Implementation of DOE in the Heat Sink Design for LED Application

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Abstract – **In this article there is analyzed the influence of various design parameters of the heat sink and their influence on the junction temperature of the LED system. Tests are performed by thermal simulations and by the use of technology for design of experiments (DOE) to find the optimal design of the heat sink. The results from the thermal modeling and simulations have been validated experimentally and they show good matching results.**

Keywords – **Heat sink Design, Heat Transfer, Design of Experiment**

I. INTRODUCTION

The development of LED technology has led to the emergence of more compact and more powerful LED devices, which, despite their higher efficiency dissipate a lot of heat. Heat negatively affects the performance of LED devices and must be dissipated effectively because it can cause damage and reduce reliability. Therefore, proper thermal management is essential for the good design of each LED device or system [1], [2].

Management problems in heat exchange of LED systems are analyzed and studied by many scientists. A number of studies focus on improving the heat transfer through MCPCB (Metal Core Printed Circuit Board), IMS (Insulated Metal Substrate) and various ceramic materials where powerful LEDs are usually mounted on [2], [3], [4].

Regardless of the type of the circuit board to dissipate heat from the more powerful LED modules heat sinks of different materials and in different sizes are typically used. The effectiveness of the heat sink does not depend only on the size and the material from which it is made, and is determined by its structure. Different design requirements are put at various LED applications according to the working conditions and installation, which require the development of customized solutions for cooling design of the final product.

The problems associated with the design of heat sinks are discussed by many researchers. H. Fengze and Y. Daoguo and others in [5] studied the thermal behavior of designed by them LED array and a heat sink with flat fins and fins pin type. Using a 3D model created in ANSYS and simulations there are investigated temperature distribution of a LED system taking into account the impact of the construction of the heat sink. Analyses show that the transition temperature of LEDs in the array is the lowest when the structure of the heat sink has fins pin type and are arranged so that the fins alternate every other fin. P. Huang, Kailin Pan and others in [6] apply thermal modeling and simulations to optimize the entire design of multi-chip LED lighting module. To optimize the LED structure there are used statistical analysis and thermal simulations by ANSYS software to evaluate the factors influencing productivity as - output of chips, layout of chips, the size of MCPCB and heat sink.

T. Kobayashi, S. Ishikawa, R. Hashimoto and others in [7] study the thermal effects of a heat sink with a round base and flat fins designed for LED bulb. In the analysis of heat transfer they use FEM (Finite Element Method) and are in the model report thermal convection and radiation. By applying the design of experiments (DOE) there are set out the parameters of the heat sink affecting the temperature of the heat sink and is evaluated the best and worst construction. Results from the simulation model of the heat sink are validated by measurements with thermocouples and thermal camera.

A. Mahalle and M. Shende in [8] numerically analyze the heat flow of a star heat sink with a round base and flat fins in natural convection. Research is done in three geometric parameters of the heat sink for finding the optimal structure. The effects of changing the geometric dimensions and the effects of heat flow on the heat resistance and the coefficient of heat exchange are analyzed. The results show that with an increase in the geometric dimensions of the heat sink, the heat resistance and the coefficient of heat transfer are usually reduced.

Although there are studies that examine different structures of the heat sinks, there are still enough challenges in their design. A good heat sink must maintain low transition temperature of the LED devices at different operating conditions; it must be compact and with an easy installation.

This article presents a study of a passive heat sink for a powerful LED module. For optimization of the geometric dimensions of the heat sink, a design of experiments is used. To assess the thermal efficiency of the optimized structure the temperature of junction of the LED source is monitorred.

II. HEAT SINK DESIGN METHODOLOGY

A. Choice of structure

The basic structure of the heat sink has a square horizontal base and circular fins pin type arranged in line. This type of construction allows different orientation of the heat sink and allows more flexible installation and use. As

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a heat sink material aluminum alloy is used, because of its low price, good thermal conductivity and a heat sink with enough complex geometric shape can be easily molded. The structure of the heat sink and the geometry of the fins are shown in Fig. 1.

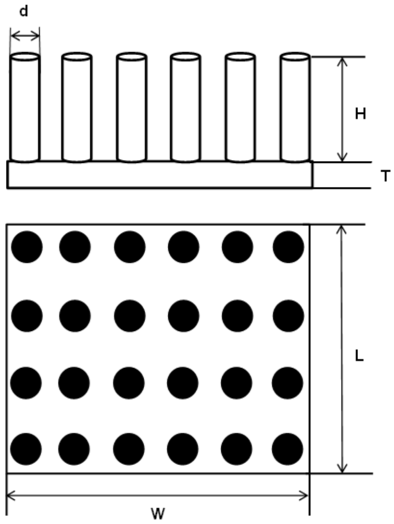

Fig. 1. Heat sink construction

B. Thermal modeling

For the design and testing of the thermal behavior of the heat sink structure CFD software Flotherm is used. Fig. 2 shows the heat-modeled structure of the heat sink fitted with LED module, situated in the center, which thermal power to be dissipated.

