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Cooling of Led Modules with Thermal Accumulators Based on Phase Change Materials

The purpose of this study is to design and develop a silent, passive cooling system based on phase change materials capable of maintaining the temperature of LED arrays within an optimal range for extended periods. The system operating principle utilizes the latent heat of fusion of the working substance and allows for the temperature of the semiconductor light source to be precisely fixed. The main condition for its normal functioning is that the melting point of the working substance does not exceed the maximum permissible temperature of the LED element. Depending on the maximum permissible temperature of the cooled elements, wax, paraffin, salt hydrates, etc. can be used as working substances. A disadvantage of phase change materials is their high thermal resistance, which hinders rapid charging and discharging of the thermal accumulator. To reduce the overall thermal resistance of the working substance, the thermal accumulator uses a modular design, in which the accumulator consists of several modules filled with phase change materials with different melting points. The defining feature of a temperature stabilization system is the constant temperature of the working substance during the melting process, which results in a constant temperature of the LED array active area. Thermal stabilization systems based on thermal accumulators offer a significant advantage: they are autonomous and independent of changing external conditions.

Keywords: LED module, luminous flux, thermal accumulator, phase change materials, thermal resistance, thermal stabilization, enthalpy.

Problem statement

Modern semiconductor lighting devices require thermal stabilization, since almost 70 % of the electrical power consumed by them is converted into heat. In order for the LED array to have the declared technical characteristics, it is necessary to ensure adequate thermal operation. As is known [1, 2], when the temperature of the LED active zone increases by every 10 °C, the

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luminous flux decreases by approximately 2.5 %. For instance, if the manufacturer indicates that the luminous flux of the CXA1310 array at an active zone temperature of 25 °C is 1000 lm, then with poor-quality heat dissipation, the temperature can increase to 125 °C, and the luminous flux will decrease by 25 %. In addition, high operating temperature worsens several important parameters at once – light output, color temperature, service life, and in total, the economic efficiency of using semiconductor lighting devices.

Active thermal stabilization systems are widely used to cool modern powerful LED arrays. Their operation is based on the forced circulation of air or liquid in the circuit. However, active cooling is often associated with noise generation. The electric motors of the fans and the air flow itself create acoustic vibrations, which are often undesirable. In addition, they require additional maintenance. All this forces us to look for alternative thermal stabilization systems.

Heat pipes are one of the most efficient and silent methods for extracting and transferring thermal energy from semiconductor devices operating in confined spaces [4–6]. Heat pipe cooling systems are often used in conjunction with air radiators.

The thermoelectric cooling system makes it possible to reduce the temperature of the LED array to values lower than the ambient temperature [7]. This is especially important in conditions where the ambient temperature is close to the critical operating temperature of the LED arrays.

Analysis of known research results

The simplest thermal accumulators are metal structures of lighting devices, radiators, fasteners, housings, etc. This method of cooling and heat removal can be used if the total heat capacity of the structure is sufficient for thermal stabilization of the operating mode. Otherwise, it is necessary to increase the mass and volume of the structure, which is not always possible, and often not rational.

In recent years, thermal energy storage using phase change materials (PCMs) has attracted considerable interest. Cooling semiconductor lighting fixtures with thermal accumulators using materials with latent heat of phase transition ensures a constant temperature during melting and high storage density [8–10]. This allows for a fairly stable temperature control of LED elements. The amount of heat absorbed by the accumulator depends on the specific heat of fusion of the PCM, its heat capacity, mass, and temperature rise.

The purpose of the work is to calculate and create a silent, passive cooling system based on phase change materials capable of maintaining the temperature of LED elements in the optimal range for a long time.

Design and calculation of a thermal accumulator

During the operation of LED array, the thermal power is generated as follows

$$P_t = (1-\eta_e)\cdot U_f \cdot I_f , \quad (1)$$

where I_f and U_f is direct current and direct voltage of LED array, η_e is quantum efficiency.

The released heat is transferred to the phase change material integrated in the *TA*. To ensure cooling, the thermal power must be completely absorbed by the *TA*, otherwise stabilization of the thermal regime will be impossible. We will assume that there is an ideal thermal contact between the LED array contact pad and the *TA* collector, then

$$P_t = P_h , \tag{2}$$

where P_h is power absorbed by the accumulator.

