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RESEARCH ARTICLE

THERMAL ENHANCEMENTS OF A LED BASED AUTOMOTIVE HEADLAMP.

Moumouni Guero Mohamed[1,2,3] and Prodjinonto Vincent[2,3]

1. University Institute of Technology, Dan Dicko Dankoulodo University of Maradi, UDDM, Republic of Niger.
2. Department of Mechanical and Energy Engineering, Polytechnic School of Abomey-Calavi, Republic of Benin.
3. Laboratory of Energetics and Applied Mechanics, University of Abomey Calavi, Republic of Benin.

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Abstract

Light Emitting Diode (LED) is a new kind of light source that is quickly being used into automotive lighting systems. In recent years, there have been increased expectations placed on vehicle headlamps, including that they not only be fully functional, affordable, and long-lasting, but also stylish, energy-efficient, and environmentally friendly. Since LED light sources are long-lasting, highly efficient, and energy-efficient, small in size, etc., they are frequently utilized in headlamps, turn signals, brake lights, position lights, etc. and will soon dominate the automotive light source industry. Although it has a greater energy conversion efficiency, the thermal management of LED headlamps is still a problem. In this research, the response surface method is used to optimize the heatsink designs for LED automotive headlamp module. The finite element (FE) approach and numerical simulation are used to model the test sample's temperature distribution. Then, in order to maximize the heatsink potential for thermal dissipation, we tested different types of material, and used the response surface method. The LED headlamp hot spots decrease by 2 to 8 degrees when the heat sink's thickness, fin spacing, and height are optimized; and decrease by 7.64 degrees when the heat sink and PCB substrate are made of 6063 aluminum alloy and AlN, respectively.

Introduction:-

The light-emitting diode (LED) is a new kind of light source that has the benefits of being compact, simple to design, and meeting automotive lightweight standards. Additionally, LED has high photoelectric performance, quick response times that effectively boost the active safety of the vehicle, excellent energy-saving capabilities, and vibration-free properties [1]. Currently, LED light sources are mostly employed in automobile instrument lights, taillights, brake lights, turn signals, and reverse lights. However, there are still technological barriers preventing the adoption of LED in automobiles. For instance, one of the biggest obstacles is the thermal effect brought on by inadequate heat dissipation [2].

In LED lighting systems, thermal management is a critical issue because the primary system parameters, such as light output, light quality, and lifetime, depend on the temperature generated. Previous work has shown that for led automotive headlamps, temperatures are much more concentrated on the led chip [3]. Temperature as a result of inefficiency becomes the most significant design parameter, beginning with the LED die's junction temperature and

Corresponding Author:- Moumouni Guero Mohamed
Address:- University Institute of Technology, Dan Dicko Dankoulodo University of Maradi, Republic of Niger.

ending with the luminaire housing's maximum surface temperatures defined in international standards [4]. The basic function of the "generate light" system is becoming more and more related to the issue of "dissipating heat". Appropriate design of an LED system should ensure the continued heat flow of the heat source into the surrounding atmosphere of the system. Nowadays, considering the overall efficiency of the light output sector, about 75% of an LED lighting system is a loss. Even with the most efficient future LEDs (150lm / W), about 50% of the input power needs to be dissipated. The aim is to reduce the thermal resistance of the entire LED lighting system [5]. Due to the LED lamp's minimal energy usage, natural convection heat sinks are most frequently used to cool it in the heat dissipation portion. To improve the design of the heat sink, many geometrical factors, including length, height, and the number of fins, as well as packaging orientation, have been explored [6, 7].

The design of fins has been the subject of several research, including studies on plate fins with a relatively small slope [8], plate fins with cut corners [9], honeycomb fins [10], fillet profile fin heat sinks [11], trapezoidal and inverted trapezoidal fins [12], and combination trapezoidal grooves [13]. In terms of temperature distribution, Şevik and Özdilli [13] compared four different geometries, such as trapezoidal, trapezoidal-groove, groove, and groove trapezoid. The results revealed that the plate-fin height, rather than the plate-fin geometry, has a greater influence on the maximum temperature. Geometry is critical in heat sink design. Özdilli and Şevik [14] analyzed the main design (Cylindrical heat sink) and four different geometries derived from it (Cylindrical-concave, cylindrical-convex, cylindrical wave, and cylindrical-wave). According to the simulation results, the cylindrical concave cooler design provides the best cooling performance while reducing the weight and surface area of the main design cylindrical heat sink by 31% and 20%, respectively. Joel et al. [15] investigated how fin design affects the cooling of computer microchips using MATLAB. Geometries such as rectangle spine fin, triangular fin, and triangular spine (conical) wings are employed together with pin-fins made of materials such as aluminum, copper, silver, beryllium, and zinc. The pin fin has three different geometries: rectangular spine fin, triangular fin, and triangular spine (conical) fin. The triangular spine fin geometry demonstrated higher heat dissipation per unit volume and more maximum heat loss per fin number than pin and rectangular spine fins. Copper's high thermal conductivity made it perform better as expected. The effect of different fin geometries on thermal/fluid performance was studied by Khan et al. [16]. Square geometry performed poorly in terms of heat transfer and drag force, while circular, rectangular, and elliptical shapes performed best. Kim et al. [17] thermally optimized three distinct plate-fin heat sinks, including rectangular, triangular, and inverted trapezoidal fins. When compared to the reverse trapezoidal heat sink, the rectangular heat sink has lower thermal resistance values. Yang and Peng [18] analyzed the numerical modeling of the heat sink with non-uniform fin height and indicated that by raising the height of the fins around the heat sink's center, the junction temperature could be reduced more effectively.