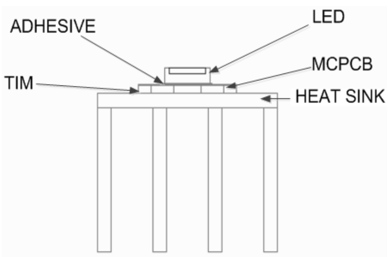

Fig. 2. LED system - made up of LED, MCPCB and a heat sink

The maximum heat power set to the thermal modeling of 3W LED (at maximum operating voltage U_f = 4.1V, maximum current I_f = 700mA and a coefficient of conversion of electrical energy into heat H = 75%) is calculated as follows [8]:

$$P_{th} = U_f I_f H = 4{,}1V \cdot 0{,}7A \cdot 0{,}75 \approx 2{,}15W \qquad (1)$$

Table 1 shows the physical characteristics of the materials constituting the LED system.

TABLE 1. PHYSICAL CHARACTERISTICS OF THE MATERIALS

Material	Conductivity [W/m·K]
Heat Sink – Aluminum 6061	180
GaN Chip	130
SnAgCu Solder	58
FR4 – Dielectric Layer	0.2
Top Layer Copper	385
MCPCB – Aluminum Plate	150
TIM – Silver grease	3

When creating a geometric model of the different variants of heat sinks, the length L, width W and the thickness of the base of the heat sink T do not change with thermal modeling and simulations, because of the specific requirements of LED application.

The heat sink is modeled with a length L = 40mm, width W = 40mm and thickness of the base T = 3 mm.

In order to optimize the parameters of the fin - the height of the fin, the fin diameter and the number of fins in the design of the heat sink, a design of experiments (DOE) is used.

C. Use of DOE in the heat sink design

To obtain optimum thermal characteristics in the design of the heat sink there must be identified the factors having the greatest impact on improving the capacity for heat dissipation.

The geometrical factors of the structure of the heat sink, which are selected as design parameters, are the height of the fins (A), the fin diameter (B) and the number of fins (C) of the heat sink.

Full Factorial Experiment for three factors for each one on two levels is used as a tool for the realization of DOE. Table 2 shows the three design parameters, whose influence is analyzed.

TABLE 2. PARAMETERS AND LEVELS OF EXPERIMENT

Factor	Factor Latter	Level	
		Low	High
Height of Fins, [mm]	A	15	30
Diameter of the Fin, [mm]	B	3	4
Number of Fins, [mm]	C	24	42

In Table 3 there are shown the eight possible experiments and the different configurations of the design parameters.

TABLE 3. COMBINATION OF DESIGN PARAMETERS

Experi-ment №	Height of Fins [mm]	Diameter of the Fin [mm]	Number of Fins
1	15	3	24
2	15	3	42
3	15	4	24
4	15	4	42
5	30	3	24
6	30	3	42
7	30	4	24
8	30	4	42

In Full Factorial Experiment there can be estimated all main effects and interactions, since the method has full resolution.

III. ANALYSIS AND DISCUSSION OF RESULTS

All thermal simulations are conducted at specified ambient temperature of 25^0C.

Fig. 3 shows the distribution of heat and the maximum temperature of the LED system at the first design configuration (with a height of the fins 15mm, diameter of the fin 3mm and 24 fins), and the Fig. 4 of the latter configuration (with a height of the fin 30 mm, a diameter 4 mm, and the number of the fins - 42) of Table 3.

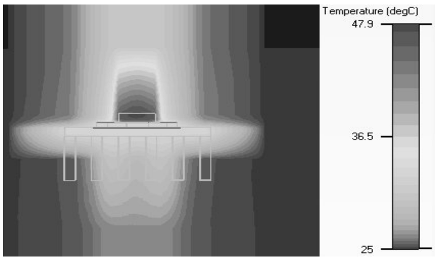

Fig. 3. Temperature distribution in the design configuration of the fins with a height of 15mm, a diameter of 3mm and 24 fins

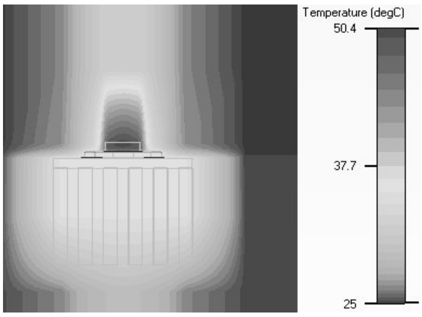

Fig. 4. Temperature distribution in the design configuration of the fins with a height of 30mm, a diameter of 4mm and 42 fins

The effects of various configurations of heat sink design parameters on the maximum temperature of the LED system simulations are shown in Table 4.

TABLE 4. THERMAL SIMULATIONS RESULTS

№	Height of Fins	Diameter of the Fin	Number of Fins	Max. Temp. [^{0}C]
1	15	3	24	47,9
2	15	3	42	47,1
3	15	4	24	49
4	15	4	42	51,9
5	30	3	24	45,4
6	30	3	42	45,7
7	30	4	24	46,1
8	30	4	42	50,4

After analyzing the results of the simulations the factor of influence of each parameter of the heat sink on the maximum temperature of the LED system is represented graphicall in Fig. 5.

