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CALCULATION OF TERMOSTABILIZATION SYSTEM LED MATRICES BY HEAT PIPES

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Summary. *Using the method of electrothermal analogy, a mathematical model of the thermal stabilization system of the LED matrix with a heat pipe was developed. The system of differential equations is solved, including the stationary equation of heat conduction and the equation of heat generation, which are supplemented by boundary conditions of conjugation for heat fluxes and temperatures. The calculated temperature distribution in the structural elements of the thermal stabilization system depending on the power of the LED matrix, heat pipe parameters and the temperature of the environment. It is shown that the use of the proposed thermal stabilization system will allow to increase the luminous flux of the LED-matrix (increase the light power) without increasing the temperature of its active zone. This will allow to reduce the number of LED-matrix in the semiconductor lamp and its cost without shortening the service life.*

Key words: *LED-matrix, light stream, thermal mode, thermal resistance, thermalstabilization, thermal pipe.*

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Formulation of the problem. Massive introduction of semiconductor light sources has resulted in a significant reduction in power consumption for various types of lighting. However, despite the high efficiency of LEDs, almost 70% of the supplied electrical energy is converted into heat.

Violation of the thermal regime of LEDs and their operation at a core temperature higher than the critical temperature ($Tc = 125°C$) causes degradation of light characteristics: reduced brightness and light output, deteriorated colour rendering, reduced light transmittance of the optical system, etc. This factor requires the search for effective ways of thermal stabilisation.

To stabilise the thermal regime of modern high-power LED matrices (HPLMs), active cooling systems are widely used, based on the forced circulation of cold air or liquid in the circuit [1]. However, active cooling is associated with noise generation. Electric motors of the fans and the air flow itself create sound vibrations that are usually undesirable. In particular, when lighting residential premises, concert halls, classrooms, etc. In addition, they require additional maintenance. All this suggests the need to consider alternative thermal stabilisation systems. Heat pipes (HPs) are one of the most efficient methods of heat extraction and transfer.

A heat pipe is a passive two-phase heat transfer device designed to improve the performance of heat transfer from a source to standard radiators. The transfer process takes place through a cycle of evaporation and condensation of the working fluid contained in a vacuum-sealed capsule. As a rule, HPs are used when the heat from a semiconductor element cannot be moved or dissipated efficiently enough by standard radiators. Due to the use of latent heat of vapour for heat transfer, its effective thermal conductivity is thousands of times higher than that of copper or aluminium, reaching $\sim 10^6$ $W/m\ K$. High thermal conductivity and the easy bending and shaping of heat pipes, as well as their long service life, make them ideal when heat needs to be transported from areas that are difficult to access to the cooling or condensing zone.

Analysis of available research results. Thermal stabilisation of electronic equipment with heat pipes shows the high efficiency of these devices [2]. Obviously, they can also be effective for stabilising the thermal regime of LED matrices. In particular, [3] experimentally investigated the system of thermal stabilisation of LED matrices, which operates on the principle of a heat pipe. It is proved that the considered thermal stabilisation system provides the required thermal regime of LEDs in a wide temperature range. In [4], a system for thermal stabilisation of an LED under different operating conditions of a heat pipe was studied. The authors experimentally verified its higher efficiency compared to a radiator with an identical profile and surface area. However, only practical designs were considered in these works. Thus, the thermal mathematical model of the thermal stabilisation system was not considered and no theoretical analysis was carried out.

Objectives of the research are to develop a thermal mathematical model of the LED matrix thermal stabilization system based on a heat pipe and calculate the temperature distribution in its structural elements.

Statement of the problem. By means of theoretical analysis, to establish analytical relationships between the power of the LED matrix, the parameters of the heat pipe, the temperatures of the medium and the active zone of the matrix. This will make it possible to rationally select a thermal stabilisation scheme to ensure an adequate thermal regime of the *LED matrix*.

The computational model of the *LED matrix* is based on the principle of electro-thermal analogy [7]. In particular, the similarity of the differential equations describing the electric field in the conductor and the temperature field outside the heat sources. To calculate the thermal regime of the *LED matrix*, a thermal mathematical model of the *LED matrix* mounted on the heat pipe body will be considrered as a basic one. It will be assumed that all the generated heat power is completely absorbed by the hot end of the *HP*

$$P_t = P_h, \tag{1}$$

and excess power is removed from the surface through convective heat exchange with the medium. To intensify the heat transfer, the surface of the *HP* has cooling fins. We assume that the pipe is in an environment with a constant temperature T_a.