The process of heat absorption by the PCM occurs at constant pressure. In this case, according to the first law of thermodynamics, the amount of heat absorbed by the thermal accumulator can be represented as

$$\delta Q|_p = dU + p \cdot dV = d\left(U + p \cdot V\right) = dH , \tag{3}$$

where U is internal energy of PCM, V is its volume, p is pressure,

$$H = U + p \cdot V , \tag{4}$$

H is enthalpy.

Enthalpy is a key thermodynamic function that describes the heat content of a system. Enthalpy reaches a maximum in an isochoric process and is equal to the amount of heat absorbed by the accumulator during the primary heating, melting, and secondary heating of the molten working substance. In this case

$$\Delta H = Q_p . \tag{5}$$

Thus, the change in specific enthalpy during heating and melting of the working substance is the sum of three separate processes:

- heating of PCM from the initial temperature T_a to melting point;
- phase change at melting point;
- heating of PCM from the melting point to maximum temperature T_m.

$$\Delta h = \int_{T_a}^{T_f} c_s\left(T\right) \cdot dT + \lambda\left(T\right) + \int_{T_f}^{T_m} c_f\left(T\right) \cdot dT , \tag{6}$$

where $c_s\left(T\right)$ and $c_f\left(T\right)$ are the specific heat capacity of the working substance in the solid and liquid states, respectively, $\lambda\left(T\right)$ is the specific heat of fusion. Since these parameters are weakly temperature-dependent, we will treat them as constant in the following calculations.

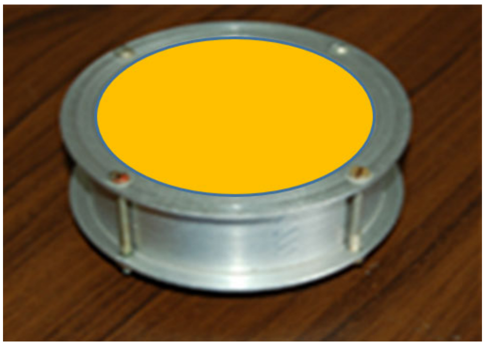


Fig. 1. Appearance of thermal accumulator module on PCM with LED array (shown without external radiators)

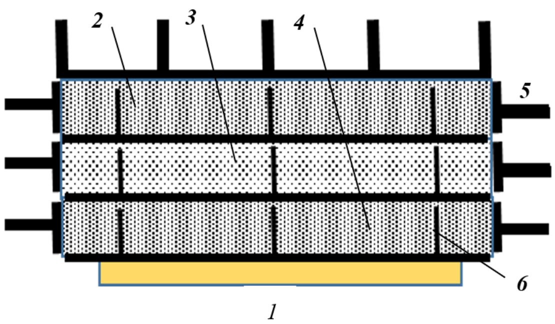


Fig. 2. Schematic structure of the thermal accumulator. 1 – LED array, 2, 3, 4 – modules with working substances, 5 and 6 are external and internal radiators, respectively

Paraffins, fatty acids, salt hydrates, etc. are widely used as phase change materials. A feature of PCMs is their high thermal resistance, which prevents rapid charging and discharging of the thermal accumulator. To reduce the overall thermal resistance of the working substance, a modular design is provided, in which the accumulator consists of several modules filled with PCMs with different melting points.

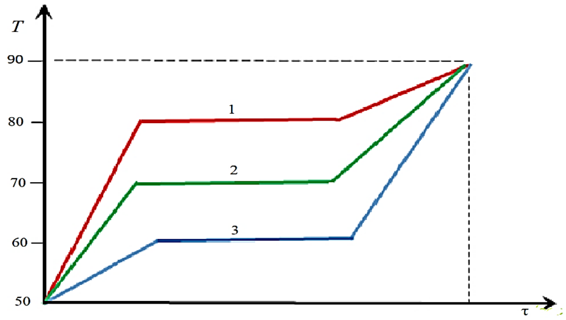


Fig. 3. Temperature change of a phase change material upon heating of the solid phase, melting and heating of the liquid phase. 1 – naphthalene, 2 – stearic acid, 3 – sodium acetate trihydrate

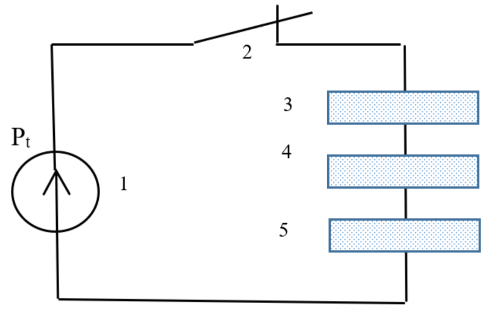


Fig. 4. Generalized model of the thermal process of the LED array cooling system. 1 – heat source, 2 – switch, 3, 4, 5 – thermal modules

