. A radiator with radially placed plate fins was studied in [26], the characteristics of a radiator consisting of a series of long fins with short fins located perpendicular thereto were studied in [27], and [28] studied the characteristics of a radiator in the form of pintles.

When developing a typical cooling system of dual application, it should be considered that the design of the cooling systems for civil purposes, for example, for household LED lighting devices, has its own peculiarity. Namely, the cooling system should not only efficiently transfer heat from the electronic component to the radiator and dissipate it into the environment, but also meet certain aesthetic requirements and produce a pleasant visual perception at home. This feature should be considered when designing civil cooling systems.

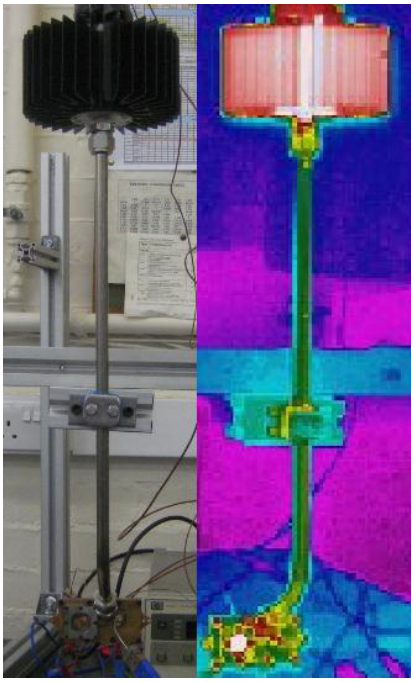


Fig. 1. A device and temperature field of the cooling system of a power amplifier of telecommunication equipment

2 Unresolved tasks and purpose of work

A wide variety of air cooling systems based on heat pipes, subject to the specifics of their purpose, leads to increasement in the cost for their manufacturing. It would be feasible to have a typical cooling system based on the heat pipe of the simplest design, which could be used for air cooling of electronic modules in devices of both special and civil purposes.

The purpose of this work is to select and study the thermal characteristics of a universal typical cooling system for heat-loaded electronic modules using a heat pipe equipped with a decorative radiator, which would produce a pleasant visual perception if used in devices intended for domestic use.

3 Selection of a typical design of the cooling system with heat pipes

As a typical cooling system of dual application, suitable for air cooling of electronic modules in devices of both special and civil purposes, the cooling system described in the patent of Ukraine [29] (Fig. 2a) has been selected, which allows to efficiently remove heat from heat-generating electronic modules located in a sealed volume to a decorative radiator located outside it using a heat pipe.

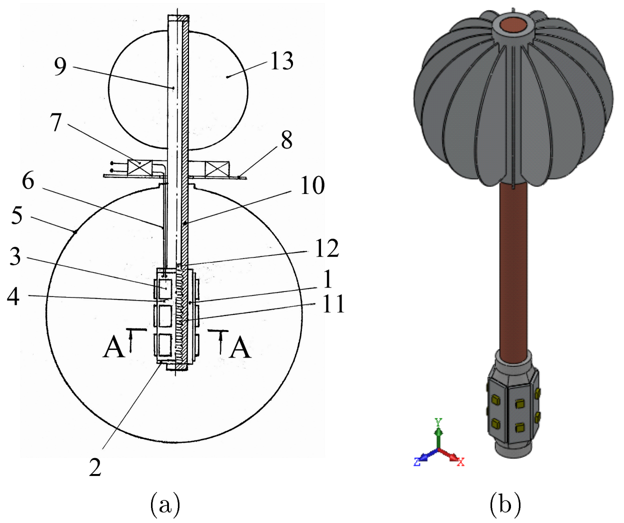


Fig. 2. A structural diagram of the cooling system of the LED lighting device based on the gravitational heat pipe with a threaded capillary structure (a) and its three-dimensional computer model (b): 1 – dimensional LED module; 2 – the base of the module with flat side faces; 3 – powerful LEDs; 4 – thermally conductive aluminum printed wire board; 5 – spherical ceiling; 6 – electrical connectors; 7 – power source; 8 – mounting plate; 9 – heat pipe; 10 – heat pipe housing; 11 – threaded capillary structure; 12 – heat carrier; 13 – radiator with cooling fins

A distinctive feature of this design of the cooling system is the use of the gravitational heat pipe with a simple capillary structure and a radiator in the form of a ball with flat radial fins, producing a pleasant external pleasant visual perception (Fig. 2b). The capillary structure of the heat pipe is made in the form of a thread with a fine pitch, for example 0.5 mm, cut on the inner side in the evaporation zone of the heat pipe. The condensation zone of the heat pipe is located above the evaporation zone. Such technical solution enables to produce a heat pipe at almost any enterprise specializing in mechanical-engineering, instrument-making, electrical engineering or electronics.