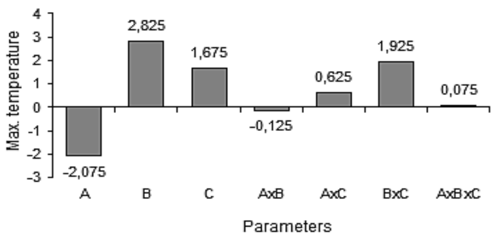

Fig. 5. Factor of influence of each parameter on the maximum temperature

From the graph above it is clear that the effects of A (the height of the fins) and AxB (the interaction between the height of the fins and the diameter of the fins) are the most important parameters of the heat sink to lower the temperature.

On Fig. 6a, b and c there are presented plots of the interaction between each of the parameters on the basis of the processed data from the simulations.

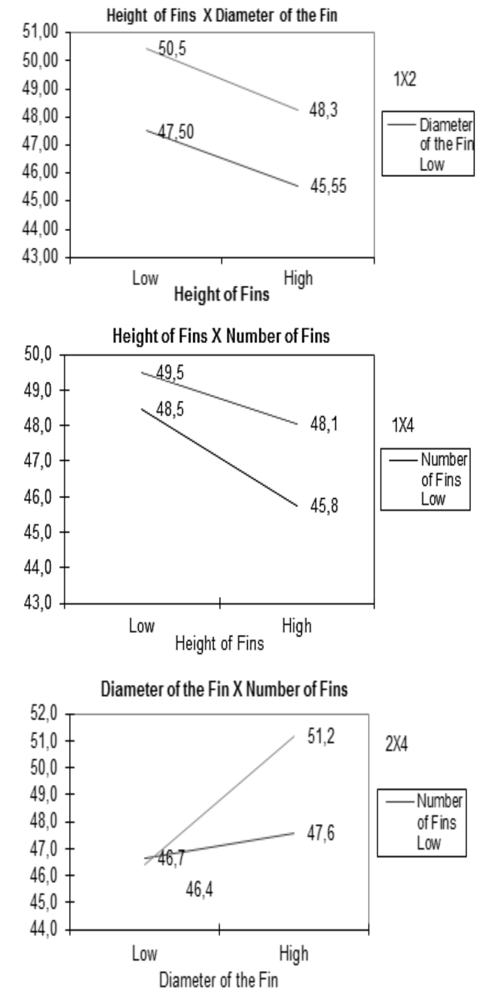

Fig. 6. Graph of interaction between: a) the height of the fins X the diameter of the fins; b) the height of the fins X the number of fins; c) the diameter of the fins X number of fins

It can be seen that the greatest interaction between the parameters is observed in Fig. 6c, where the two lines intersect. From there we can determine that the small value of the diameter (3mm) and the small number of fins (24 fins) provide optimal project results and lead to lowering the temperature of the LED system.

The studies carried out show that the optimal design parameters of the heat sink are - height of the heat sink 30mm, diameter of the fin 3mm and 24 fins. At these values of design parameters the temperature of the LED system is the lowest - 45,4^{0}C. Very low temperature 45,7^{0}C has the heat sink with a fin height of 30mm, fin diameter of 3mm and 42 fins, but it is more expensive to be made. Worst heat sink design parameters are - height of the fin 15mm, diameter of the fin 4mm and 42 fins, then the temperature of the LED system is the highest - 51,9^{0}C.

IV. VALIDATING OF RESULTS

To validate the results of thermal simulations there is used a prototype of the heat sink, which is made with the optimal parameters and has a mounted a LED module on it supplied by 3,6V DC voltage. Temperature measurement using K-type thermocouple, which is connected to the data acquisition system (UNI-T UT804) and fully dedicated computer with software for data processing are performed. Fig. 7 shows the place of the thermocouple on the LED structure during the measurements.

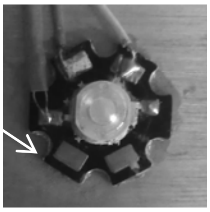

Fig. 7. The place of the thermocouple for measuring the temperature of the module

During the measurements, the ambient temperature is 24^0C and the LED works without interruption for 30min. By substituting the measured temperature at the solder T_S and other thermal parameters of the LED package, for the transition temperature Tj we get:

$$T_j = T_s + (R_{j-s})P_d = 33^0 C + \left(8^0 C/W \cdot 1{,}89W\right) = 48{,}12^0 C \quad (2)$$

The resulting temperature of the LED junction of $48{,}12^0$C is very similar to that obtained by the thermal simulations - $45{,}4^0$C. The relative error between the simulated and measured temperature is about 5.6%, which demonstrates accordance of the results.

V. CONCLUSION

Analyses show that the heat sink design with circular fins pin type the larger number of fins is not a factor of influence to increase the cooling capacity.

To increase the heat exchange capacity of the heat sink a major role plays the height of the fin and the interaction between the fin height and diameter of the fin.

For obtaining a better evacuation of heat flow from the heat sink structure the diameter of the fins must not be large, but the number of fins must be carefully selected so as not to hinder the movement of the hot air to the environment.

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