Study of thermal modes of operation of SMD-LEDs in phyto-lamps

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Abstract. LED phyto-irradiators are promising for use in irradiation systems for growing plants in greenhouses using photoculture technology. Cases, when the thermal calculation of phyto-irradiators is performed incorrectly, have an overheating in the active area of the crystal. It results in faster degradation of the semiconductor, reduces the output luminous flux and the service life of the device. To evaluate and analyze scientific works studying thermal models of LED operating modes, examples of the application of modern methods for determining thermal resistances, to study local heating zones on phyto-irradiator boards when using different types of LEDs and modern thermal imagers to detect soldering defects. The authors classified and analyzed the collected materials according to application criteria and implementation prospects. In the course of the research the authors applied methods of systematic approach. To assess the effectiveness of dissipation of thermal energy released by a LED crystal, they calculate the following parameters: thermal resistance between p-n transition and housing, thermal resistance between housing and PCB, thermal resistance between PCB and the environment. The thermal resistance between the p-n junction and the housing is due to the design of the LED, other parameters are set by the thermal models of the developed lighting devices. The applied methods of cooling do not essentially influence the complexity of thermal models, liquid cooling allows to refuse radiator for the linear thermal model, that slightly raises the accuracy of measurements and simplifies the process of calculation of thermal resistance of transition-housing. The primary role in thermal management of luminaires with SMD elements lies in the following elements: power supply circuits, SMD LED soldering quality and materials used, LED locations, PCB dimensions and location in space, ambient temperature, adequate calculation of thermal resistance between the LED and the environment and selection of radiators.

1. Introduction

Optical radiation sources based on LEDs are promising for use in phyto-irradiation systems for growing plants in greenhouses using photoculture technology [1]. Application of point compact LEDs in phyto-irradiator allows to create different variations of spectral composition, in addition, the efficiency of conversion of electrical energy into optical radiation in LEDs is 1.5-2 times higher than in sodium lamps [2].

While developing LED phyto-irradiator it is necessary to consider their efficiency (light output), which depends on the material of the semiconductor crystal and, as a result, on the radiation wavelength. The efficiency of modern LEDs in the field of PHAR is within 2.0÷3.0 (µmol/s)/W [1]. According to research data, 65-85% of the electrical energy consumed by the LED is converted into
heat radiation, which needs to be effectively removed from the crystal, scattered on the radiator or transferred to the coolant, thus providing optimal thermal conditions for the crystal semiconductor.

The value of electric current passing through the crystal of the semiconductor increases proportionally with increasing radiation power in solid-state optical radiation sources (LEDs) [3]. In cases where the thermal calculation of the phyto-irradiator is incorrect, overheating occurs in the active area of the LED crystal and results in faster degradation of the semiconductor, reducing the output photon flux and the service life of the device.

The purpose of the research is to evaluate and analyze scientific research, considering thermal models of LED operating modes, examples of modern methods of determining thermal resistances and prospects of implementing these technologies in the research and production of LED phyto-irradiators, the study of local heating zones on the boards of phyto-irradiators using different types of LEDs, the use of modern thermal imagers to detect defects in soldering.

2. Methods and Equipment

This paper considers studies aimed at evaluating individual elements of the phyto-irradiator and their functions in controlling the thermal modes of the device with SMD LEDs. The authors classified and analyzed the collected materials according to application criteria and implementation prospects. In the course of the research they applied methods of a systematic approach to the research problem.

The place for experimental studies of local heating zones using different types of LEDs on one printed circuit board was chamber boxes with a volume of 15 m³ at an air temperature of 24 °C. The study examined PCB with a different number of LED types, the characteristics of PCBs are shown in Table 1.

