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New Optimal Heat Sink Design with Concave Fins for Cooling System in Light Emitting Diode Lamp

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ABSTRACT

The heat sink is considered one of the most critical issues in designing and operating light-emitting diode (LED) lamps. The manufacturers in the technical catalogs indicate the maximum temperature tolerable by LED chips, which causes the light to drop and the color of the lamp output to change when this temperature range is not met. The selection and design of the cooling system usually affect the costs associated with the construction of the heat sink. This paper introduced a new heat sink system incorporating concave fins for the LED lamp cooling system. The numerical method was applied to solve the governing heat balance equations to examine this heat sink's capability. The optimum geometry was determined to achieve minimum electronic chip temperature and heat sink weight at different LED lamp capacities based on the coupled numerical solution of heat transfer and particle swarm optimization (PSO) optimization algorithm. A comprehensive database was created and used as input for genetic planning tools based on two objective optimal solutions for different LED lamp capabilities. Based on genetic programming results, an analytical relation was presented to determine the optimal geometric parameters for LED power. Therefore, it is possible to determine the optimum geometry for a given power without numerical resolution and optimization. The efficiency and volume of sinks are significantly improved in optimal heat sinks with concave fins compared to fixed cross-sections based on the results.

***Index Terms*—**Heat sink, LED, optimized geometry, numerical solution, analytical correlation

I. INTRODUCTION

A light-emitting diode (LED) lamp is a solid-state lamp that uses a diode for illumination. Unlike many misconceptions, LED lamps produce heat, which can adversely affect the performance of the LED due to a lack of thermal management. Heat sink systems commonly use different strategies to maintain an LED electronic chip's temperature in a standard range. The problem affecting heat sinks in LED lamps is the price of materials used and manufacturing costs. Therefore, many studies have been conducted on designing and optimizing the cooling system in LED lamps.

The jet cooling methods with various jet configurations were numerically examined by Lio et al. [1]. The results show that the jet arrangement with a particular inlet and two outlets can improve cooling efficiency. The results show that the LED's maximum temperature with jet cooling was 23 K lower than the LED cooled by the existing empirical cooling arrangement. The thermal characteristics of a LED headlamp module with a new cooling arrangement were analyzed by Jang et al. [2]. An air-circulating cooling arrangement was created for the LED headlamp module. The perfect fluid field modeling and heat transfer investigation using computational fluid dynamics were implemented according to the headlamp's working conditions. The joint temperatures of LEDs were determined to decrease by utilizing the air-cooling method, thus increasing the LED array's heat-dissipating capacity. The improvement in the thermal properties of a high-power LED package by applying a loop heat pipe was conducted by Lu et al. [3]. High-power LED packages' thermal properties are examined, and a new loop heat-pipe cooling equipment is developed for this type of LED. The results indicate that the junction temperature of LED could be examined under 100°C for the heat load of 100 W. Wang et al. [4] show the F.E. model of LED packaging heat loss based on the thermal model of LED packaging and the basis of thermoelectric cooling. Performance parameters were examined in the position of various chip power and various input current of TEC. The optimized parameters of packaging heat loss in different states were investigated by examining the thermoelectric cooling arrangement simulation and the natural convection cooling arrangement without and with