For efficient LED headlamp operation, heat management and reliability are essential for high power LED subassemblies. Appropriate thermal and thermomechanical design of the LED modules is required. When LED lights are in working condition, the chip junction temperature would get a rise. The excessively high junction temperature would seriously affect the efficiency of LED lights and shorten its life. Therefore, finding a feasible design to decrease the impact of junction temperature to LED heat transfer is very essential. Heat dissipation of LED mainly through heat conduction and heat convection between the heat sink and the air was obtained. Thus, to improve the heat dissipation performance of LED lamps, we herein studied the optimum matching scheme between materials and structure of LED to achieve the goal of thermal resistance reduction. This optimization was done by using FEA simulation with Ansys software and the response surface method based on the Minitab program.

Materials and Methods:-

The original led headlamp was tested and analyzed in the previous paper [3]. The results obtained are presented in the following table.

Table 1:- Results for the previous study done (°C) [3].

Power	Temp. FEA	Temp. Experiments		Temp. Simulation
		IR Camera	Thermocouple	
0.45	28.5	28	31	29
0.6825	35.8	38.1	39.1	35.5
1	40	42.3	42.8	41.6
1.6	48.3	48.9	50.2	48.7
2	57.375	62.6	63.4	59

2.8	71.7	76.4	77.1	73
3.5	80.7	80.4	81.8	80

The improvements of the automotive headlamp will be done at several levels. These one is presented and explained in the following paragraphs.

Effect of substrate material on the temperature distribution

During the heat dissipation process of the headlamp, the substrate not only supports the wiring of the LED device but also acts as the heat transfer from the LED device to the external radiator, which is a very important part of the heat dissipation channel. Therefore, the substrate material should not only provide structural strength but also achieve the heat dissipation requirement by matching the materials themselves well with their chemical/physical structure. As the device calorific value of the traditional LED device is not big, ordinary PCB can meet the demand of cooling, however, with the increase of LED power, ordinary PCB has been unable to meet the demand. Thus, the aluminum-based metal circuit board (MCPCB) and ceramic substrate (Al3O2, AlN) appeared. In order to make clear the impact of different substrate material on the heat dissipation, we focus on a series of substrate materials with better properties such as the aluminum metal circuit board (MCPCB) and ceramic substrates (Al_3O_2, AlN), respectively, then developing simulation calculation on thermal dissipation characteristic of LED lamps.

Effect of heat sink material on the temperature distribution

Heat sinks are made of high thermal conductivity materials such as aluminum alloys and copper. Copper has high thermal conductivity, antimicrobial resistance, biofouling resistance, corrosion resistance, and heat absorption properties. Although its qualities make it a good heat sink material, it is more costly and denser than aluminum.

In the auxiliary heat sink design for LED lamps, the heat dissipation effect can be achieved through air convection between the interior lamp and the base of the heat sink. Thus, the thermal characteristics of the heat sink would have a direct influence on the heat transfer of the headlamp. To understand the influence rule of the heat sink to LED junction temperature distribution, a numerical investigation on steady-state analysis is developed for temperature distribution based different materials in the heat sink.

Effect of heat sink design on the temperature distribution

There are many variables that can be modified for the optimization problem such as fin spacing/density, fin thickness, fin height, the dimension of the heat sink, airflow velocity, etc. However, we limit the problem to be a geometrical optimization and only vary the thickness, height, and a number of fins. Table 2 presents the heatsink parameters assessed in this design optimization study.

Table 2:- Heatsink DoE Parameters.

Base Thickness (mm)	Height (mm)	Width (mm)	Length (mm)	Fin Thickness (mm)
3.6	70	75	100	1.6
3.6	63	75	100	1.6
3.6	68	75	100	1.6
3.6	70	75	100	1.6

Table 3:- Symbols and definitions for equation below Table 4 : Constraints due to the design specification.

Symbol	Definition
δ	Thickness
h	Fin height
N	Number of fins
Tmax	Maximum temperature
s	Fin spacing
w	Heat sink width

Minimum fin height	0.625 mm
Minimum number of Fins	2

Maximum total height	75 mm
Heat sink width	75 mm
Heat sink length	100 mm

As we have specified the objective, variables, and constraints, we can then formally state the optimization problem,
Minimize (Tmax),
subject to $\delta \geq 7.5 \times 10^{-4}$ (Minimum thickness),
$6.25 \times 10^{-4} \leq h \leq 4.875 \times 10^{-2}$ (Minimum and maximum height),
$N \geq 2$ (Minimum number of fins),
$h/s \leq 60$ (Maximum height: spacing ratio),
$s \geq 8 \times 10^{-4}$ (Minimum spacing),
$N\delta + (N - 1)s = w$ (Spacing equality).

Response Surface Method for optimization
The response surface method (RSM) is a valuable tool for optimization modeling that uses mathematical analysis and statistical methodologies. It combines experimental design with regression analysis to carry out the trials in a systematic manner within the given region. After gathering the appropriate response data, regression analysis is performed to aggregate the relationships between response values and parameters for an ideal solution identified within the scheduled trials. RSM combines both techniques regarding the design of experiments (DoE) and fitting method to describe the correlation between design parameters with its target/response values [19]. We can efficiently estimate the parameters by using RSM design optimization to confirm the influences with respect to the target value.

Design of Experiments
When process factors (independent variables) satisfy an important assumption that they are measurable, continuous, and controllable by experiments, with negligible errors, the RSM procedure is carried out as follows:
1. Conducted a series of experiments for adequate and reliable measurement of the response of interest.
2. A mathematical model of the second-order response surface with the best fit was developed.
3. The optimal set of experimental parameters producing the optimum response value was determined.
4. The direct and interactive effects of the process parameters (factors) were represented through two and three-dimensional plots.