| Table 1. Characteristics of PCBs and LEDs included in the laboratory test |
|---------------------------------------------------------------|
| **PCB 1** is from Al material, thickness is 1 mm, length is 485 mm, width is 12 mm, mask is H-8100 type, foil thickness is 35 microns, soldering paste is type 3. |
| **LED name** | **LED characteristics** | **Producer** |
| White LED with continuous emission spectrum | power is 0.5 W; standard size is 2835; operating current is 92 mA. | Refond |
| RF-W40QI35DS-DF-J-Y E0 TG-1022NP 4000K Ra>95 | | |
| **PCB 2** is from Al material, thickness is 0.8 mm, length is 485 mm, width is 12 mm, mask is H-8100 type, foil thickness is 35 microns, soldering paste is type 3. |
| **LED name** | **LED characteristics** | **Producer** |
| White LED with continuous emission spectrum | power is 0.5 W; standard size is 2835; operating current is 92 mA. | Refond |
| RF-W40QI35DS-DF-J-Y E0 TG-1022NP 4000K Ra>95 | | |
| Red LED | power is 0.5 W; standard size is 2835; operating current is 92 mA. | Refond |
| RA32A1-RUT-FR 655-658nm | | |

The researchers soldering LEDs in the TermoPro LED melting furnace according to the thermo-profile recommended by the LED producer.

They measured the temperature on the 5th and 10th minute of luminaire operation using the Fluke Ti32 thermal imaging camera.

3. Results and Discussion

Almost all modern LEDs have the following model of thermal resistance [3] shown in Figure 1, where Θjc is the thermal resistance between p-n transition and housing, Θcb is the thermal resistance between housing and PCB, Θba is the thermal resistance between PCB and environment.
We can calculate the p-n transition temperature using the following formula:

\[ T_{p-n} = T_a + P_D (\theta_{jc} + \theta_{cb} + \theta_{ba}) \]  

(1)

where \( T_{p-n} \) is the temperature of p-n transition, \( T_a \) is the ambient temperature, \( P_D \) is the power dissipation factor which is equal to the product of direct voltage per direct current passing through the LED.

Thermal resistance will be the ratio of the temperature difference to the power dissipation:

\[ \frac{T_{p-n} - T_a}{P_D (\theta_{jc} + \theta_{cb} + \theta_{ba})} \]  

(2)

\[ T_{ja} = P_D (\theta_{jc} + \theta_{cb} + \theta_{ba}). \]  

(3)

In his work Vinokurov [3] conducted research on the influence of thermal resistance of board materials, ambient temperature, the spatial location of boards, the number of holes in the board on the p-n transition temperature of SMD (surface mounted device) LEDs. The carried out laboratory tests have shown that FR4 glass foil with aluminium foil at equal dimensions (20x20x2 mm) has a higher thermal resistance between the board and the environment, which is 59.8°C/W vs. 51.6°C/W. If the board has holes, the situation changes to the opposite and the thermal resistance of FR4 glass foil becomes 50.5°C/W. This author also provides research into the dependence of the thermal resistance of FR4 glass foil on the number of holes.

The researcher conducted tests on the influence of PCB size, its location in space and the use of radiators on the value of thermal resistance between the LED and the environment. The resulting measurements are summarized in the table and allow determining the best PCB parameters for a given number of LEDs and the selected thermal mode.

Muna’s work with co-authors has similar studies [11]. It conducted research to determine the thermal parameters of LEDs depending on the material used in the textolite board. The results obtained by the researcher coincide with those obtained by Vinokurov [3].

Maltsev A.A. et al. [4] consider the advantages of liquid and evaporative cooling system over convection method. The paper presents one-dimensional equivalent thermal patterns derived by Kaurern and Foster [5]. The author has conducted comparative studies of different ways of cooling SMD LEDs of MX6AWT series. They tested three types of cooling devices: forced convection cooling, jet cooling and immersion cooling, where the LEDs were immersed in a vessel with an intensely moving liquid. The research presents only the results of measurements for the liquid nozzle type device as the most effective way of cooling, the thermal resistance of transition-hull was 5.1-5.4°C/W. Application of liquid cooling allows refusing radiator of the linear thermal model, that increases the accuracy of measurements and simplifies the process of calculation of thermal resistance of transition-housing.