To simplify the calculation, we will consider the idealized phases of the melting state of the PCM, which are depicted in Fig. 3. Moreover, the melting points of the PCM decrease in the direction opposite to the temperature gradient and perpendicular to the phase separation plane. Each of the modules is equipped with a system of internal radiators (Fig. 2). Given the complexity of describing the melting (solidification) processes in an interconnected multi-module system, each of the modules of which is in a state of phase change, we introduce a simplification:

1. We assume that in *TA*, melting occurs in only one module at a time.
2. The substance in the module closest to the heat source begins to melt first.
3. After it is completely melted, the substance in the next module melts, and so on until all modules are completely melted.
4. The operating time of the *TA*-based thermal stabilization system consists of the time required for warming up and complete melting of the PCMs in all modules.
5. The analysis will be carried out under the assumption that all the heat coming from the light source is consumed for melting the PCM in each module.

To intensify the heat exchange, the outer surface of the *TA* has cooling fins. We assume that the *TA* is in an environment with a constant temperature T_a. During operation, the main part of the heat generated by the LED array due to the heat conduction process is transferred to the PCM where it is absorbed due to the latent heat of fusion. Let us find the total enthalpy of the thermal accumulator

$$\Delta H = \sum_{i=1}^{n} m_i \cdot h_i = \sum_{i=1}^{n} m_i \cdot \left[c_{si} \cdot \left(T_{si} - T_a \right) + \lambda_i + c_{fi} \cdot \left(T_m - T_{fi} \right) \right], \quad (7)$$

where m_i is the mass of the working substance in the *i*-th module, *n* is the number of modules. To increase the thermal stabilization time, the outer surface of *TA* has cooling fins. We assume that *TA* is located in an environment with a constant temperature T_a.

The minimum operating time of the cooling system $\tau_{\min}$ is determined from the heat balance equation

$$\Delta H = P_t \cdot \sum_{i=1}^{n} \left(\tau_{si} + \tau_i + \tau_{fi} \right) = P_t \cdot \tau_{\min}\,, \tag{8}$$

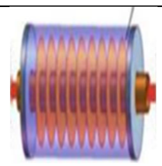
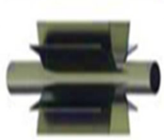
where $\tau_i = \tau_{si} + \tau_{\lambda i} + \tau_{fi}$, $\tau = \sum_{i=1}^{n} \tau_i$. τ_{si} – heating time from the initial temperature to melting point, $\tau_{\lambda i}$ – melting time, τ_{fi} – time for heating the melt to the limit temperature T_m in the *i*-th module. Whence

$$\tau_{\min} = \frac{\Delta H}{P_t}\,, \tag{9}$$

Thus, the minimum operating time of the thermal stabilization system is determined by the heating time and complete melting of the working substance in all modules and the thermal power of the LED elements.

Table 1

Some types of internal heat exchange radiators

№	Radiator	Fin type
1.		Radial
2.		Cylindrical
3.		Plate-shaped
4.		Pin
5.		Disc
6.		Tree-shaped

Numerical analysis of results. For the analysis, we will choose a medium-power white LED CXA1310 with parameters U_f = 17.80 V, I_f = 0.75 A, η_e = 0.25 and a critical temperature of the active radiation zone T_c = 125 °C. In this case, its power and luminous flux are equal to P = 13.35 W and 1000 lm, respectively. As a filler for the first module we choose naphthalene with the parameters: $T_{s1} = 80$ °C, c_{s1} = 1.30 kJ/kg K, c_{f1} = 1.70 kJ/kg K, λ_1 = 152.2 kJ/kg; for the second module – stearic acid with the parameters: T_{s2}=69.6∘C; c_{s2} = 1.76 kJ/kg K; c_{f2} = 2.30 kJ/kg K; λ_2 = 198.9 kJ/kg; for the third – sodium acetate trihydrate with the parameters: T_{s3} = 58.0 °C, c_{s3} = 2.57 kJ/kg K; c_{f3} = 4.88 kJ/kg K; λ_3 = 280 kJ/kg.

Since the optimal temperature for LED crystals is in the range $90-100^{\circ}C$, we choose the maximum temperature of the PCM T_m = 90 °C. Let $m_1 = m_2 = m_3$ = 0.4 kg and $T_a = 20^{\circ}C$. With the specified parameters, the total enthalpy of the accumulator on PCM will be H = 556.4 kJ (for comparison, H_{H2O} = 220 kJ) and the minimum time for stabilizing the thermal regime of the CXA1310 array will be 15.5 hours.