In order to determine if a relationship existed between the factors and the responses investigated, the collected data were analyzed statistically using regression analyses. A regression design is employed to model response as a mathematical function of a few continuous factors and desired good model parameter estimates [20].Each response of Y is represent by a mathematical equation that correlates the response surface. The responses are expressed as second-order polynomial equations, according to the equation below:

$$Y = f(X) = \beta 0 + \sum_{i=1}^{k} \beta iXi + \sum_{i=1}^{k} . \sum_{j=i+1}^{k} \beta ijXiXj + \sum_{i=1}^{k} \beta iiXi2$$

where Y is the predicted response (Temperature) used as a dependent variable; k the number of independent variables (factors: fin thickness and number of fin), x_i $(i = 1, 2)$ the input predictors or controlling variables (factors); β_0 the constant coefficient, and β_i, β_{ij} and β_{ii} the coefficients of linear, interaction and quadratic term, respectively. The coefficient parameters are estimated using multiple linear regression analysis. The results of the experimental design are analyzed and interpreted using MINITAB statistical software, to find the 3-D surface and 2-D contour plots of the response models.

Table 5:- Experimental layout and resultant data for simulations and variables.

Numerical variable		**Variable**		**Response**
Fin thickness	Numb of fin	X_1	X_2	Y
1	4	-1	-1	70
1	8	-1	1	73
1.5	9	1	-1	85
1.5	9	1	1	85

2	8	0	-1	80
2	12	0	1	70
1	9	-1	0	73
1	10	1	0	72
1	10	0	0	71
2	10	0	0	77
2	10	0	0	78
2	11	0	0	75
2	11	0	0	74

Results And Discussions:-

Simulating results demonstrate that when using FR-4 CCL, MCPCB board, Al_3O_2, and AlN ceramic substrate board, headlamp highest temperature is 80.12 ℃, 79.07 ℃, 78.36 ℃, and 72.46 ℃, respectively. Especially, the chip junction temperature underwent an obvious decline when using AlN ceramic substrate board, which builds the essential basis for selecting AlN ceramic substrate board as a novel applicable substrate material in high power LED lighting systems.

Table 6:- The temperature distribution of different substrate materials.

Materials	FR-4	MCPCB	Al_3O_2	AlN
Thermal conductivity (W/m·K)	16.5	21	29	200
High Temp point	80.12	79.07	78.36	72.46
substrate	77.1	76.8	75.2	69.2
Heat sink	40.2	39.6	37.9	35.4

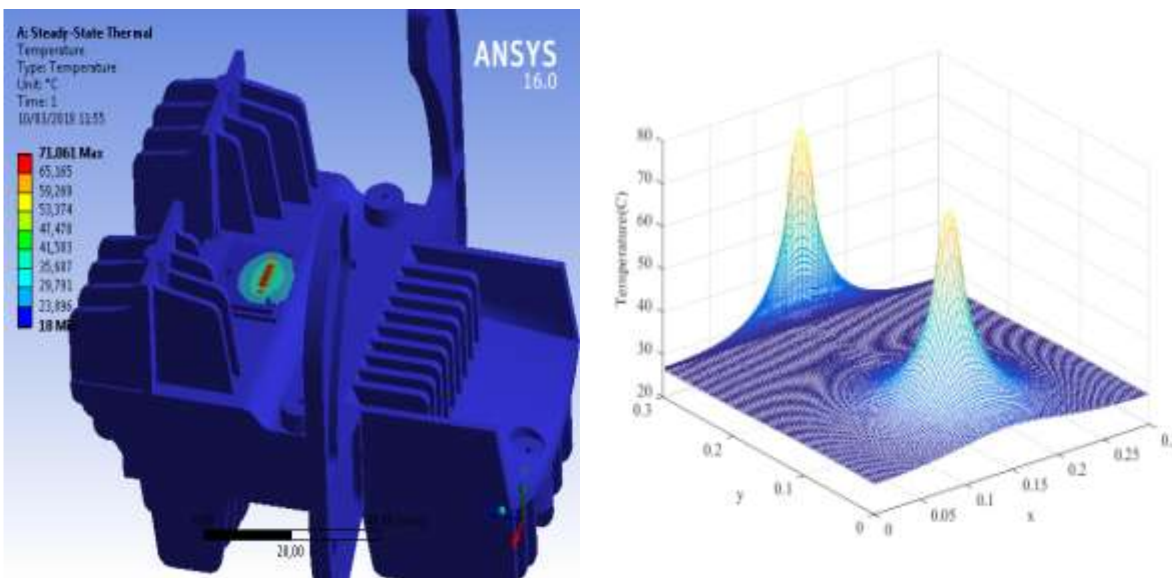
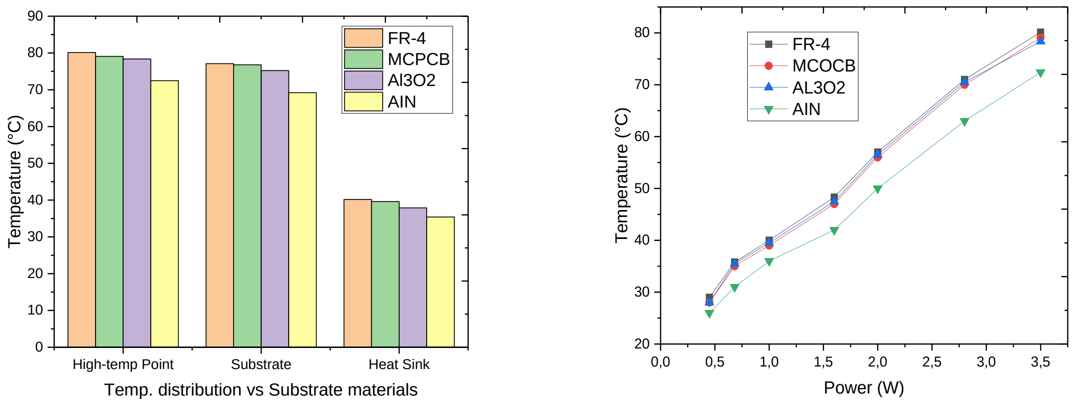


Figure 1:- Simulation for the AIN substrate material by FEA and numerical simulation.



a) b)

Figure 2:- (a) Temperature distribution vs Substrate materials in condition of 700 mA and (b) represent the highest temperature point in different conditions

Figure 2 shows the relationship between several substrate materials with different thermal conductivity and the highest temperature point of the headlamp. In the figure, with the increase of the thermal conductivity of the substrate material, the highest temperature point of the headlamp experiences a decreasing trend.