Researcher Paul A. [6] examines the requirements, recommendations and provides calculations to create an effective system of heat removal for high power SMD LEDs such as PLCC with a permissible temperature p-transition to +125 °C. The author provides models of thermal resistance for a single LED and for several LEDs on a single medium to calculate the generated heat in the p-n transition and determine the amount of heat to be removed from the housing of the LED. The paper points out the importance of defining three main performance requirements for proper design of the
heat dissipation system: maximum ambient temperature, maximum p-n LED transition temperature, maximum dissipation power per transmitter. Using these parameters, it is possible to accurately determine the cooling system characteristics required for the lighting system under development. In this work there is an example of calculations for definition of requirements to radiator characteristics and to forms of soldering platform. It deals with the method of determining the p-n transition temperature indirectly by applying the introduced thermal resistance model. Following the recommendations given in this article it is possible: to provide operation of a light-emitting diode at higher currents, to minimize reduction of light output because of selfheating, to reduce speed of degradation of a crystal, to choose correctly system of heat removal.

Long Ngo et al. [7] study the thermal characteristics of SMD LEDs mounted on a radiator with plate cooling fins, estimate the heat dissipation efficiency depending on the spatial location of the LEDs, the width of the PCB tracks. Experimental results have shown that the width of the tracks on the PCB significantly affects the uniformity of heat distribution. The maximum difference that was recorded in the temperature deviation between the two LEDs, one of which was connected via a narrow path, the other was connected via a wide path, was 23.6°C. The author concludes that the power supply circuit, LED locations play a primary role in managing the thermal modes of luminaires with SMD elements.

Hosung et al. [8] offers new innovative methods and algorithms to form the characteristics of heat dissipation systems for high power SMD LEDs. They propose an analytical algorithm for designing the LED radiator. Following the proposed method, it is possible to calculate rather accurately the thermal characteristics of the radiator, the amount of heat dissipation depending on the location of LEDs on the printed circuit board, the ambient temperature and the characteristics of the materials used. The article also discusses a new experimental method to determine the p-n transition temperature of the LED using infrared telemetry in the isothermal chamber. They compared the results with other measuring methods, which indicates the high accuracy of the proposed method.

In work [9] the author's collective considers thermal models to define thermal resistance of the radiators intended for heat removal from SMD LEDs. The main purpose of the research is to determine the optimal characteristics of radiators to reduce their thermal resistance and increase their cooling capacity. IR cameras and Raycam System software allowed experimental testing of the models under consideration.

The article [10] deals with the problem of cooling powerful SMD LEDs to 100 W. The study looks at modern methods and examples of cooling systems using heat tubes of various shapes and sizes embedded in PCBs. The author's team offers to use a single U-shaped heat pipe for the whole PCB to simplify installation and reduce maintenance time of this luminaire. The temperature of the LED housing was 85°C.

The article [12] presents studies on optimization of SMD LED design. The authors have noted that there is a significant relationship between the photometric, electrical and thermal parameters of the device and described it in the photoelectrothermal theory of the LED device. The paper presents simulation theoretical models that determine the heat dissipation factor, thermal resistance of the LED and their impact on the optical power of radiation at a given current consumption and ambient temperature. The presented models were experimentally tested. The results showed a high accuracy of coincidence of calculated and measured values.

The considered works indicate a significant influence of thermal resistance between the LED housing and PCB on the cooling efficiency of SMD elements. This parameter is influenced by several main facts: the materials used (flux, solder paste, PCB material, contact finish), LED design features (contact design, geometric dimensions), the assembly and soldering process (manual, automatic, quality of installation and fixing elements, the resulting curves and deformations of the PCB, the type of soldering equipment and the shape of the thermal profile), the environment (temperature, humidity, vibration, electrical loads) [13].

In his work, Chernyak A. and Shchekin V. [13] reviewed in detail the influence of the quality of solder connection on the reliability and durability of LED modules, gave methods for selecting the
solder material for specific series of SMD LEDs. In the conducted experiments the researchers considered 9 types of soldering pastes: ALPHA Lumet P33, Qualitek 862, ALPHA Lumet P39, Multicore MP218, ALPHA OM-5300, AIM NC254, Union Soltek G4(A)-SM833, Indium NC-92, ALPHA CVP-520. The metal content was between 88.5 and 90 %. The researchers used FR-4 PCBs of 1 mm thick coated with HAL, ImAu and OSP, and Al 1.5 mm PCBs with HAL coating. The above solder uses 4 different alloys:

- SAC305 (Sn - 96.5%, Ag - 3%, Cu - 0.5%) - lead-free soldering, melting point 217°C (ALPHA Lumet P33, Qualitek 862, AIM NC254);
- SACX PLUS 0807 - lead-free solder, analogue of SAC305 with reduced Ag content of 0.8%, melting point is 225 °C (ALPHA Lumet P39);
- Sn62Pb36Ag2 (Sn - 62%, Pb - 36%, Ag - 2%) - lead-containing eutectic solder, melting point is 179°C (Multicore MP218, ALPHA OM-5300, ALPHA OM-5300, Indium NC-92);
- Sn42Bi57.6Ag0.4 (Sn - 42%, Bi - 57.6%, Ag - 0.4%) - lead-free soldering, melting point is 138°C (ALPHA CVP-520).

They examined 3 types of finish coating:

- HAL - coating is a layer of Sn-Pb alloy with thickness from 1 to 40 microns. The disadvantages of this coating include its non-uniformity, resulting in soldering spikes.
- ImAu - the coating is an alloy of nickel and immersion gold. Gold in the form of a thin film 0.05 - 0.2 µm thick is applied to a nickel layer 4 - 5 µm thick. These coatings have a "black pad" defect (black contact surface) resulting in solder joints detaching.
- OSP is an organic solderability preservative (OSP) coating with thickness of 0.2 - 0.6 µm consisting of an organic layer based on benzotriazole or imidazole, applied to the copper surface intended for soldering.

The researchers evaluated the quality of the compounds in two stages: thermography and X-ray analysis, thermocycling with subsequent analysis of microshells. The research has shown that the correct technological process of solder application and soldering of elements leads to the formation of a small number of defects, types of soldering paste and finish coatings have little effect on the temperature distribution of the board, the area and thickness of the tracks, the variation of SMD LED parameters has a greater influence. Thermographic study did not reveal significant differences from the application of different types of pastes and finishes.

In their next paper [14] the authors made an attempt to reveal the influence of types of solder and finish coatings on the board temperature distribution during long-term operation of the equipment and applied the method of aging based on thermal cycling for these purposes. The results of the research revealed that tin-bismuth paste showed the best wetting and no significant changes in solder structure during the whole period of thermal cycling. The presence of soldering defects significantly reduces the service life of SMD components by increasing the thermal resistance at the contact point.

Figures 2 and 3 present results of laboratory tests to study local heating zones in chamber boxes.

In the data obtained demonstrates (Figure 2), that the one type of LEDs leads to uniform heating on the entire PCB, there are no local overheating zones, by 10 minutes of operation the temperature on the LEDs exceeds the temperature on the PCB only 2 °C.

The temperature distribution for the phyto-irradiator differs significantly (Figure 3), with the declared equal power of 0.5 W white and red LEDs, the picture shows that the heat dissipation to the white LEDs is much higher and reaches 48-49 °C, red is 45 °C. This difference complicates the overall calculation of the luminaire thermal model and the service life of the product. Large groups of different types of LEDs can create local high and low temperature zones, which must be considered in the design of phyto-luminaires.
Figure 2: Snapshot of a thermal imaging camera for a white LED luminaire with phosphor with a continuous emission spectrum of 410-700 nm, 0.5 W, after 5 minutes of operation (a), after 10 minutes of operation (b).

Figure 3: Snapshot of a thermal imaging camera for a luminaire with white phosphor LEDs with a continuous emission spectrum of 410-700 nm, 0.5 W and red LEDs with a peak of 660 nm, 0.5 W, after 5 minutes of operation (a), after 10 minutes of operation (b).

The following tests allowed evaluating the possibility of modern thermal imagers to detect poor quality solder joints: a Kromatech 50-500x microscope showed a red LED installed with a defect on a printed circuit board of a phytoelectric illuminator with two types of LEDs (Figure 4). The researchers took a picture of this LED and a Fluke Ti32 diesel locomotive standing next to it after 10 minutes of operation, the results are shown in Figure 4.

The images received show the difference of 1.8 °C between the LED installed without a defect (Figure 4 a) and the LED installed with a defect (Figure 4 b). The observed results prove that this method of searching for defects is feasible, the efficiency of searching for hidden defects of solder joints (air bubbles, cavities and cracks) using the thermal imaging camera will be studied in the next works.
4. Conclusion

The applied methods of cooling do not essentially influence complexity of thermal models, liquid cooling allows to refuse radiator of linear thermal model that slightly raises accuracy of measurements and simplifies process of calculation of thermal resistance of transition-hull.