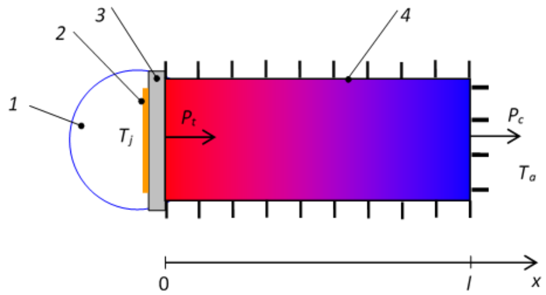

Figure 1. Scheme of the thermostabilization system of LED-matrix with a heat pipe. Here 1 – LED-matrix, 2 – active zone, 3 – contact pad, 4 – heat pipe. Tj – the temperature of the active zone of the LED-matrix, T_h and T_c – the temperatures of the hot and cold ends of the heat pipe, Ta – the temperature of the medium

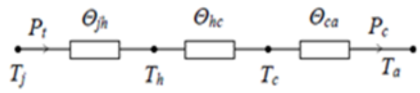

Figure 2. Scheme of the thermal circuit of thermostabilization of LED-matrix. Thermal supports: Θ_{jh} – active zone-contact area, Θ_{hc} – contact area – radiator, Θ_{ca} – radiator- medium

Heat propagation in a heat pipe is described by the stationary heat conduction equation [6]

$$\nabla^2 t - \gamma^2 t = 0, \tag{2}$$

and the Joule equation of heat generation

$$P_t = (1-\eta_e)\ I_f U_f \ , \tag{3}$$

where $\nabla = \vec{i}\frac{\partial}{\partial x} + \vec{j}\frac{\partial}{\partial y} + \vec{k}\frac{\partial}{\partial z}$ is the Hamiltonian operator, U_f is the forward voltage, I_f is the forward current, η_e is the quantum efficiency of the matrix,

$$t = T - T_a \tag{4}$$

T is the temperature of the tube surface, T_a is the temperature of the medium, $\gamma = \sqrt{\alpha p / \kappa S}$, p and S are the perimeter of the side surface and the cross-sectional area, α is the heat transfer coefficient between the surface of the *HP* and the medium.

We assume that the heat flux is uniformly distributed across the cross-section of the pipe. For the heat flux density, we obtain:

$$q_t = \frac{P_t}{S} \ . \tag{5}$$

At the edges of the structural elements, we set the traditional interface conditions for heat fluxs and temperatures

$$-\kappa \frac{dt}{dx}|_{x=0} = q_t , \ -\kappa \frac{dt}{dx}|_{x=l} = \alpha t\,|_{x=l} \ . \tag{6}$$

The solution to the differential equation is:

$$t(x) = C_1 e^{\gamma x} + C_2 e^{-\gamma x} , \tag{7}$$

where C_1 and C_2 are the integration constants, which we find from the boundary conditions

$$C_1 = \frac{q_t}{2\kappa\gamma}\left(1 - \frac{\alpha}{\kappa\gamma}\right)\left(\frac{e^{-\gamma l}}{sh\,\gamma l + (\alpha_l/\kappa\gamma)\ ch\,\gamma l}\right), \tag{8}$$

$$C_2 = \frac{q_t}{2\kappa\gamma}\left(1 + \frac{\alpha}{\kappa\gamma}\right)\left(\frac{e^{\gamma l}}{sh\,\gamma l + (\alpha/\kappa\gamma)\ ch\,\gamma l}\right). \tag{9}$$

As a result, for the surface temperature HP we obtain:

$$T(x) = T_a + \frac{P_t}{\alpha S}\left(\frac{ch\,\gamma(l-x) + sh\,\gamma(l-x)}{sh\,\gamma l + (\alpha_l/\kappa\gamma)\ ch\,\gamma l}\right)\frac{\alpha}{\kappa\gamma} \ . \tag{10}$$

Find the temperature of the hot end of the HP. Assuming $x = 0$ we obtain

$$T_h = T_a + \frac{P_t}{\alpha S}\left(\frac{1+(\alpha/\kappa\gamma)\ th\,\gamma l}{(\alpha/\kappa\gamma)+th\,\gamma l}\right)\frac{\alpha}{\kappa\gamma}. \qquad (11)$$

Similarly, for the cold end temperature, when $x = l$ we have

$$T_c = T_a + \frac{P_t}{\alpha S}\left(\frac{1}{(\alpha/\kappa\gamma)+th\,\gamma l}\right)\frac{\alpha}{\kappa\gamma}. \qquad (12)$$