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a heat sink. An active cooling method utilized liquid metal as the coolant as it was suggested for high-power LEDs by Deng et al. [5]. In this research, a series of experiments under different operation conditions were implemented to estimate the liquid metal cooling arrangement's heat dissipation. Results showed that liquid metal cooling was a robust method for the heat loss of high-power LEDs. Anithambigai et al. [6] studied the influence of the dual interface method in the specification of the exact point of separation within the LED package and the board. It was recognized that the junction to board thermal resistance was not concerned. Still, the total thermal resistance from junction to ambient was decreased by 55.6% upon cooling with water. The performance and the reliability of an LED are utterly dependent on the optical characteristics of the device. Kim et al. [7] examined smart heat sinks' thermal characteristics consisting of hybrid pin fins, including inner channels, and combined with fins. In this article, the computational fluid dynamics (CFD) analysis estimates the cooling performance and the thermal operation of the SHSs under different parametric conditions. An individual loop heat pipe with identical condensers is suggested for LED chips by Li et al. [8], and the mechanism of the loop heat pipe is investigated theoretically. In conclusion, a global multipurpose arrangement of the LED lighting device is recommended. Alvardo et al. [9] employed microjet and mini channels cold plates as cooling means for LEDs and implemented entropy generation minimization to optimize the mini channels' geometry. Results show that entropy generation minimization-based objects display low flow resistance, and mini channels cold plates are cost-effective for cooling LED arrays. Chen et al. [10] used ionic wind to increase the heat transfer of an LED on a substrate. The impacts of electrode polarity, aligned angle, separation distance, and ground arrangement on the LED substrate's thermal permanence are considered in this study. It is observed that the impact of the vertical separation distance between the needle/ground electrodes is slightly higher than that of the horizontal separation distance. Costa et al. [11] examined the numerical approach for a particular LED lamp's spiral heat sink. In this study, the circular heat sink is taken from an extruded aluminum bar, and the necessary cooling effect is accomplished using the minimum mass of metal. Hsieh et al. [12] displayed a micro sprays-based cooling method for the thermal control of LEDs and analyzed the effect of cooling in a non-boiling condition. Sufian et al. [13] implemented a thermal analysis of an LED package cooled by coupled piezoelectric fans and examined the transient temperature and LEDs flow. In this research, a couple of fans were vertically located to the LED package in different arrangements and results determine that the best performance was obtained for arrangement B. A cooling system consisting of a cylinder and a spiral heat sink is proposed by Park et al. [14]. Results confirm that a hollow cylinder section improves the thermal performance of the radial heat sink. Ahn et al. [15] suggested a thermal control arrangement for a LED with a heat exchanger module. Conclusions determine that the cooling power demand was decreased by 19.2% compared with the conventionally established LED. Zhao et al. [16] examined the thermal design and examination of the high-power LED automotive headlight cooling equipment. The authors observed an optimal length of conductive heat plates for a provided heat power, and the impact of the chip unit depth on the joint temperature cannot be neglected. The cooling of LED in automotive is examined based on free convection cooling by Sökmen et al. [17]. In this research, the Monte Carlo method is employed as a radiation model, and a novel algorithm is given for creating the optimum fin arrangement. Shin et al. [18] produced a heat sink with the ionic wind utilizing the CFD method. Results reveal that the ionic wind had the best performance when the wire was located near the rear angle, and the number of fins to the fin width ratio had the optimum value of 1. A cooling arrangement consists of a chimney, and Park et al. [19] improve a spiral heat sink. The results display that a chimney set-up increases the cooling effectiveness of a heat sink and decreases an arrangement's mass. In this study, the chimney design is optimized considering the cooling performance. Moon et al. [20] implemented heat pipe to the high-power LED, and for this design, an individual unit cooling fins flat heat pipe with U configuration is developed. In this study, the heat transfer properties of the AFHP with pair condensers have been studied. The LED module's junction temperature was also evaluated within 85°C at 100 W of input power. Young et al. [21] examined the cooling properties of a heat sink for an LED's LED in passenger cars. This study used the experimental and numerical investigation of the heat sink heated at uniform heat fluxes without airflow. Results show that the convective heat transfer coefficient was reduced by improving the heat sink base's heat flux.