The primary role in thermal management of phyto-irradiators with SMD elements lies in the following elements: power supply circuits, LED locations, PCB dimensions and location in space, ambient temperature, adequate calculation of thermal resistance between the LED and the environment influencing the selection of radiators.

The quality of soldering joints plays a major role in temperature conditions. Defects such as voids and cracks in the fillets significantly reduce the life of SMD elements. It is necessary to note that the correct technological process of applying solder and soldering elements on the temperature distribution of the board has a greater influence on the area and thickness of the tracks, the spread of thermal resistance parameters of the SMD LEDs themselves, environmental parameters.

Large groups of different types of LEDs can create local high and low-temperature zones, which must be considered in the design of phyto-luminaires. The temperature difference on the PCB complicates the overall calculation of the luminaire thermal model and the product life.

Laboratory tests have shown the feasibility of the method of searching for defects using modern thermal imaging cameras, the effectiveness of searching for hidden defects in solder joints (air bubbles, cavities and cracks) that requires additional researches.

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Conflict of Interest

The authors have no conflict of interest to declare.
References

[1] Smirnov A A, Proshkin Yu A, Dovlatov I M, Sokolov A V and Kachan S A 2019 Development of phyto-irradiators based on LEDs with a custom spectrum ratio PAR *Innovations in agriculture* 4(33) 247-254

[2] Smirnov A A, Proshkin Yu A and Sokolov A V 2019 Optimization of the spectral composition and energy efficiency of phytoradiators *Electrotechnologies and electrical equipment in the agricultural sector* 1(34) 53-60

[3] Vinokurov A 2006 Thermal conditions of high-power LEDs DPRADO *Components and Technologies* 5 68-71

[4] Maltsev A A and Koryakin I D 2018 Measurement of thermal resistance of the transition-case of smd LEDs with liquid cooling *New technologies, mater. and equipment of the Russian aerospace industry: Mater. of the All-Russian sci.-pract. conf. with int. participation* (Kazan: Kazan State Technical University named A. N. Tupolev)

[5] Siegel B 1978 Thermal resistance measurement is the key to ensuring proper cooling of semiconductor components *Electronics* 14 43-51

[6] Andreas P 2010 Features of the calculation of heat dissipation systems when using LEDs in PLCC housings *Semiconductor lighting technology* 5 54-57

[7] Ich Long Ngo, Jang H and Byon Ch 2018 Experimental study on thermal performance of SMD-LED chips under the effects of electric wire pattern and LED arrangement *Int. J. of heat and mass transfer* 127 746-757

[8] Jang H, Lee J H and Byon Ch 2018 Innovative analytic and experimental methods for thermal management of SMD-type LED chips *Int. J. of heat and mass transfer* 124 36-45

[9] Ouhadou M, El Amrani A and Ziani S 2018 Experimental modeling of the thermal resistance of the heat sink dedicated to SMD LEDs passive cooling *3rd Int. Conf. on Smart City Applications (SCA’)* (Tetouan, Morocco)

[10] Moon S, Park Y and Yang H 2017 A single unit cooling fins aluminum flat heat pipe for 100 W socket type COB LED lamp *Applied thermal engineering* 126 1164-1169

[11] Raypah M E, Devarajan M 2016 Investigation on thermal characterization of low power SMD LED mounted on different substrate packages *Applied thermal engineering* 101 19-29

[12] Raypah M E, Sodipo B K and Devarajan M 2016 Estimation of Optical Power and Heat-Dissipation Factor of Low-Power SMD LED as a Function of Injection Current and Ambient Temperature *IEEE transactions on electron devices* 63 408-413

[13] Chernyak A and Shchekin V 2020 An experiment to study the reliability of soldered LED connections, part 1. Retrieved from: http://alphametals.ru/articles/eksperiment-po-pajke-led-1/

[14] Chernyak A and Shchekin V 2020 An experiment to study the reliability of soldered LED connections, part 2. Retrieved from: http://alphametals.ru/articles/eksperiment-po-pajke-led-2/