Table 2

Technical characteristics of some phase change materials with high specific heat of fusion

№	Phase change material	Chemical formula	Melting point °C	Specific heat capacity solid phase (kJ/kg K)	Specific heat capacity liquid phase (kJ/kg K)	Specific heat of fusion (kJ/kg)
1.	Glauber's salt	Na_2SO_4 $10H_2O$	32.4	2.09	4.88	267
2.	Myristic acid	$C_{14}H_{28}O_2$	54.0–58.8	1.89	2.00	198.7
3.	Paraffin wax	$C_{25}H_{52}$	55	214	2.90	200–220
4.	Sodium acetate trihydrate	$NaC_2H_3O_2$ $3H_2O$	58	2.57	4.88	264–280
5.	Palmitic acid	$C_{16}H_{32}O_2$	62.9	1.81	2.64	163.9
6.	Stearic acid	$C_{18}H_{36}O_2$	69.6	1.76	2.30	198.9
7.	Naphthalene	$C_{10}H_8$	80	1.30	1.70	152.2
8.	Sodium	Na	98	1.23	1.28	113
9.	Water (for comparison)	H_2O	0	4.18	4.20	333.5

To obtain an effective cooling system, it is necessary to introduce a switch into the LED array electrical power supply circuit that will turn off the heat source when the PCM is completely melted in all modules. The main condition for its normal functioning is that the melting point of the working substance does not exceed the maximum permissible temperature of the LED element. This approach is especially relevant for powerful LEDs or lamps operating in a re-periodic mode or in environments with limited space for traditional radiators. After the LED array is turned off or its power is reduced (when heat generation decreases), the accumulated heat is gradually discharged into the environment, and the accumulator returns to its original state, "recharging" for the next cycle of operation. To intensify regeneration, the outer surface of the *TA* has cooling fins.

Conclusions

Using thermal accumulators made of PCMs allows for a precise temperature control of the cooled LED elements. The ability of the thermal accumulator to maintain temperature depends on the LED device's power and the type and number of PCMs. For long-term continuous operation and high-power LED elements, the *TA* will require the assistance of heat sinks.

PCMs must be selected for specific temperature conditions. Thermal stabilization systems based on PCM thermal accumulators offer a significant advantage over traditional heat-capacitive systems. Specifically, they have several times higher enthalpy and are unaffected by changing external temperature conditions. PCMs allow for the creation of more compact cooling systems, as they have a high thermal energy storage density per unit mass compared to traditional materials (e.g., metals or water).

With an increase in weight and dimensions, a thermal accumulator equipped with a thermoelectric generator can be used as an emergency power supply in places where emergency backup is required [13].

Authors' information

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Тернопільський національний технічний університет імені Івана Пулюя, Україна

Охолодження світлодіодних модулів тепловими акумуляторами на основі фазоперехідних матеріалів

Метою роботи є розрахунок та створення безшумної, пасивної системи охолодження на основі фазоперехідних матеріалів здатної підтримувати температуру світлодіодних матриць в оптимальному діапазоні протягом тривалого часу. Принцип роботи системи базується на використанні прихованої теплоти плавлення робочої речовини і дозволяє досить жорстко зафіксувати температуру напівпровідникового джерела світла. Основною умовою її *нормального функціонування є умова не перевищення температурою плавлення робочої речовини максимально допустимої температури світлодіодного елемента. В залежності від гранично допустимої температури охолоджуваних елементів в якості робочих речовин можуть використовуватися віск, парафін, гідрати солей, та ін. Недоліком фазоперехідних матеріалів є їх великий тепловий опір, який перешкоджає швидкому заряджанню і розряджанню теплового акумулятора. Для зменшення загального теплового опору робочої речовини ТА передбачена модульна конструкція, при якій акумулятор складається з кількох модулів, заповнених ФПМ з різною температурою плавлення. Визначальною особливістю системи стабілізації температури є незмінність температури робочої речовини в процесі плавлення, що призводить до незмінності температури активної зони СДМ. Системи термостабілізації на базі акумуляторів тепла мають важливу перевагу, зокрема, вони є автономними та незалежними від мінливих зовнішніх умов.*

Ключові слова: світлодіодний модуль, світловий потік, тепловий акумулятор, фазоперехідні матеріали, тепловий опір, термостабілізація, тепловміст.