LED Lamp for Application in Horticulture

Petko Hristov Mashkov, Berkant Seydali Gyoch, Katya Konstantinova Asparuhova, Hristo Ivanov Beloev and Rostislav Yuriev Kandilarov

Abstract – **In this paper the results related to the construction and testing a LED lamp with special spectral characteristics and radiant flux, suitable for industrial applications in horticulture are presented. By selection of different types of LEDs and control of their operation the desired spectral distribution of lamp's luminous flux is achieved. Thermal management analysis and experimental investigations in thermal chamber are made. Safety operation conditions for LEDs are determined in dependence of LEDs' operation regimes and ambient conditions.**

Keywords – **LEDs' thermal management, greenhouse lighting, power LEDs**

I. INTRODUCTION

Nowadays replacing current light sources with new LEDs becomes hot topic. Latest LEDs have luminary efficacy even higher than 100 lm/W in contrast to the best fluorescent lamps that reach 60-65 lm/W [1, 2]. Considering the light loss in the case being times lower in LEDs, the overall energy efficiency is twice as much as those reached by the fluorescent lamps and even more efficient in comparison with other conventional light sources. Other overcoming property of the LEDs are the typically five to fifty times longer life and there are no sudden drops of functionality during the exploitation time. When properly designed and operated for tens of thousands of hours (over 50,000 hours) LED reduces the output light by about 30% (typical parameter of lighting equipment of this type - L_{70}) [1,2]. LED's luminous flux can be adjusted easily within a wide range (dimming) which is a great convenience for operation.

Important advantage of LEDs lighting sources is the ability to obtain desired spectral characteristics of the luminous flux by combination of different types of LEDs. Thus one can produce light sources with a desirable correlated color temperature, color rendering index, and optimal spectral characteristics for various industrial applications - as lighting for growing different species of animals, greenhouses, etc. [1 ÷ 10].

It should be noted that the main advantages of LED lighting can be realized only if proper design is made and proper operation during lifetime is ensured. About 75% of electricity energy consumed by the LEDs is dissipated in the form of heat [1, 2]. This heat must be removed from the area of the p-n junction where it is generated and must be dissipated in environment. The successful resolution of this problem is the main condition for ensuring reliability and long life of lighting equipment. Increase in the temperature of the p-n junction leads to decrease in luminous efficacy of LEDs and reduction of their life (L_{70}). The above data on the life and light efficiency of LED lighting can be realized only if the temperature of p - n junction during operation doesn't exceed 80°C. The aim of this work is to design and test energy efficient light source with spectral characteristics suitable for use in illumination of various types of greenhouses.

II. PROBLEM STATEMENT

Photosynthesis is a complex process that includes more than 30 types of chemical reactions. Photosynthesis pigments play major role as the primary photons acceptors and support further conversion of chemical energy. All pigments can be divided into 4 types: chlorophylls, carotenoids, phycobilins, anthocyanins.

Chlorophyll is green pigments found in leaves in 1818 by Peletier and Kaventon. It takes a crucial part in photosynthesis - absorbs sunlight and converts it in energy of the chemical bonds in the organic compounds which are synthesized in the process. There are 5 types of chlorophyll: chlorophyll A (with cyan); Chlorophyll B (green-yellow); Chlorophyll C and chlorophyll D - in red and brown algae; bacteriochlorophyll - in sulfur, nonsulfur, purple and green bacteria. Chlorophyll absorbs light selectively - spectral characteristics are shown in Figure 1 [3-9].

The most intensive photosynthesis takes place in the red and violet-blue region of the spectrum - Fig. 1 [3 ÷ 10]. In the process of evolution plants have adapted to absorb those rays of the spectrum whose energy is the most effective in photosynthesis. The intensity of each photochemical reaction is determined not by the amount of energy absorbed but by the number of ingested quanta.