The present study aims to achieve a heat sink system with minimum weight to obtain the electronic chip's minimum temperature. The proposed heat sink has concave fins with specific geometrical properties. An interface between COMSOL and MATLAB Software was used to solve the proposed heat sinks' numerical thermal analysis and optimization. For the thermal analysis of the proposed heat sink, the COMSOL software was used for numerical analysis. The heat sink's geometrical dimensions developed in COMSOL software were optimized for different capacities of the LED lamps using PSO algorithm (in MATLAB software) to achieve minimum weight and electronic chip temperature. For evaluating the proposed heat sink, a comparison was made between the heat sink with concave fins and the thermal sinks with fixed sections. Hence, the LED lamp's optimum geometrical characteristics were determined for each specific power, and the optimum geometrical database was used as the input of the genetic programming tool. The genetic programming tool provides analytical relations for the heat sink's optimum geometrical characteristics in terms of the LED lamp's power. The provided relations make finding the optimum geometry for LED lamps independent of numerical resolution.

II. MODELING

A. Definition Section

Light-emitting diode lamps were initially used as red lights inside electronic devices. The low power consumption of LED lamps compared with others, the extremely long life, and new technology for the manufacturing of other colors have expanded these lamps' application in the industry. Light-emitting diode manufacturers in their product catalog list the maximum tolerable LED temperature chips. When this temperature limit is not met, the light drop and the LED lamps' color change occur. On the other hand, inappropriate heat management design causes an increase in the lamp's operating temperature and reduces the lamp's life. Heat sinks are commonly used to manage the produced heat in LED lamps and keep an electronic chip's temperature in the standard range. Since the heat sinks are usually made of aluminum and are relatively expensive, the manufacturers use an optimum thermal management system to save money. However, the operating temperature must be fixed at the standard range to achieve the desired product life, which requires proper scientific design and accurate calculations. In the design of heat sinks, new method is considered that

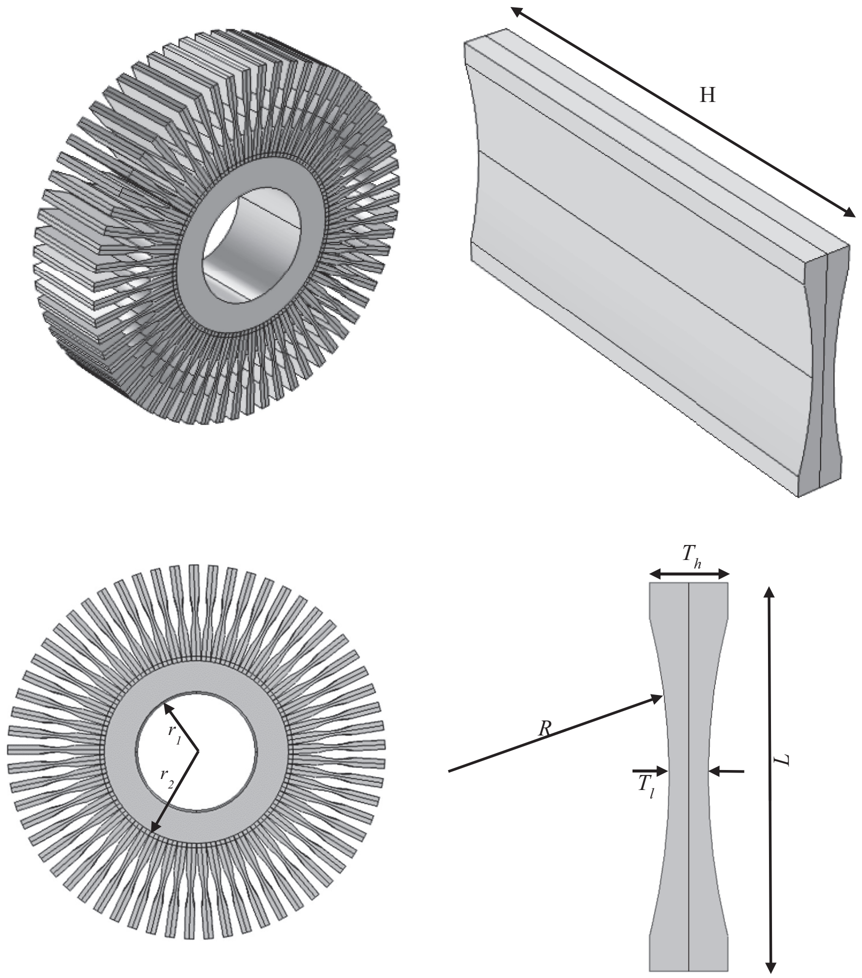

Fig. 1. Schematic view of the proposed heat sink with concave fins.