Table 7:- The temperature distribution of different heat sink materials.

Materials	Cu	Al	6061 Al alloy	6063 Al alloy
Thermal conductivity (W/m·K)	400	237	154	209
High temp point	70.8	80.1	89.1	83.2
Substrate	66.7	74.8	78.9	76.3
Heat sink	47.3	58.2	60.01	61

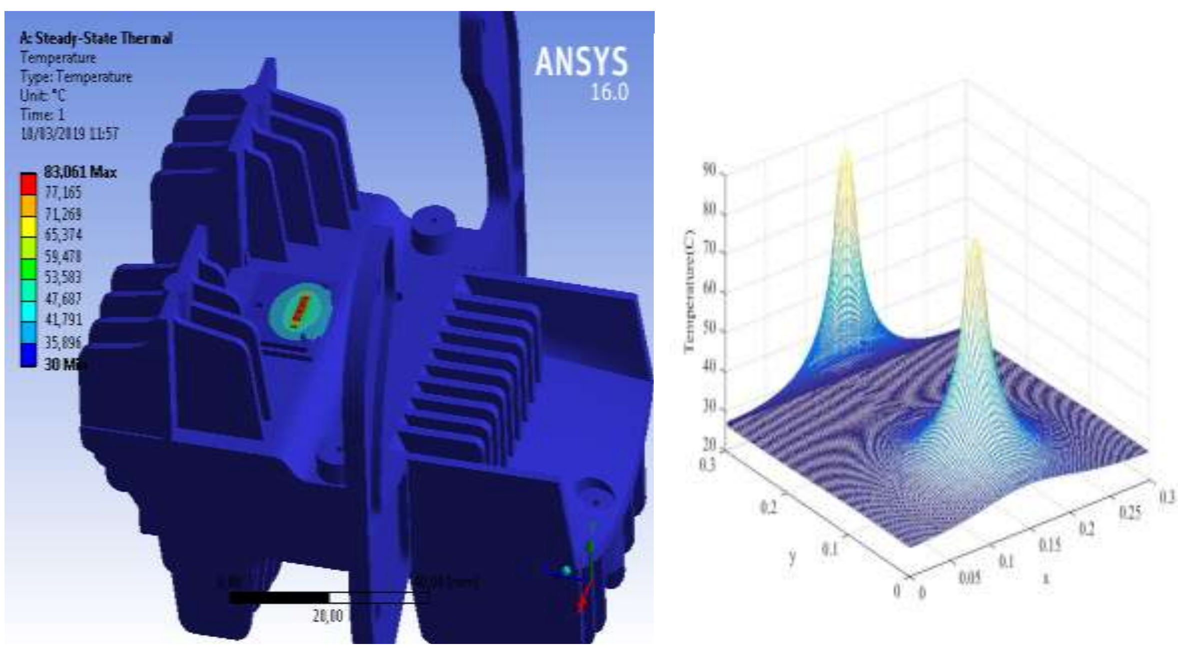
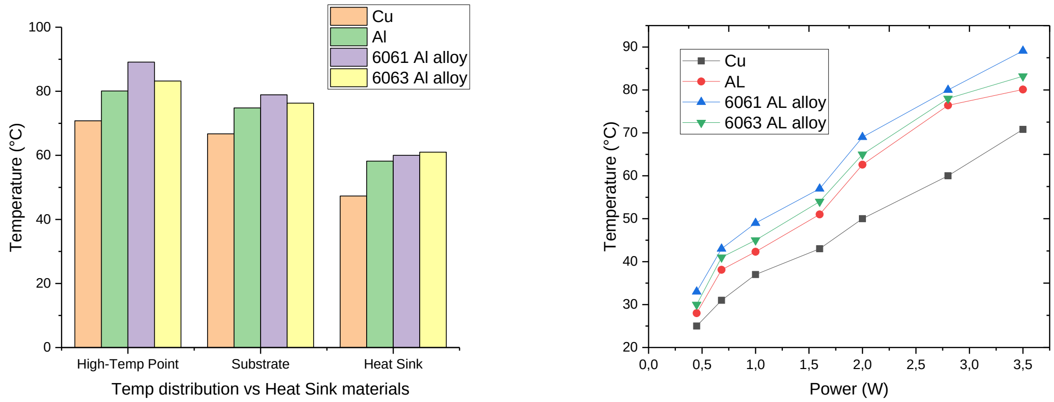


Figure 3:- Simulation for 6063 AL alloy material for heatsink by FEA and numerical simulation.



a) b)

Figure 4:- (a) Temperature distribution vs Heat sink materials at 700mA and (b) represent the highest temperature point under different conditions

Simulating results of the headlamp with different thermal conductivity of the heat sink material shows that the higher the thermal conductivity of the heat sink own, the lower high-temperature point it has. Based on our comprehensive study and research, the selection of 6063 aluminum alloys for heat sink material could be a good choice considering the trade-off between cost, strength, and heat dissipation.

For common heat sink materials, copper has high thermal conductivity, which can achieve up to 400W/m.K at room temperature. While using copper as the base material, LED lights chip junction temperature goes to 70.79℃. Compared with using aluminum as light and heat dissipation-based material, the junction temperature experienced a drop of 9.56 ℃. As the density of copper is three times higher than that of aluminum, the weight of copper-based heat sink with the same structure is three times higher than that of the aluminum-based heat sink. At the same time, the price of copper is higher than aluminum, so aluminum is generally applied as a raw material for the LED heat sink. The hardness of pure aluminum is too low to prepare force-resistant products; therefore, it is not suitable to be taken as a heat sink material. Compared with pure aluminum, aluminum alloys possess better physical properties and a simpler preparation process with a lightweight, which has wide applicability. Considering the aspects of weight and material cost, the copper with high thermal conductivity is used as the material of lamppost, and the aluminum alloy with high thermal conductivity is used as the material for the heat sink base.