Carotenoids - yellow or orange colored pigments, that constitute 98% of the yellow pigments in the photosynthetic apparatus of higher plants. They also have selective absorption spectral characteristics (Fig. 1a). Phycobilins - contained in the sea red cryptophyta algae (phycoerythrin), cyanobacterias and some blue-green algae (phycocyanin). They transmit absorbed light quanta to chlorophyll in yellow-green spectrum, so seaweeds can absorb light energy far deep in the ocean. Anthocyanins -

P. Mashkov is with the Department of Phisycs, Faculty of Transport, University of Ruse, 8, "Studentska" Str, 7017 Ruse, Bulgaria, e-mail: pmashkov@uni-ruse.bg

B. Gych is with the Department of Phisycs, Faculty of Transport, University of Ruse, 8, "Studentska" Str, 7017 Ruse, Bulgaria, e-mail: b_gyoch@uni-ruse.bg

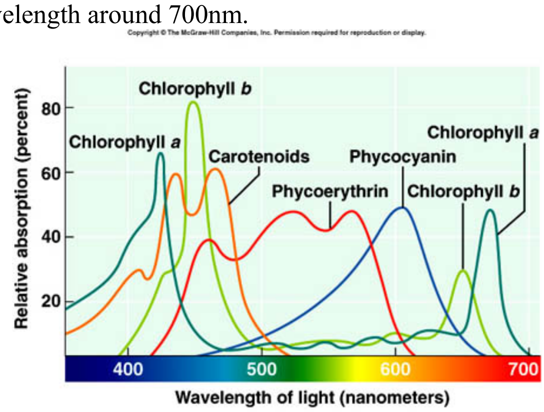
K. Asparuhova is with the Department of Electronics and Electronics Technologies, Faculty of Electronic Engineering and Technologies, Technical University - Sofia, 8 Kliment Ohridski blvd., 1000 Sofia, Bulgaria, e-mail: k_asparuhova@tu-sofia.bg

H. Beloev is with the Department of Agricultural Machinery, Agricultural and Industrial Faculty, University of Ruse, 8, "Studentska" Str, 7017 Ruse, Bulgaria, e-mail: hbeloev@uni-ruse.bg

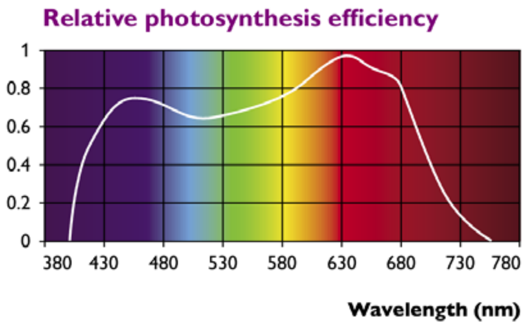
R. Kandilarov is PhD student with the Department of Phisycs, Faculty of Transport, University of Ruse, 8, "Studentska" Str, 7017 Ruse, Bulgaria, e-mail: rkandilarov@uni-ruse.bg

water-soluble pigments located in the cytoplasm. They stained plant parts in purple, red, brown in autumn and at low temperatures.

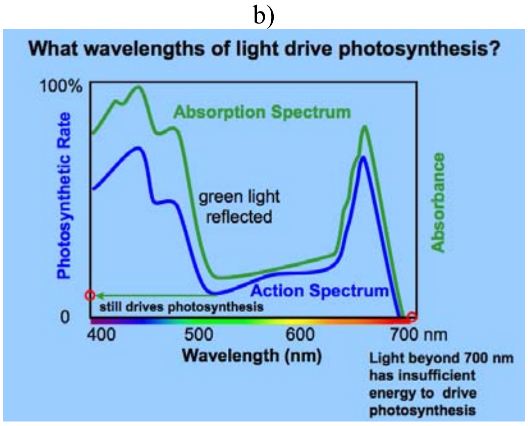
Energy quanta in the red region of the spectrum is lower, so the same amount of energy absorbed by the red rays is produced by greater number of quanta compared with blue-violet rays. There may be a quantum with so little energy that it is not sufficient for inducing chemical effect. This means that when photochemical reactions there is a threshold limit of quantum energy in which responses are impossible i.e. there is an upper limit to the length wavelength around 700nm.



a)



b)



c)

Fig. 1. Spectral characteristics: a) plant pigments, b) and c)-photochemical efficiency [8, 9, 10].