Fig. 2b shows a three-dimensional computer model of a typical design of a cooling system with a heat pipe and a spherical radiator, designed to ensure normal thermal regime of the dimensional electronic module.

Along with the numerical experiment, a full-scale experiment has also been conducted. To perform thereof, the same cooling system design was used, consisting of a heat pipe with a threaded capillary structure. A dimensional heat-loaded module with electronic components in the form of semiconductor LED light sources, and a radiator, the fins of which were optimized to perform a free-convective heat transfer, were installed on the heat pipe as an electronic module. The heat released during the operation of the electronic module has been effectively removed by the heat pipe to a remote distance and dissipated into the environment using a radiator installed in the condensation zone of the heat pipe. The thermal characteristics of the selected cooling system were determined using computer simulation.

4 Methods of studying the thermal characteristics of the cooling system

It is known that thermo-convectional phenomena in liquids in general, and in air in particular, are described by a rather complex nonlinear system of equations in partial derivatives. This system contains equations of conservation of energy, momentum and mass and equations of state. In numerical modeling, various approximate approaches are widely used; the most popular approach is the Boussinesq approach. When using this approach, it is believed that physical parameters of the medium are constant, the density depends only on the temperature, and this dependency should be considered only when expressing gravity. Therefore, in the developed model, this known initial system of equations of Newtonian fluid is formed as follows [30]:

$$\begin{cases} div\,\vec{\upsilon} = 0, \\ \dfrac{\partial \vec{\upsilon}}{\partial \tau} + (\vec{\upsilon}\cdot\nabla)\,\vec{\upsilon} = -\dfrac{1}{\rho_0}\nabla P + \nu\nabla^2\vec{\upsilon} + \beta\vartheta\vec{g}, \\ \dfrac{\partial \vartheta}{\partial \tau} + \vec{\upsilon}\cdot\nabla\vartheta = a\nabla^2\vartheta, \\ \rho - \rho_0 = -\rho_0\beta\vartheta, \\ \vartheta = T - T_0, \\ \beta = -\dfrac{1}{\rho_0}\left(\dfrac{\partial P}{\partial T}\right)_T, \end{cases} \tag{1}$$

wherein ρ_0 – average value of medium density at temperature T_0.

This system, which determines unknown functions, $\vec{\upsilon}$, ρ/ρ_0, ϑ, includes three parameters: thermal conductivity coefficient a, kinematic viscosity coefficient ν, free fall acceleration g and air volume expansion coefficient β. All of the above coefficients in the model are described using polynomial temperature dependencies.

The computational region of the studied structure is modeled using an unstructured computational grid, the shape of the finite element in this case is a prism. The processes observed in all these solid-state volumes are processes of non-stationary thermal conductivity [31, 32].

The thermal conductivity equations describing non-stationary thermal conditions in a three-dimensional body have the following form:

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

wherein: a_m – average specific heat capacity of the material, J/(kg·K); ρ – density, kg/m^3; T – temperature, K; τ – time, sec; λ – thermal conductivity, W/(m·K); x, y, z – grid coordinates, м.

The initial conditions of equation (1) is the temperature $T(x, y, z)$ for the elements of the studied structure at $\tau = 0$. The boundary conditions for solid-state volumes are the boundary conditions of the first kind. As this boundary condition, there is used a wall temperature on the inner surface of the fins with area S, preliminary determined by the Fluent software package, as defined below

$$T = T(S, \tau). \tag{3}$$

One of the ways to solve the boundary problems of thermal conductivity is to minimize the corresponding functional on the set of functions that satisfy the conditions of the task. From the variational point of view, the solution of equation (1) with the necessary boundary conditions (2) is equivalent to finding the minimum of the functional:

$$Э = \frac{1}{2} \int \lambda \times \left[\left(\frac{\partial T}{\partial x} \right)^2 + \left(\frac{\partial T}{\partial y} \right)^2 + \left(\frac{\partial T}{\partial z} \right)^2 + 2 \left(c_{\text{м}} \frac{\partial T}{\partial \tau} \right) T \right] dv + \int_{S_\alpha} \alpha \left(\frac{1}{2} T - T_\infty \right) T dS. \tag{4}$$