Optimization Analysis

A mathematical model is formulated based on the values shown in Table 5 and found the regression Equation in Uncoded Units:

TEMPERATURE = -32.72 + 125.16 fin thickness + 5.813 numb of fin – 37.95 fin thickness*fin thickness – 0.3572 numb of fin*numb of fin – 0.556 fin thickness*numb of fin

The coefficients with one factor represent the effects of that particular factor, while the coefficients with two factors and those with second-order terms represent the interaction between the two factors and the quadratic effects, respectively. The positive sign in front of the terms indicates a synergistic effect, while the negative sign indicates an antagonistic effect. The Analysis of Variance checked the fitness of the model. The model is found to be significant and is presented through the ANOVA table shown in Table 8.

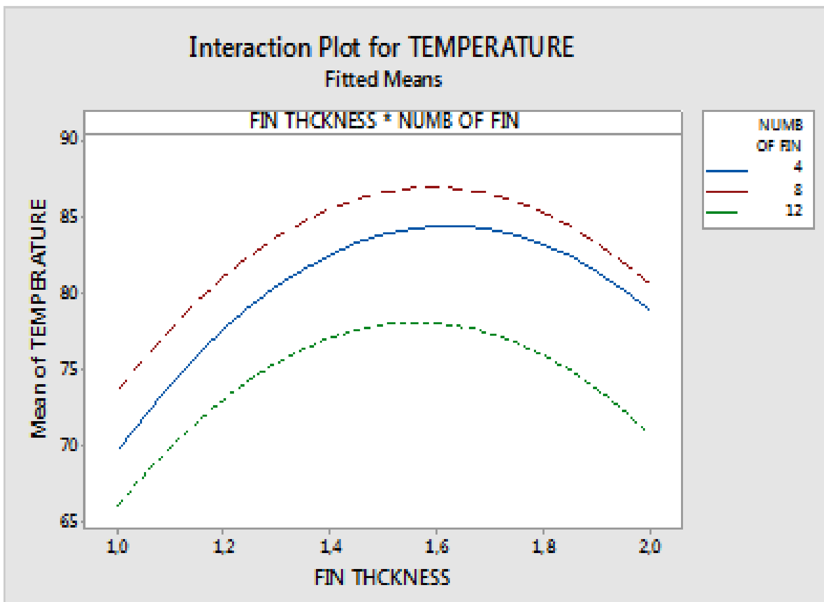
Table 8:- Analysis of Variance table for the Experiment.

Source	DF	SS	MS	F-Value	P-Value
Model	***5***	**332,869**	**66,574**	**119,49**	**0,038**
Linear	***2***	**27,973**	**13,987**	**25,10**	**0,011**
FIN THICKNESS	***1***	**27,421**	**27,421**	**49,22**	**0,020**
NUMB OF FIN	***1***	**11,404**	**11,404**	**20,47**	**0,003**
Square	***2***	**165,782**	**82,891**	**148,78**	**0,000**
FIN THICK*FIN THICK	***1***	**132,214**	**132,214**	**237,30**	**0,000**
NUMB OF FIN*NUMB OF FIN	***1***	**9,202**	**9,202**	**16,52**	**0,005**

2-Way Interaction	1	0,484	0,484	0,87	0,042
FIN THICK*NUMB OF FIN	1	0,484	0,484	0,87	0,012
Error	7	3,900	0,557		
Lack-of-Fit	3	1,900	0,633	1,27	0,028
Pure Error	4	2,000	0,500		
Total	12	336,769			

Table 9:- Regression coefficients of predicted models for the investigated responses and independent effects of factors.

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Constant		86,594	0,547	158,30	0,000	
FIN THICK	6,858	3,429	0,489	7,02	0,020	4,68
NUMB OF FIN	-5,895	-2,947	0,651	-4,52	0,003	2,23
FIN THICK*FIN THICK	-18,975	-9,487	0,616	-15,40	0,000	1,15
NUMB OF FIN*NUMB OF FIN	-11,43	-5,72	1,41	-4,06	0,005	5,20
FIN THICK*NUMB OF FIN	-2,22	-1,11	1,19	-0,93	0,012	8,63



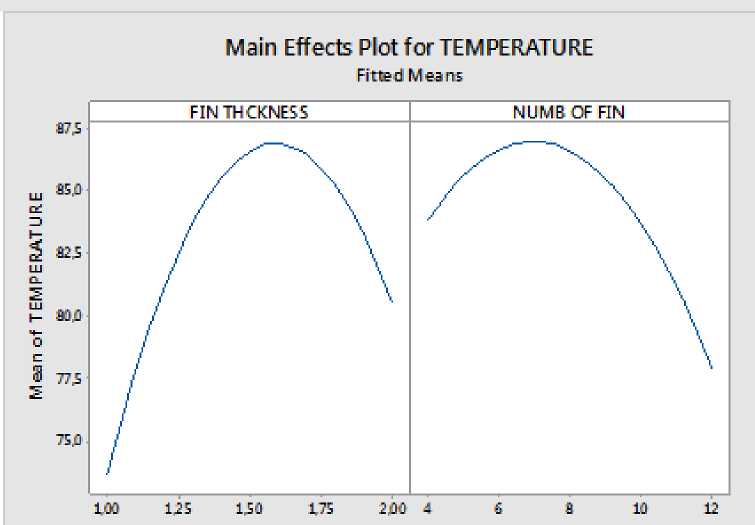


Figure 5:- Interaction of fin thickness and number of fins on temperature.