The efficiency of energy conversion of light into chemical energy in plants is estimated between 3 and 6%. The actual efficiency of the photosynthesis (between 0.1 and 8% [3 ÷ 10]) varies considerably with changes in light spectrum, light intensity, temperature and carbon dioxide concentration.

As can be seen from Fig. 1b, and Fig. 1c various authors present a somewhat different characteristics for the effectiveness of the process of photosynthesis; the most effective is radiation in the blue and the red part of the spectrum.

The main goal of this work is design of energy effective LED lamp module with spectral power distribution (SPD) of the radiant flux corresponding to the spectral photosynthesis efficiency.

III. Experimental

Used LEDs are XLamp XPC series produced by CREE Inc. There are several reasons for this choice: they have good exploitation properties [2]; in this series white LEDs are available with color temperatures in a wide range - from 2600K to 10000K; a range of colored LEDs required to achieve the objectives set are also available. All LEDs can operate with the same power supply that is essential advantage. In current study all LEDs are powered by a constant current source. White LEDs operate at currents of 350 mA; for colored LEDs forward current is changed from 100 mA to 350 mA.

The spectral characteristics of LEDs being used are determined experimentally with spectrophotometer of the company StellarNet-Inc and are presented in Fig. 2 and Fig. 3.

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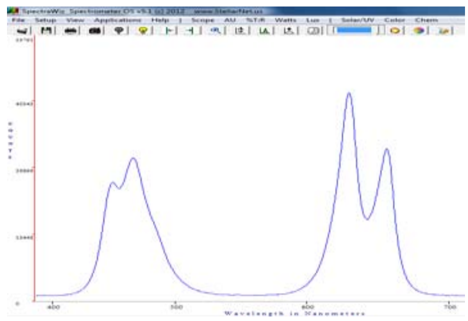

Fig. 2. LEDs' spectral characteristics (from left to right): royal blue (XPCROY), blue (XPCBLU), red (XPCRED) and deep red (HPL).

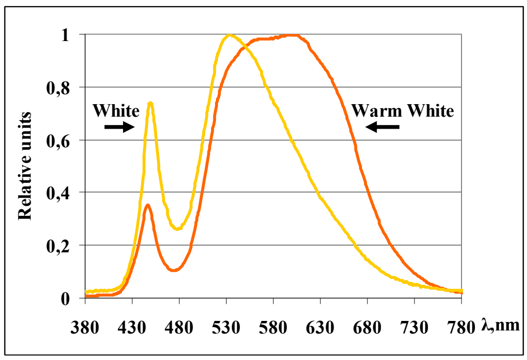

Fig. 3. LEDs' spectral characteristics (from left to right): neutral white (XPC) and warm white (XPC).

During experimental investigations three warm white LEDs (XPC), three neutral white LEDs (XPC), one blue LEDs (XPCBLU); one royal blue LED (XPCROY), one red LED (XPCRED), and one deep red LED (HPL) are used. All LEDs are soldered to circuit boards with metal core (MCPCB) and mounted on aluminum heatsink with thermal resistance between the heat sink and the ambient environment $R_{th\ hs\text{-}a} = 1^{o}C/W$.

In Fig. 4 a photo of the LED module is presented.

Fig. 4. Realized lamp module with one warm white, three neutral white; one blue, one royal blue one red and one deep red LEDs.

IV. Experimental Study on Spectral Characteristics

At the first stage of experimental investigations (module 1) all white LEDs operate at 350 mA current and the current of colored LEDs is changed between 100 mA and 350 mA. Spectral characteristic of the module's 1 luminous flux is shown in Fig.5.

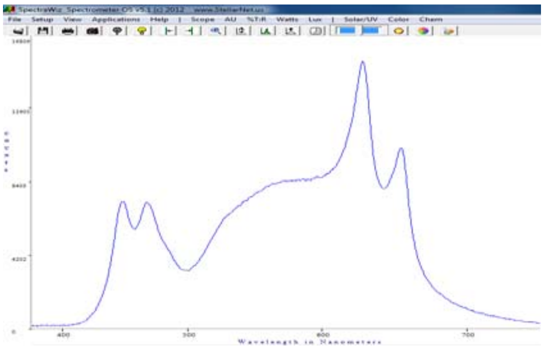

Fig. 5. LEDs' spectral characteristics: three warm white LEDs at 350mA; royal blue (XPCROY), blue (XPCBLU), red (XPCRED) and deep red (HPL) at 200mA.