can provide the maximum external surface in minimum volume. A fin with a convex surface can increase the external surface (for heat transfer purposes) among the existing anteaters without imposing more volume. In this study, a heat sink system, including fins with concave surfaces, was introduced to control LED lamps' temperature. Fig. 1 displays a schematic overview of this heat sink and the geometrical.

The present study aimed to solve the heat transfer equations numerically for different LED lamp power values and provide analytical relations for optimum geometrical properties in terms of LED lamp power.

B. Governing Equations

The overall heat balance equation in the steady-state form for the suggested heat sink can be displayed with the following equation:

$$\rho C_p u.\nabla T - \nabla.\left(k \nabla T\right) = 0 \quad (1)$$

In the above expression, the velocity (u) is zero. It is assumed that the heat generated by the LED lamp enters the heat sink from the inner surface to apply the boundary conditions for the investigated sink.

$$-n.q = P \quad (2)$$

P is the thermal power produced by the LED lamp. It is assumed that the external surfaces of the heat sink transfer the produced heat via free convection. This heat dissipation is displayed using the convective heat transfer coefficient, h, defined with an approximate experimental correlation. These correlations depend on the outside temperature of the heat sink. Thus, the final heat transfer coefficient is defined with the primary surface temperature estimate and an iterative plan between heat transfer coefficient and outside temperature to achieve a converged value. The experimental correlation applied for Nusselt number in the current research is displayed as follows [22]:

$$Nu = \left[\left(0.09112 El^{0.6822}\right)^{-3.5} + \left(0.5170 El^{0.2813}\right)^{-3.5}\right]^{1/3.5} \quad (3)$$

where El is Elenbaas number and defined as follow:

$$El = \frac{g\beta\left(T - T_{amb}\right) Pr w_c^4}{L v^2} \quad (4)$$

where v and β are the kinematic viscosity and volume expansion coefficient of the air. Also, w_c and L are the width and length of the heat sink's channel; g, Pr, T, and Tamb are acceleration of gravity, Prandtl number, fin, and ambient temperature, respectively. The ambient temperature in this study is 25°C.

Based on the above correlation for the Nusselt number, the convective heat transfer coefficient can be calculated as below:

$$h = \frac{Nu \times k}{L} \tag{5}$$

C. PSO Optimization

Achieving a heat sink that can keep the electronic chip's temperature at a minimum point is considered necessary in LED lamps. Thus, this paper's primary objective function is the electronic chip temperature which should be minimized. However, the weight of the material used in the heat sink construction should be considered a limiting factor. The weight directly affects the cost of materials and the manufacturing process. As mentioned before, the following functions were selected as optimization objective functions:

(1) The temperature of the electronic chip should be minimized;
(2) Heat sink volume is designed to be minimized.

The chosen decision variables as the geometrical parameters of the heat sink are shown in Table I. In multi-objective optimization, it is normally unclear what produces an optimal result. A solution may be optimal for one objective function but suboptimal for another [23]. In the current article, a new optimization procedure, multi-objective particle swarm optimization (MOPSO), is employed for the optimization method. The MOPSO is an optimization technique that optimizes goal objectives by iteratively examining to develop a candidate answer about a given degree of quality [24]. This algorithm optimizes the goals by creating a group of candidate solutions named particles and moving them in the search space according to specific equations over the particle's location and velocity. Particle movement is affected by its most common location. Still, it is directed to the most popular spaces in the search space, which are replaced as other particles find the best positions. This is required to run the swarm to the best solutions.