The Ansys software product used to create the CFD model uses matrix methods to minimize the functional (3). Therefore, the thermal conductivity matrix for the n finite element is as follows

$$[R^n] = \int_{S_\alpha^n} \alpha [T^n]^T [T^n] \, dS, \tag{5}$$

wherein $[T^n]$ is the shape matrix, determined by differentiating the temperature matrix $[T^n]$ with respect to x, y, z.

The vector of right-hand sides allows equations for the n finite element

$$F^n = \int_{S_\alpha^n} \alpha T_\infty [N^n]^T dS. \tag{6}$$

The heat capacity matrix is as follows

$$[C^n] = \int_V c_{\text{м}} \rho [T^n]^T [T^n] \, dV. \tag{7}$$

Due to the symmetry of the studied problem, when the flow structure is the same in all channels formed by the radiator plates, it becomes possible to simulate only one sector of the studied structure. It is only necessary to set the frequency of the flow at the boundary of the region.

The form of the computational grid is shown at Fig. 3.

5 Results of the numerical simulation

An important indicator when using a heat pipe is the value of its effective thermal conductivity. It is known that the heat pipe is a heat transfer device that combines the principles of both thermal conductivity and phase transition for efficient heat transfer. Due to the high efficiency of heat transfer observed during boiling and condensation of the heat carrier, with which the heat pipe is partially filled, this heat transfer device is a highly efficient heat conductor. The values of the effective thermal conductivity of the heat pipe taken during the simulation, were set equal to $2 \cdot 10^3$, $5 \cdot 10^3$ and $2 \cdot 10^4$ W/(m $\cdot ^\circ$ C). The area of the heat-transmitting surface of the radiator is $680 \cdot 10^{-4}$ m^2. The results of numerical simulation of the temperature of the electronic module are given in Fig. 4. Knowing the permitted base temperature of the electronic module, according to the diagram, you can determine the permitted thermal load of the module. Data analysis of Fig. 4 indicates that the use of heat pipes even with relatively low effective thermal conductivity allows to ensure a normal thermal regime of the electronic module.

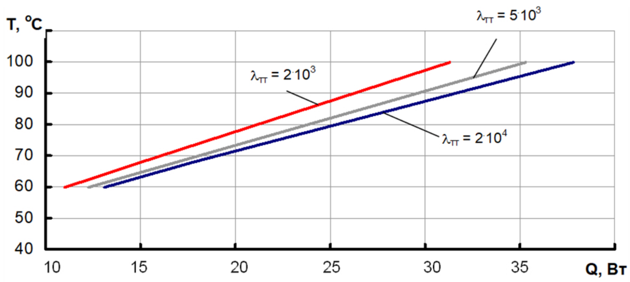
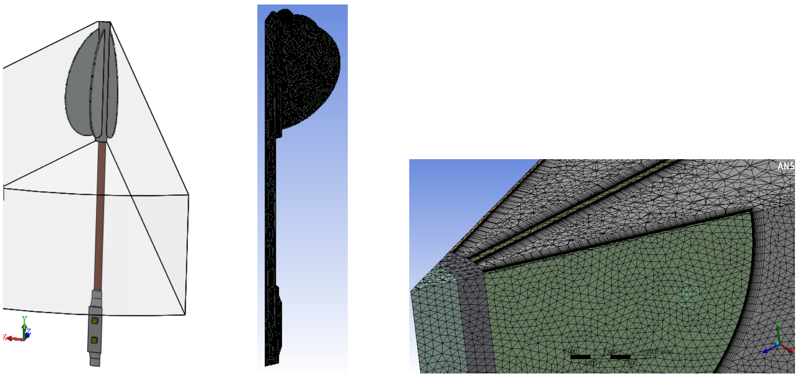