Figure 5 shows that by using 12 fins with 1 millimeter of thickness, we stabilize the temperature in a comfort zone reducing it by about 10 °C. Table 8 shows the Lack-of-Fitvalue is 0,028, which explains that the model is significant. The interaction of the number of fins and the fin thickness has P = 0.012, we consider it has an effect on the temperature distribution.

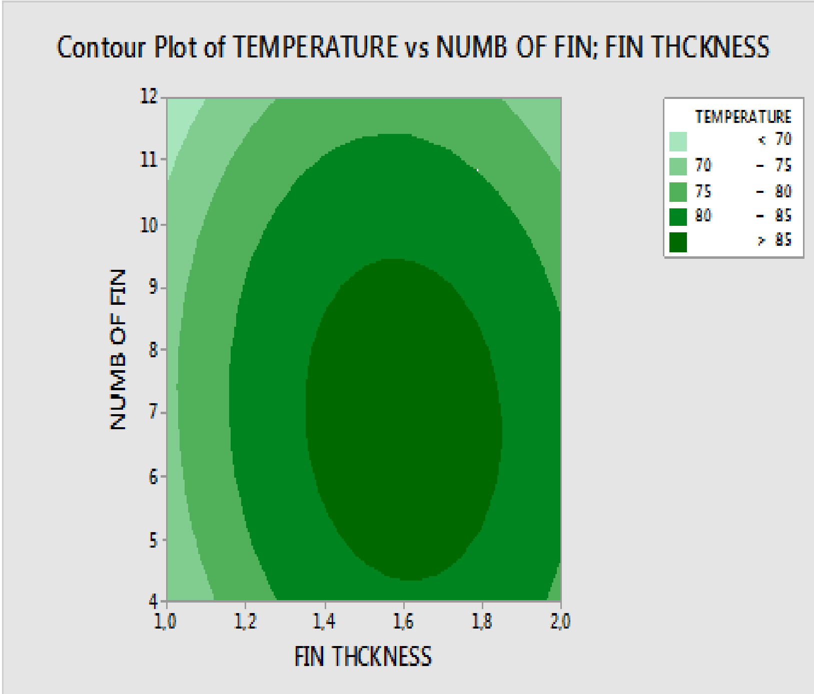


Figure 6:- 2-D contour plot.

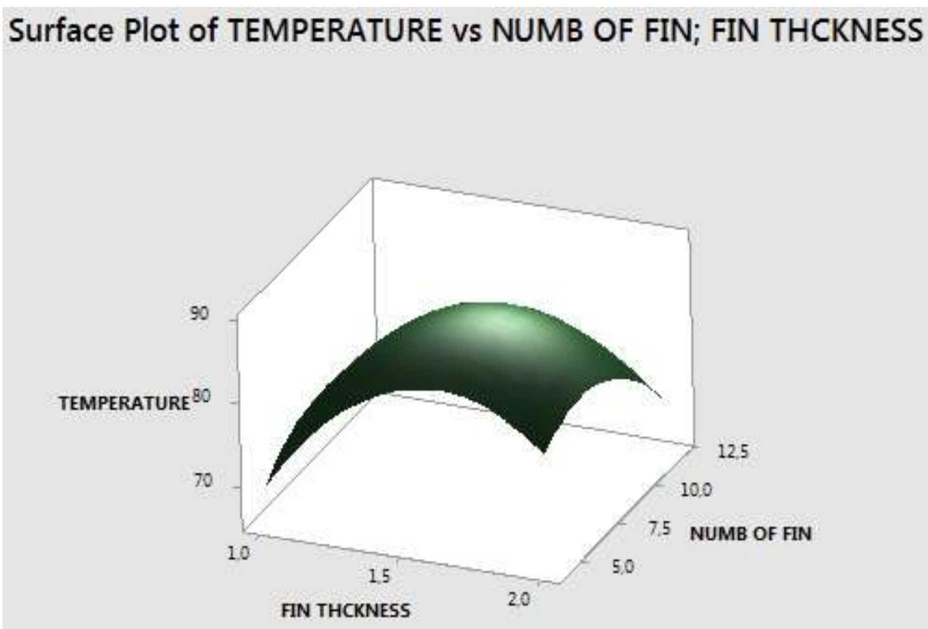


Figure 7:- 3-D surface plot.

Figures 6 and 7 show the 3-D surface and 2-D contour plots, respectively. The response surface and contour plots are the graphical representation of the regression equation used to visualize the relationship between the response and experimental levels of each factor. As shown in these plots, the increased temperature was observed with increasing the fin thickness and the number of fins. However, an increase in both factors beyond the optimum region resulted in a decrease in temperature. By analyzing the two curves, we can easily observe that the zone of comfort, in which the temperature is minimal, is the interaction zone in light green. In this zone, we have a thickness of the fin close to 1 millimeter and the number of fins around 12.

The objective of the study is to find the right combination of the heatsink blades in number and thickness to minimize the temperature of the headlamp. The optimal combination of the influence parameters to reduce the temperature using the response surface method is found, as shown in Table 9. By these results, the heat sink is designed in the best way to minimize the temperature. In table 2, all geometrical dimensions of the heat sink are fixed and decided to vary only the thickness and number of fins. According to our results, the heat sink with 12 fins of 1 millimeter of thickness is designed and manufactured. After that, it is tested to confirm the results.