The nominal drive current for color LEDs is 350 milliamps; when they operate at low current are not fully exploited; the energy efficacy of the LED module is decreased. Therefore, during further investigations all LEDs are connected in series and operate at 350 mA current. The number of warm and neutral white LEDs and their ratio is changed to achieve the desired spectral power distribution.

During experiments the following combinations are used:

- Always one blue, one royal blue, one red and one deep red LEDs;

- Three warm white LEDs; - three warm white and one neutral white LEDs; two warm white and two neutral white LEDs; one warm white and three neutral white LEDs; three neutral white LEDs. Some of spectral characteristics of different LED modules are shown in Fig. 6 and Fig.7.

The decisive criterion for the successful implementation of our objective is the appropriate spectral characteristics of the luminaire - similar to those shown in – Fig. 1 [8 ÷ 10].

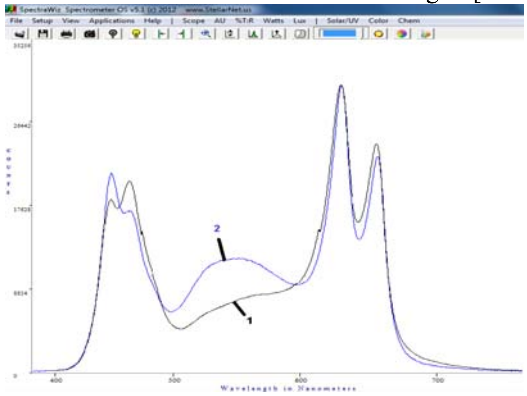

Fig. 6. Comparison between SPD of two variants of the LED module: 1 - three warm white, one blue, one royal blue, one red and one deep red LEDs; 2 - three neutral white, one blue, one royal blue, one red and one deep red LEDs.

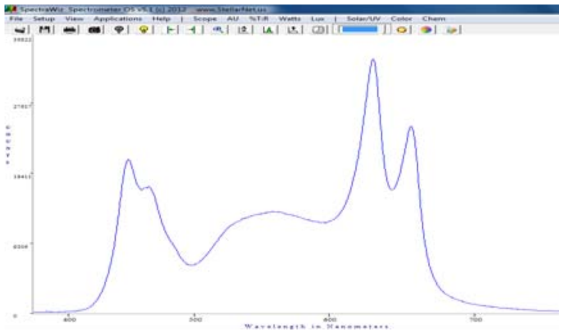

Fig. 7. Spectral characteristics of the LED module: two neutral white, two warm white, one blue, one royal blue, one red and one deep red LEDs.

Comparison between spectral power distribution of luminous flux of LED module (three neutral white, one blue, one royal blue, one red and one deep red LEDs), and the desired SPD [8] is shown in Fig. 8. The result clearly shows that spectral characteristics of the constructed lamps are suitable for its use in the process of photosynthesis for plants of various kinds.

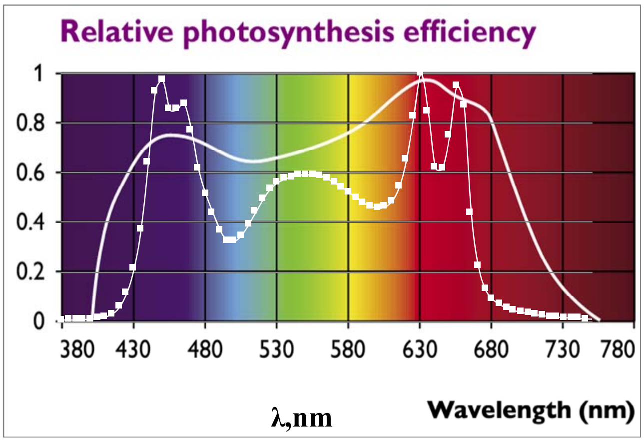

Fig. 8. SPD of LED module (three neutral white, one blue, one royal blue, one red and one deep red LEDs, which spectrum is shown in Fig. 6, curve 2), compared to the relative photosynthesis efficiency [8].