The choice of MOPSO variables has a vital influence on optimization performance. The selection of optimum arrangement from the possible answer required the decision-making method. The method applied in the current paper is linear programming technique for multidimensional analysis of preference (LINMAP) decision-making. In this method, each objective becomes Euclidian non-dimensional, and the equation is established as the length of each particular solution on the Pareto frontier from the ideal unreachable point. Thus, the optimal solution has the shortest length from the ideal inaccessible point [23].

D. Extracting Analytical Relations by Genetic Programming Method

Genetic programming (G.P.) is a biologically stimulated computer training method used for multivariable regression. It makes this by randomly generating a group (population) of machine schedules and next by mutating and moving over the most beneficial accomplishing trees to create a new society. This method is renewed until the population covers methods that (positively) do the task well. Genetic programming consists of different machine program groups named G.P. answers. These answers have a mathematical form and a possible solution to the problem, which can be structured in changing plans like the tree, graph, etc. In this study, the optimal geometry for heat sinks at different LED lamps is defined by two-objective optimization. This comprehensive database of optimized heat sinks at various LED lamp capacities is compiled as genetic planning input. The power of the LED lamp determines the analytical relations of the optimum geometry.

III. DISCUSSION

As mentioned in the previous sections, thermal analysis was done based on the COMSOL software's modeling. Based on the modeling, the temperature distribution in a given case is shown in Fig. 2. The effects of the proposed heat sink's geometrical parameters are shown in Figs. (3-7). Figs. (3-5) show that by increasing the length and width of the proposed fins and outer radius of the heat sink, the mean temperature will decrease significantly and the volume will increase. This is justified by the increase in the external thermal surface and, consequently, the heat transfer rate.

As shown in Fig. 6 and 7, changing the maximum and minimum fin thicknesses has opposite effects on the proposed thermal sink's mean temperature and volume. An increase in the minimum fin thickness leads to a decrease in the mean temperature and an increase in the proposed heat sink volume. However, an increase in the maximum fin thickness leads to a rise in the average temperature and decreased heat sink volume. Because increasing the maximum thickness of fins reduces the number of fins and the heat transfer rate.

As stated in the definition section, multi-objective optimization is used to achieve the optimal design which meets the minimum electronic chip temperature in the minimum volume. The Pareto front for

TABLE I. THE OPTIMIZATION RESULTS IN DIFFERENT POWER AND IMPROVEMENT RATES

	Decision Variables							Improvement	
Power	R	T_e	L	H_L	T_c	r_2	r_2/r_1	Efficiency	Volume
10	0.0143	0.0018	0.0314	0.0372	0.0006	0.0182	1.2344	0.1392	0.9774
15	0.0134	0.0014	0.0309	0.0331	0.0009	0.0184	1.2965	0.2413	0.9536
20	0.0119	0.0015	0.0215	0.0348	0.0010	0.0169	1.2019	0.4276	0.9272
25	0.0191	0.0015	0.0395	0.0367	0.0011	0.0185	1.2071	0.2119	0.9439
30	0.0298	0.0011	0.0142	0.0347	0.0006	0.0177	1.2096	0.2008	0.8838
35	0.0251	0.0015	0.0220	0.0129	0.0006	0.0403	2.8889	0.1235	0.9560
40	0.0234	0.0013	0.0109	0.0301	0.0009	0.0584	1.9472	0.5202	0.7857