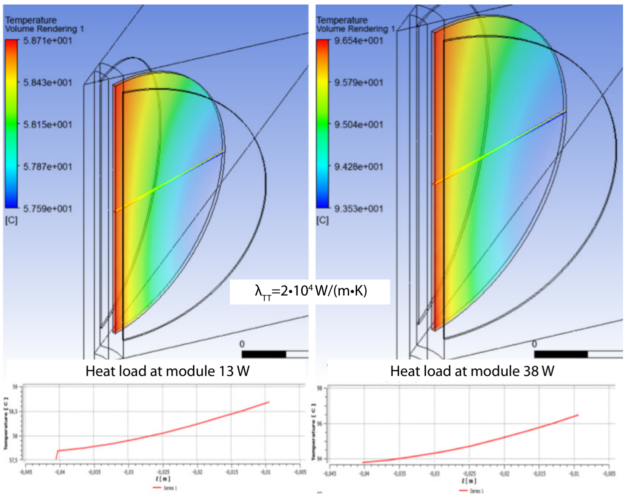
Fig. 4. Dependence of the base temperature of the electronic module on the heat load at various values of the effective thermal conductivity of the heat pipe

Fig. 5 shows the temperature field of the heat pipe radiator. There are also given diagrams of the temperature difference along the height of the fins in order to determine its effectiveness. As shown at Fig. 5, the effectiveness of the proposed finning is in the range from 0.96 to 0.98, depending on the heat load, which is a sufficiently good indicator.



(a) (b) (c)

Fig. 3. Computational region (a), general view of the computational grid (b) and a fragment of the computational grid in the region of free convection flows (c)



(a) (b)

Fig. 5. The temperature field of the heat pipe radiator fins with effective thermal conductivity λ_{TT}=20,000 W/(m·K) at a heat load of 13 W (a) and 38 W (b)

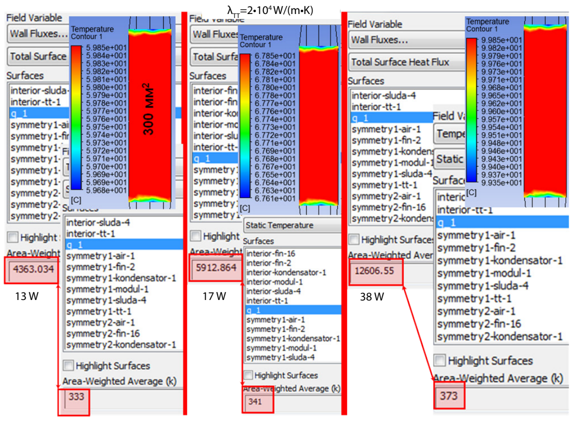


Fig. 6. The value of average temperatures in the installation area of the electronic module depending on the heat load

The results of numerical modeling (Fig. 6) show that when using a heat pipe with effective thermal conductivity λ_{TT} = 20,000 W/(m·K) and a given maximum value of the electric power of the electronic module, for example, equal to 17 W (which is twice as much as the power of the most modern LED lamps of direct replacement), the base temperature of the electronic module under natural convection of ambient air with a temperature of 25 ± 1 °C does not exceed +70 °C, which corresponds to the long-term reliable operation of the electronic module with semiconductor electronic components and confirms the effectiveness of the proposed technical solutions. However, if to exceed the value of the thermal load twice (up to 34 W), the temperature at the base of the module will increase up to + 95 °C. Therefore, to ensure the necessary thermal regime, it is recommended to use forced convection of air instead of free convection.

6 An example of practical implementation of the typical cooling system based on the heat pipe in household products

At the Heat and Power Engineering Faculty of the National Technical University of Ukraine "Igor Sikorsky Kyiv Polytechnic Institute", there has been developed and manufactured a demonstration and exhibition operating sample of a typical design of a cooling system based on the heat pipe for cooling electronic LED module of a wall lamp (Fig. 7b).

The efficiency of the developed cooling system has been determined by comparing the thermal and light characteristics of the existing basic version of the wall lamp (Fig. 7a) with a LED lamp of direct-replacement with a radiator integrated in the housing, and a modernized same lamp with an LED module mounted on a heat pipe with a remote decorative radiator (Fig. 7b). The studies have been performed in a certified laboratory of the V.E. Lashkaryov Institute of Semiconductor Physics NAS of Ukraine.