V. Thermal Management

For the evaluation of thermal loads at different environmental conditions the LED modules are placed in a thermal chamber. The temperature in the chamber is gradually changed from 20°C to 45°C. Studies were carried out at constant current through the LEDs 350 mA.

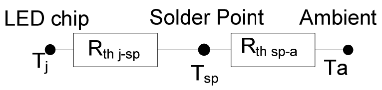

Fig. 9. Schematic diagram of the thermal resistances in the heat flow path from the p-n junction to the ambient environment; Temperature notations are as follows: Tj – temperature of p-n junction; Tsp - temperature of solder point; Ta - ambient temperature; Rth j-sp and Rth sp-a - thermal resistance between the p-n junction and solder point and between the solder point and the ambient.

The temperature distribution of the different LEDs under different operating conditions was assessed by measurement using thermocouples installed in accordance with the producer recommendations [1]. Most convenient way for investigating the temperature regimes for all the LEDs is the infrared thermography. Fig. 10 shows infrared image of the LED lamp (shown in Fig. 4) in the heating chamber, using thermography measurements taken with an infrared camera ThermaCam E300 - FLIR-Systems.

Using obtained experimental data for the temperature of the solder point (T_{sp}) the thermal loading of the LEDs is estimated by calculating the temperature of the p-n junction T_j using (1).

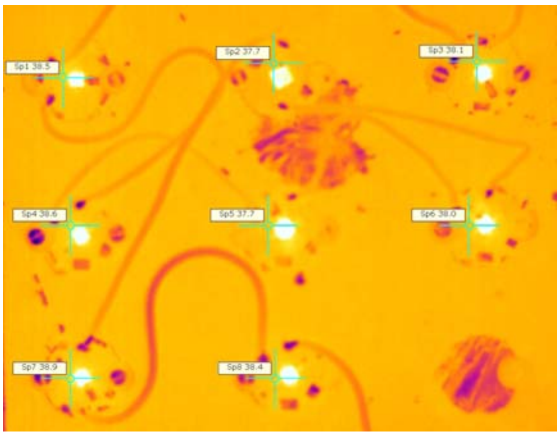

Fig. 10. A study of temperature distributions on LEDs cases using infrared thermography; ambient temperature is 35 ° C.

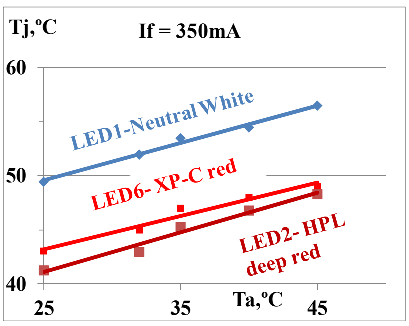

Fig. 11. XPC – White, blue, red and deep red LEDs' p-n junction temperature (**Tj**) in dependance of the ambient temperature (**Ta**).

$$T_j = T_{sp} + R_{th\ j\text{-}sp} * P_{LED} \qquad (1)$$

The thermal resistance between the p-n junction and solder point $R_{th\ j\text{-}sp}$ is given by the manufacturer: for XLamp XPC – White and blue, $R_{th\ j\text{-}sp}$ = 12 K/W; for red LEDs $R_{th\ j\text{-}sp}$ = 10 K/W; for deep red LEDs $R_{th\ j\text{-}sp}$ = 5 K/W.

In Fig. 11 the calculated junctions' temperatures of LEDs during operation at different ambient temperatures are shown.

The results show that the operating modes of the LEDs in designed modules are far from the dangerous temperatures of the p-n junction (over 85°C). This ensures smooth operation and long life of the lamp. From the other hand it allows an industrial production LEDs to be soldered on a common circuit board and to reduce the size of the cooling radiator.

VI. Conclusion

LED modules for industrial applications in horticulture are designed and tested. Performed experimental studies show that the spectral features are suitable for the cultivation of a wide class of plants. The operating temperatures of the LEDs ensure smooth operation and long life of the developed equipment. Used light sources and their power supply can provide very good energy efficiency at relatively low cost of lighting equipment.

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