For the thermal stabilisation process, an important parameter is the temperature gradient averaged over the pipe surface. Taking into account expressions (11) and (12), we have:

$$\lambda(\gamma l) = \frac{T_h - T_c}{l} = \frac{P_t}{\alpha S}\left(\frac{\alpha}{\kappa\gamma}\right)^2 \frac{th\,\gamma l}{(\alpha/\kappa\gamma)+th\,\gamma l}. \qquad (13)$$

In the case of a long HP, the average temperature gradient is

$$\lim_{\gamma l\to\infty}\lambda(\gamma l) = \lim_{\gamma l\to\infty}\frac{P_t}{\alpha S}\left(\frac{\alpha}{\kappa\gamma}\right)^2 \frac{th\,\gamma l}{(\alpha/\kappa\gamma)+th\,\gamma l} = 0. \qquad (14)$$

This suggests that the surface of the heat pipe is isothermal, and the entire surface of the heat pipe is simultaneously involved in heat exchange with the medium. This ensures uniform, fast and efficient heat transfer to the medium.

The temperature of the core zone of the LED-matrix T_j is determined by the method of electro-thermal analogy from the Ohm's law for a thermal circuit [7]

$$T_j = T_h + \Theta_{jh} P_t, \qquad (15)$$

then

$$T_j = T_a + P_t\left[\frac{\varepsilon}{\alpha S}\left(\frac{1+\varepsilon\ th\,\beta}{\varepsilon + th\,\beta}\right) + \Theta_{jh}\right], \qquad (16)$$

here $\varepsilon = \alpha/\kappa\gamma$, $\beta = \gamma l$ is effective length of the pipe.

As the pipe length increases, the core temperature will decrease asymptotically approaching the limit value

$$T_j = T_a + P_t\left[\frac{1}{\kappa\cdot p} + \Theta_{jh}\right]. \qquad (17)$$

Obviously, there is an optimal length of the HP, above which it is not rational to increase its value.

Analysis of numerical results. For the analysis, we select a white medium-power LED SMA2550, the parameters of which are presented in the table. Its quantum efficiency is $\eta_e = 0.25$, and thermal resistance $\theta_{jh} = 0.01\ K/W$.

Table

White LED characteristics

Series	Max. driver current (*mA*)	Max. power (*W*)	Luminous flux (*lm*)	Min. thermal resistance (*K/W*)	Emission diameter of the surface (*mm*)	Max. temperature of the active zone (*C°*)
XL1516CMA	700–1050	41	1400–4800	0.02	9	125
XL1825CMA	350–525	61	12150–7300	0.02	9	125
XL1840CMA	500–900	87	3300–10300	0.02	14	125
XL2550CMA	1400–2100	122	4400–15000	0.01	19	125
XL3090CMA	1200–1800	174	7300–21700	0.01	23	125

Under free air convection conditions, the heat transfer coefficient varies in the range $\alpha = 5 \div 25\ (W/m^2K)$, and under induced convection in the range $\alpha = 10 \div 200\ (W/m^2K)$.

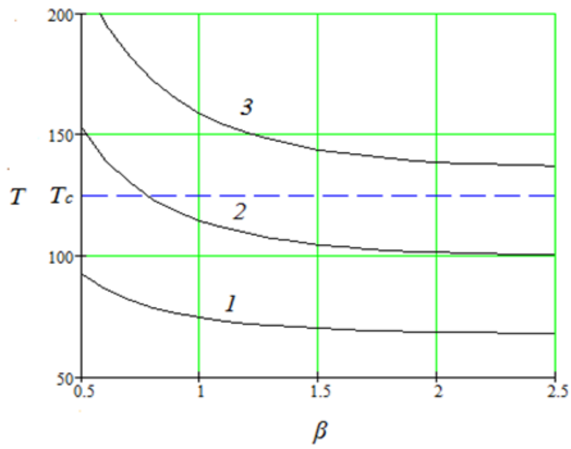

Figure 3. Dependence of the temperature of the active zone of the CMA2550 matrix with a power of P=122 W on the reduced length of the HP at the temperature of the medium Ta = 20 C and at different heat exchange coefficients. Curve 1 – during forced convection (ε=0.1), 2 - during free convection (ε=0.05), 3 – for a solid metal rod of a similar profile during forced convection (ε=0.025)

As can be seen from the graph, when the surface of the heat pipe is blown by air jets, the core temperature of the *LED-matrix* is always below the critical temperature, even when operating at maximum power. On the other hand, in the case of free air convection, the temperature regime of the *LED-matrix* deteriorates. This is particularly true for short HPs.