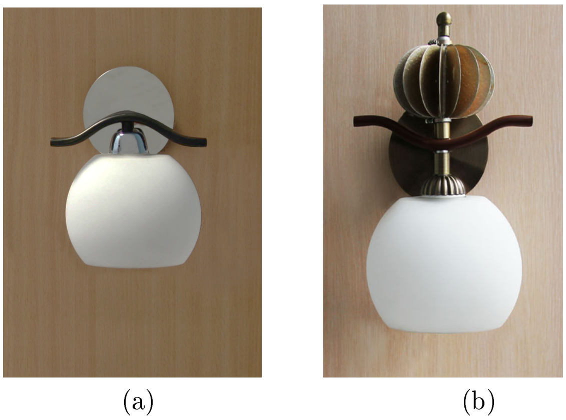


Fig. 7. Design of the basic version of the lamp (a) and LED wall lamp with a cooling system based on the heat pipe (b)

The temperature dependence of the housing of the LEDs of the electronic modules was experimentally determined for both versions of the luminaire with the heat power generated thereby from 2 to 25 W (Fig. 8). The dynamics of temperature change indicates that the use of the heat pipe allows you to increase the maximum power by 11 times (from 2.1 W to 23 W), and, accordingly, the luminous flow of the luminaire, while maintaining the temperature of the electronic module at 60 °C.

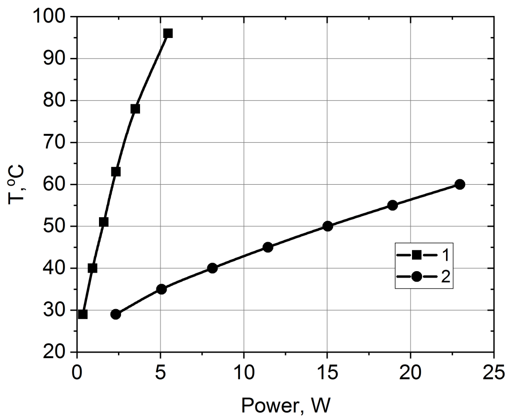


Fig. 8. The temperature of the LED housing when using a standard cooling system (1) and when using a cooling system based on the heat pipe (2)

The study of the thermal characteristics of the cooling system has shown (Fig. 9) that its thermal resistance decreases with increasement of power. Thus, with the increasement of power from 2 to 23 W, the thermal resistance of the cooling system decreased from 4.4 to 1.8 K/W.

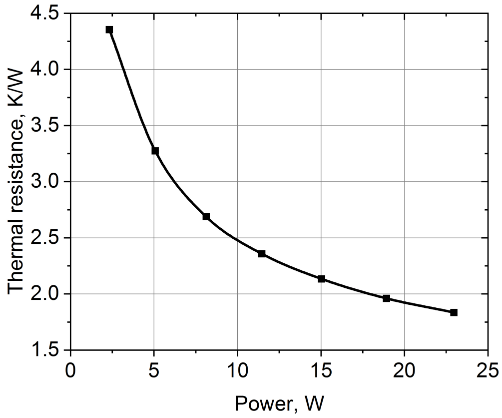


Fig. 9. The dependence of the thermal resistance of the cooling system on the power

To compare the results of the experimental study of the temperature of the electronic module with the results of numerical simulation, it is necessary to know the effective thermal conductivity of the heat pipe. To determine its meaning, the thermal resistance of the heat pipe was experimentally determined (Fig. 10) in the studied range of transmitted power (from 2 to 23 W).

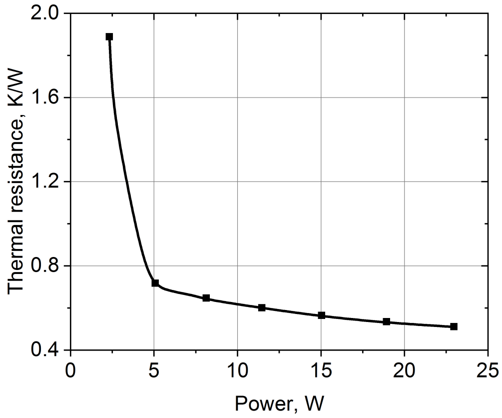


Fig. 10. The dependence of the thermal resistance of the heat pipe on the transmitted power