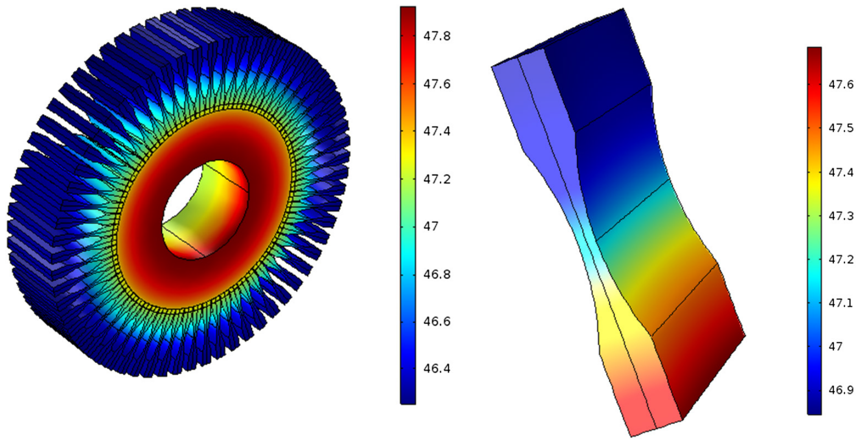

Fig. 2. Temperature distribution in proposed fin and heat sink.

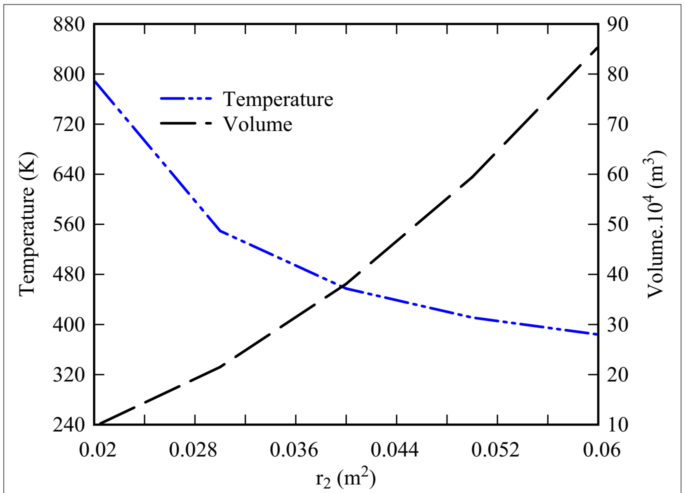

Fig. 3. Effect of heat sink's outer radius on the mean temperature and volume.

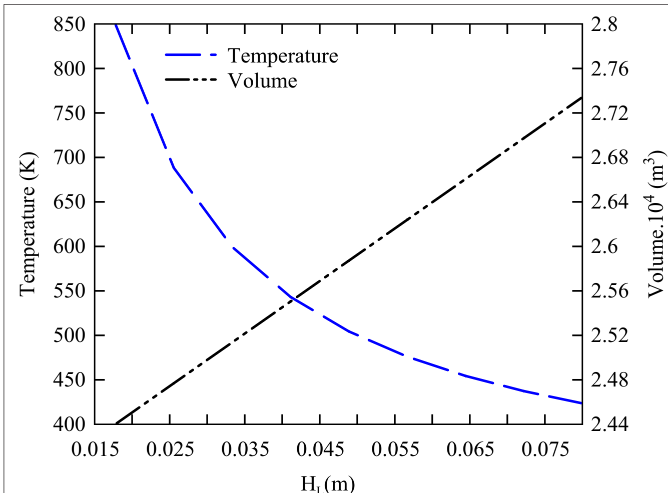

Fig. 5. Effect of fin's width on the mean temperature and volume.

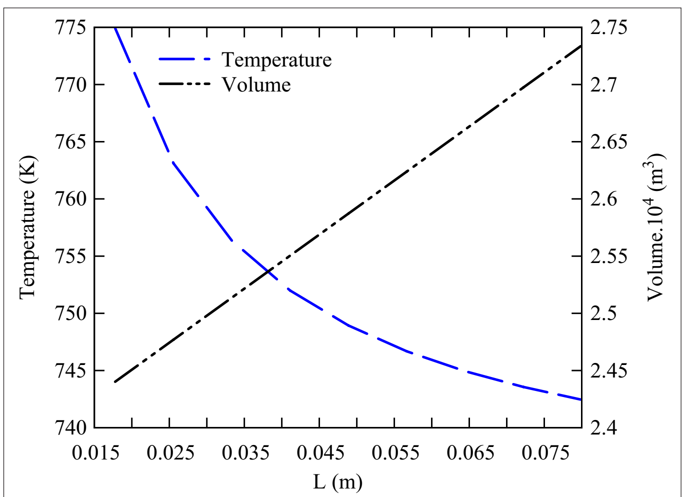

Fig. 4. Effect of fin's length on the mean temperature and volume.