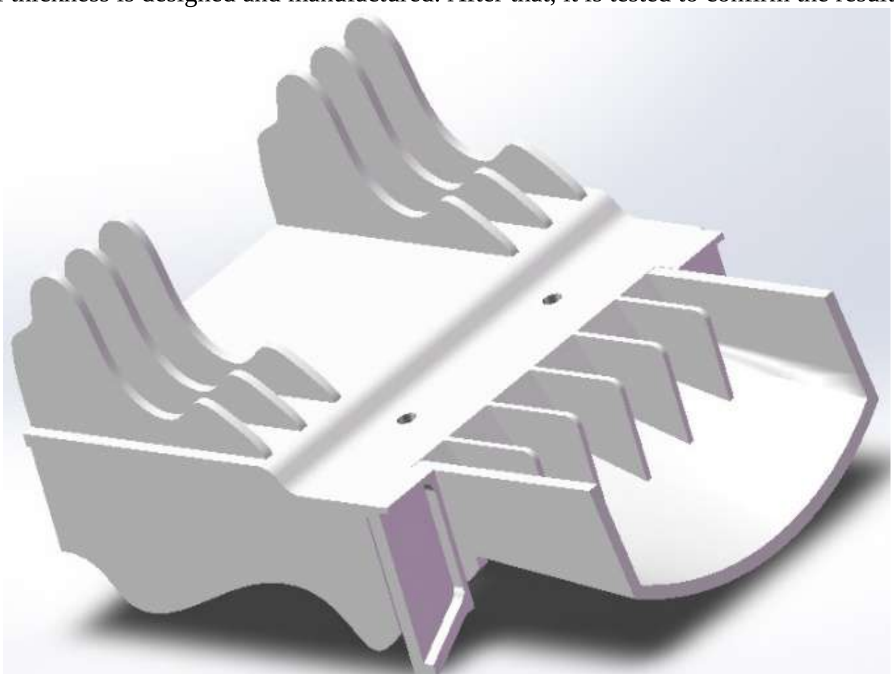


Figure 8:- Optimized heat sink configuration and design.

Experimental thermal testing

The performance of the heat sinks experimentally using the setup shown in Figure 9 was verified. The LED module is mounted on the Aluminum heat sink placed horizontally in a temperature-controlled environment and cooled by natural convection. The thermal imaging camera is placed directly above the package to get a top view of the system. Figure 10 shows the measurement setup and the thermal image of the system. The thermal imager used was the Fluke Thermal Imager, which has a high resolution and an accuracy of ± 0.1% of the reading + 0.5 ^{O}C on non-reflective surfaces. The forward voltage and current measured with the help of digital clamp multimeter.

Each measurement was obtained by first setting the supplied power and recording the temperature, with the interval time of the 1800s. All system reached a steady state in less the half of an hour and then collected the measure. The experimental conditions are the same in cases of the original sample [3]. The variation of the current is If = 100 ~ 700mA. The estimated standard deviation for all measurements is less than 0.5°C. All measurements were obtained for ambient temperatures between 22°C and 24°C.

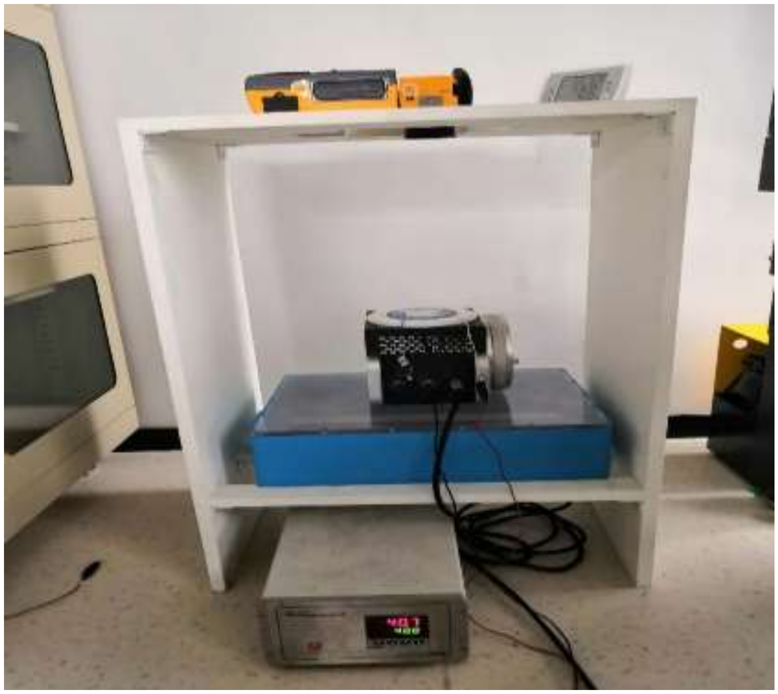


Figure 9:- Experimental setup.

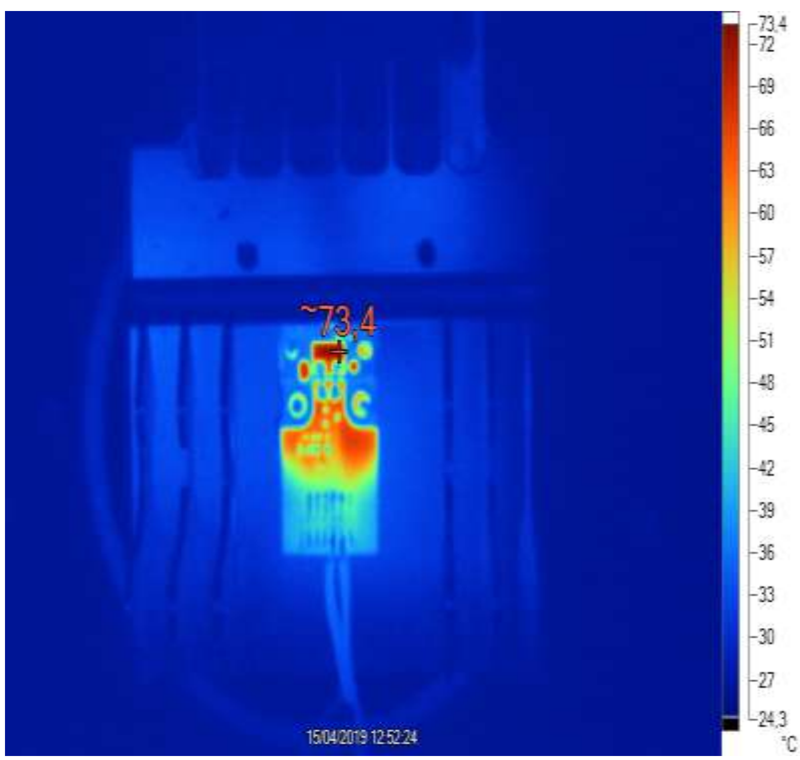


Figure 19:- Heat distribution on the headlamp collected by IR camera in condition 700mA

For the different test conditions, a significant decline in results is found and in each test condition, a drop in temperature from 2 ° C to 8 ° C was observed, which is quite interesting with the simple change of the heatsink by the optimized one. In these tests, the new physical substrate was not use, because it was not manufactured.