The above dependence of the thermal resistance of the heat pipe on the transmitted power (Fig. 10) shows that with increasement of the transmitted power, its thermal resistance significantly decreases and reaches a minimum value of 0.5 K/W at a power of 23 W. This means that the temperature drop across the heat pipe is 11.5 °C. Taking the values of the transmitted power ($P = 23\,\mathrm{W}$) and the temperature difference through the heat pipe ($\Delta t_{TT} = 11.5\,°\mathrm{C}$), its equivalent thermal conductivity λ_{eff} can be determined by the following formula:

$$\lambda_{eff} = \frac{P \cdot L_{eff}}{S_{TT} \cdot \Delta t_{TT}},$$

wherein L_{eff} is the effective length of the heat pipe, m; S_{TT} is the cross-sectional area of the heat pipe, m^2.

Substituting the initial values of the operating and geometric parameters of the experimental sample of the heat pipe ($L_{eff} = 19.5{\cdot}10^{-2}$ m, $S_{TT} = 1.13{\cdot}10^{-4}\mathrm{m}^2$)

in the above formula, we find that the equivalent thermal conductivity of the heat pipe is 3450 W/(m·K). According to the calculated dependencies shown in Fig. 4, the extrapolation can determined that with this value of the effective thermal conductivity of the heat pipe, the calculated value of the temperature of the electronic module housing at a power of 23 W is approximately 82 °C, which is 1.37 times higher than the experimental value (60 °C). This discrepancy between the calculated and experimental data can be explained by the larger area of the decorative radiator ($907 \cdot 10^{-4} m^2$) used in the experiment if to compare with that taken for calculation ($680 \cdot 10^{-4} m^2$).

The results of experimental studies of the basic version of the luminaire has shown that the temperature of the housing of the electronic module was 85 °C [33], which corresponds to the predicted lamp operating time of 21,000 hours. At the same time, in the modernized version of the luminaire with the cooling system based on the heat pipe, the temperature of the electronic module housing was 60 °C, which corresponds to the predicted LED operating time of over 60,000 hours.

Thus, the usage of the proposed typical cooling system with the heat pipe and the decorative radiator increased the predicted life of the semiconductor light source in a household wall lamp by almost 3 times.

7 Prospects of using a typical cooling system in devices of special purpose

A structural diagram of a possible usage of a typical cooling system based on a gravitational heat pipe in a multichannel transmitting and receiving module of the antenna system of a radar station is shown in Fig. 11. As a rule, the transmitting and receiving module is produced in a form of a sealed unit, which complicates the heat removal from powerful microwave active electronic components inside the sealed housing. Integration of the evaporation zone of typical heat pipes inside the sealed transmitting and receiving module and placing the condensation zone outside the housing allows to install a radiator in this zone and provide efficient cooling of powerful heat-generating microwave electronic components of the module.

Considering that most electronic microwave components have a power consumption of 10-20 W, the given cooling system can be used in conditions of natural air convection. For cooling more powerful electronic components it is necessary to use forced air convection.

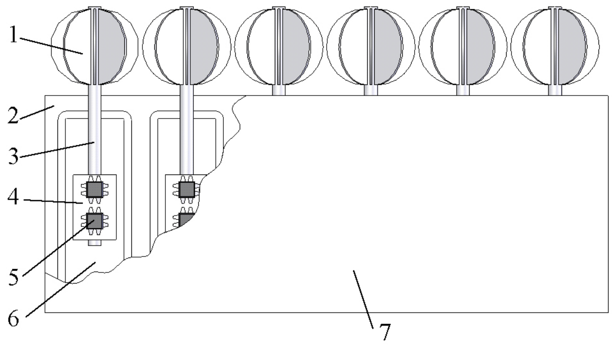


Fig. 11. A structural diagram of an advanced cooling system for a six-channel transmitting and receiving electronic module based on typical heat pipes: 1 – radiator; 2 – modular housing; 3 – heat pipe; 4 – pallet with powerful electronic components; 5 – powerful electronic component; 6 – mounting plate; 7 – cover

Conclusions

Based on the results of the research, the following conclusions were made:

- there has been selected a typical universal design of a cooling system of dual application based on a gravitational heat pipe, suitable for ensuring a normal thermal regime of a heat-loaded electronic module, which can be used in devices of both special and civil purposes;
- in conditions of natural convection of ambient air, the proposed cooling system ensures the temperature of the electronic module base in the range up to +83 °C with the consumed electric power up to 23 W;
- to further improve the efficiency of the cooling system, it is necessary to use the forced air convection;
- the studied cooling system was implemented in an experimental model of a wall-mounted LED lamp and enabled to increase the predicted life of semiconductor light sources by almost 3 times.