When a solid metal rod of a similar profile is used as a heatsink, even with active blowing of its surface, the temperature of the core of the *LED matrix* is always higher than the critical temperature at any length. Apparently, this will not allow the device to be operated in the P_{max} mode.

Thus, the thermal stabilisation system of the *LED-matrix* with a heat pipe integrated into the radiator has a significantly higher efficiency compared to a solid metal rod with a similar profile and surface area. This advantage is due to the uniform temperature distribution over the surface of the heat pipe, which means more efficient heat dissipation.

An alternative to efficient and silent cooling of high-power LED-matrices is the use of thermoelectric cooling [8, 9].

Conclusions. Heat pipes (HP) are one of the most effective passive devices for thermal stabilization of semiconductor elements, including LED matrices. Moreover, the cooling efficiency increases with the increase of its length, perimeter, heat transfer coefficient and thermal conductivity. The use of HP will significantly reduce the size and weight of the thermal stabilization system.

The system of thermal stabilization of the LED matrix with heat pipes has a higher efficiency compared to the system that uses metal rods with a similar profile and surface area. This advantage is due to the uniform temperature distribution over the surface of the heat pipe and more efficient heat dissipation.

The use of the described thermal stabilization system will increase the luminous flux of the LED matrices (increase the luminous output) without increasing the core temperature. This will reduce the number of LED matrices in the luminaire and its cost without reducing its service life.

One of the drawbacks of HPs is the fact that they have a relatively narrow temperature range for effective use. In particular, when a certain critical temperature is exceeded, the entire coolant can turn into vapor without the possibility of condensation, and vice versa, at insufficient temperature, the liquid evaporates poorly. This will lead to a sharp decrease in the thermal conductivity of the thermal stabilization system of the LED matrix with all the negative consequences.

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РОЗРАХУНОК СИСТЕМИ ТЕРМОСТАБІЛІЗАЦІЇ СВІТЛОДІОДНИХ МАТРИЦЬ ТЕПЛОВИМИ ТРУБКАМИ

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Резюме. *Тотальне впровадження напівпровідникових джерел світла дозволило різко зменшити витрати електроенергії на різноманітні види освітлення. Незважаючи на високий ККД світлодіодів, майже 70% підведеної електричної енергії перетворюється в тепло. Порушення теплового режиму напівпровідникових джерел світла і їх експлуатація при температурі активної зони більшій критичної (Tc = 125°C) спричиняє деградацію світлових характеристик: зменшується яскравість і світловіддача, погіршується якість кольоропередавання, знижується показник світлової проникності оптичної системи та ін. Ця обставина змушує шукати ефективні шляхи термостабілізації. В даний час для стабілізації теплового режиму сучасних потужних світлодіодних матриць (СДМ) широко використовуються активні системи охолодження. В основі їх роботи лежить примусова циркуляція холодного повітря або рідини в контурі. Однак активне охолодження пов'язане з генерацією шуму. Теплові трубки (ТТ) є одним з найефективніших безшумних методів відбору і перенесення теплової енергії. В роботі з використанням методу електротеплової аналогії побудовано математичну модель системи термостабілізації світлодіодної матриці тепловою трубкою. Розв'язано систему диференціальних рівнянь, що включає стаціонарне рівняння теплопровідності та рівняння термогенерації, які доповнені граничними умовами спряження для теплових потоків і температур. Розраховано розподіл температури в структурних елементах системи термостабілізації залежно від потужності світлодіодної матриці, параметрів теплової трубки й температури середовища. Показано, що система термостабілізації СДМ тепловими трубками має вищу ефективність у порівнянні з системою, яка використовує металеві стержні з аналогічним профілем і площею поверхні. Така перевага зумовлена рівномірним розподілом температури по поверхні ТТ, і ефективнішим відведенням теплової енергії. Доведено, що використання запропонованої системи термостабілізаціїї дозволить збільшити світловий потік СДМ (збільшити світлову потужність) без збільшення температури її активної зони. Це дозволить зменшити кількість СДМ у напівпровідниковому світильнику і його вартість без скорочення терміну експлуатації.*

Ключові слова: *світлодіодна матриця, світловий потік, тепловий режим, тепловий опір, термостабілізація, теплова трубка.*

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