To get an idea of the behavior of the new component manufactured, after having tested it under the same conditions as the previous study [3], the results are compared to appreciate the drop in temperature, and therefore the optimization.

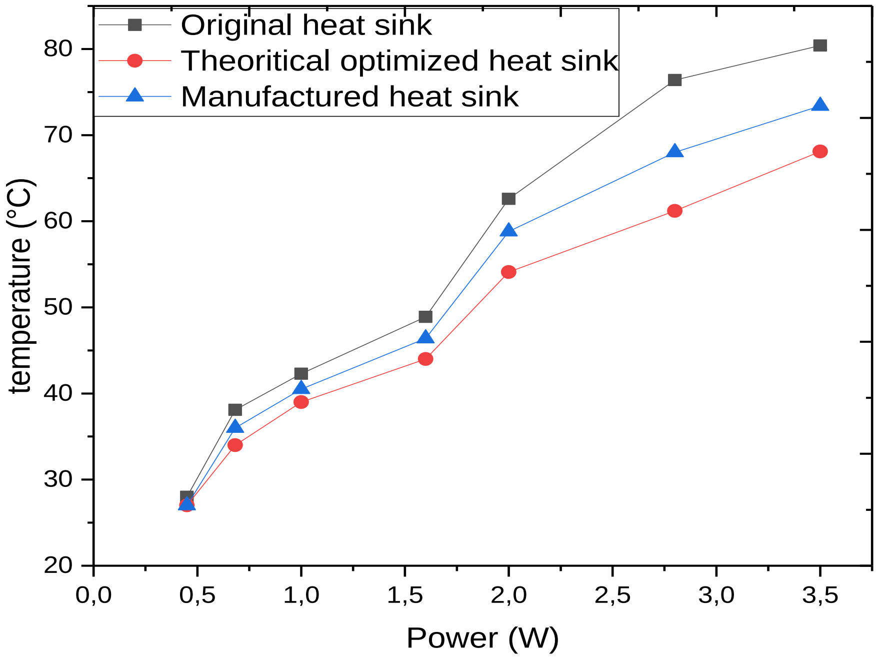


Figure 11:- Comparison of the original sample before optimization, the theoretically optimized heat sink, and the manufactured heat sink.

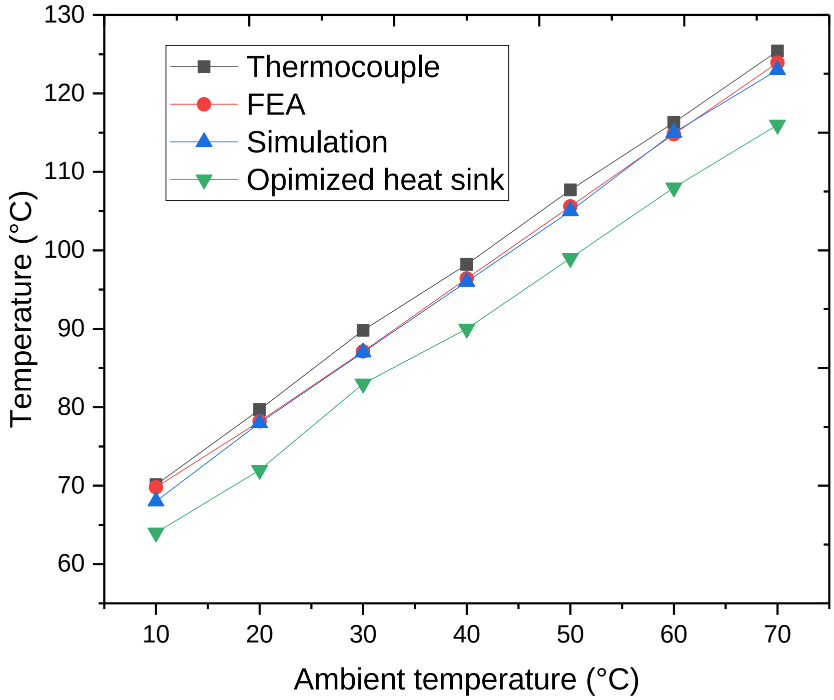


Figure 12:- Comparison of the original and optimized heat sink in different ambient temperature in the condition of 700mA.

Concluding Remarks:-

An optimization scheme for the assembly of high-power LEDs was developed by comparing the effects of different packaging materials such as substrate material, heat sink material, and heat sink design, respectively, through the numerical simulation and FEA. Finally, an AlN ceramic-based board as substrate board and aluminum 6063-T5 as a heat sink base was selected. For the heat sink geometrical optimization, the response surface method was used to find the number of the fins and their thickness. The two factors interaction shows the signification in the design with P-value equal to 0,012 < 0,05. Simulations results indicate that this optimized LED headlamp maximum temperature is only 69 ℃, which is 13, 8 ℃ lower than the LED headlamp before optimization, indicating a great improvement in heat dissipation with a balance between thermal performance and cost.

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Author Contributions:
Moumouni Guero Mohamed conceived, designed, and performed the experiments; Moumouni Guero Mohamed analyzed the data; PRODJINONTO Vincent contributed materials and analysis tools. Moumouni Guero Mohamed authored the paper.

Conflicts of Interest:
The authors declare no conflicts of interest. The sponsors had no role in the design of the study; analyses or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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