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Підвищення ефективності охолодження електронних теплонавантажених модулів

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Розроблено, виготовлено та досліджено за допомогою численних та експериментальних методів діючий зразок типової конструкції системи охолодження електронних теплонавантажених модулів подвійного застосування, який можна використовувати в пристроях як спеціального, так і цивільного призначення. Завдання представленої роботи полягало в організації ефективного охолодження теплонавантаженого модуля для безвідмовної його роботи за допомогою вільної конвекції. Це дозволить забезпечити безшумну і довготривалу роботу системи охолодження. З метою відповідності висунутим вимогам, в якості пристрою передачі теплоти використовувалася гравітаційна теплова труба з різьбовою капілярною структурою. Особливістю розробленої авторами ергономічної конструкції системи охолодження є спільне використання теплової труби і радіатора у вигляді кулі з плоскими радіальними ребрами. У теплонавантаженому модулі використовувалися потужні об'ємні електронні модулі, виконані у вигляді призми з плоскими бічними гранями, на яких були встановлені потужні напівпровідникові електронні компоненти. Дослідження проводилися за допомогою моделювання процесу передачі теплоти від теплонавантаженого модуля до охолоджуючого потоку повітря засобами програмного комплексу ANSYS-Fluent. За рахунок використання високоефективного замкнутого випарно-конденсаційного циклу передачі теплоти, що протікає в теплових трубах, вдалося більш ніж удвічі збільшити потужність електронного модуля при забезпеченні його температури в заданих межах. Моделювання засобами ANSYS-Fluent дозволило розробити конструкцію радіатора охолодження зони конденсації теплової труби, визначити ефективність оребрения радіатора і теплові потоки в зоні нагріву. Розрахунковим шляхом отримані графічні залежності температури напівпровідникових електронних компонентів від споживаної електричної потужності в діапазоні від 13 до 36 Вт. Проведено порівняння експериментальних даних з розрахунковими.

Ключові слова: напівпровідникові електронні модулі, свтодіоди, теплова труба, вільна конвекція, ефективність

Повышение эффективности охлаждения электронных теплонагруженных модулей

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Разработан, изготовлен и исследован с помощью численных и экспериментальных методов действующий образец типовой конструкции системы охлаждения электронных теплонагруженных модулей двойного применения, который можно использовать в устройствах как специального, так и гражданского назначения. Задача представленной работы состояла в организации эффективного охлаждения теплонагруженого модуля для безотказной его работы посредством свободной конвекции. Это позволит обеспечить бесшумную и долговременную работу системы охлаждения. С целью удовлетворить выдвинутые требования, в качестве устройства передачи теплоты использовалась гравитационная тепловая труба с резьбовой капиллярной структурой. Особенностью разработанной авторами эргономичной конструкции системы охлаждения является совместное использование тепловой трубы и радиатора в виде шара с плоскими радиальными ребрами. В качестве теплонагруженных модулей использовались мощные объемные электронные модули, выполненные в виде призмы с плоскими боковыми гранями, на которых были установлены мощные полупроводниковые электронные компоненты. Исследования проводились посредством моделирования процесса передачи теплоты от теплонагруженного модуля к охлаждающему потоку воздуха средствами программного комплекса ANSYS-Fluent. За счет использования высокоэффективного замкнутого испарительно-конденсационного цикла передачи теплоты, протекающего в тепловых трубах, удалось более чем вдвое увеличить мощность электронного модуля при обеспечении его температуры в заданных пределах. Моделирование средствами ANSYS-Fluent позволило разработать конструкцию радиатора охлаждения зоны конденсации тепловой трубы, определить эффективность оребрения радиатора и тепловые потоки в зоне нагрева. Расчетным путем получены графические зависимости температуры полупроводниковых электронных компонентов от потребляемой электрической мощности в диапазоне от 13 до 36 Вт. Проведено сравнение экспериментальных данных с расчетными.

Ключевые слова: полупроводниковые электронные модули, светодиоды, тепловая труба, свободная конвекция, эффективность