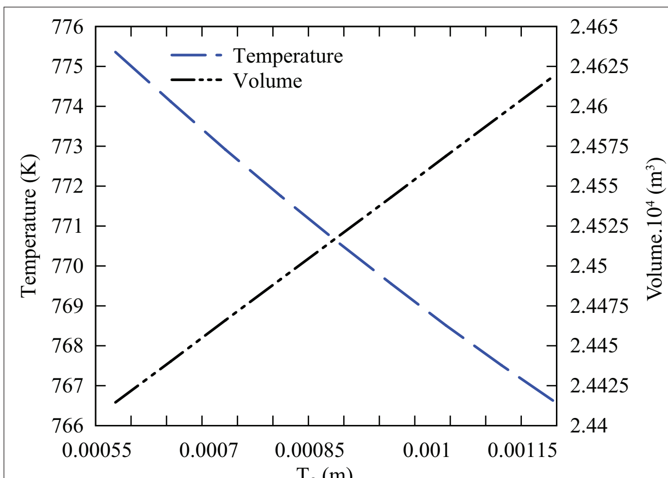

Fig. 6. Effect of fin's minimum thickness on the mean temperature and volume.

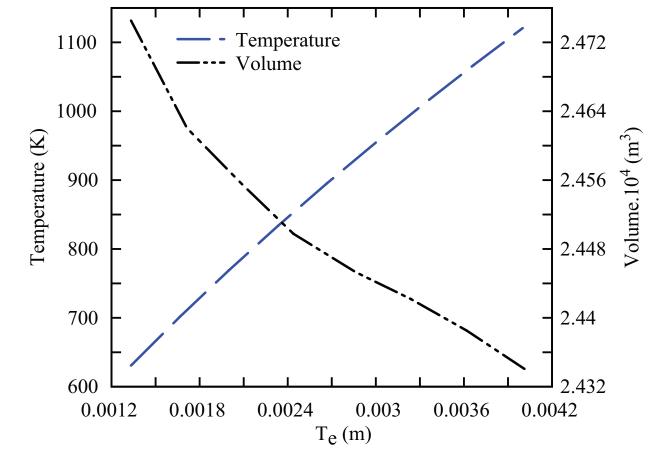

Fig. 7. Effect of fin's maximum thickness on the mean temperature and volume.

multi-objective optimization for several samples (from 45 optimizations) is shown in Fig. 8. According to the decision-making policies, all points on the Pareto front can be selected as the endpoint. As mentioned in the optimization section, a point with the least distance from the ideal unreachable point is chosen as the final optimal point in this paper. Consequently, different optimal geometries are obtained based on the various capacities of the LED lamp. These selected optimal points from the Pareto front as a comprehensive data bank are used as input to the genetic planning tool. An analytical relation is provided to determine the optimum geometry for the LED lamp's desired power. The governed analytical equations for calculating the optimal geometrical parameters at different LED power are described below:

$$R_{opt} = 0.116P_{LED} - 38.38P_{LED}^2 \times exp\left(-P_{LED}\right) + \frac{0.0003182P_{LED}}{P_{LED} - 26.5328} - \frac{43.66P_{LED}}{P_{LED} - 0.3409} + 0.0009537P_{LED}^2 + \frac{43.36P_{LED} - 0.3705}{P_{LED}^2} + \frac{0.1622P_{LED}}{0.3409 - \frac{P_{LED}}{P_{LED} - 34.7392}} + 37.6 \quad (6)$$

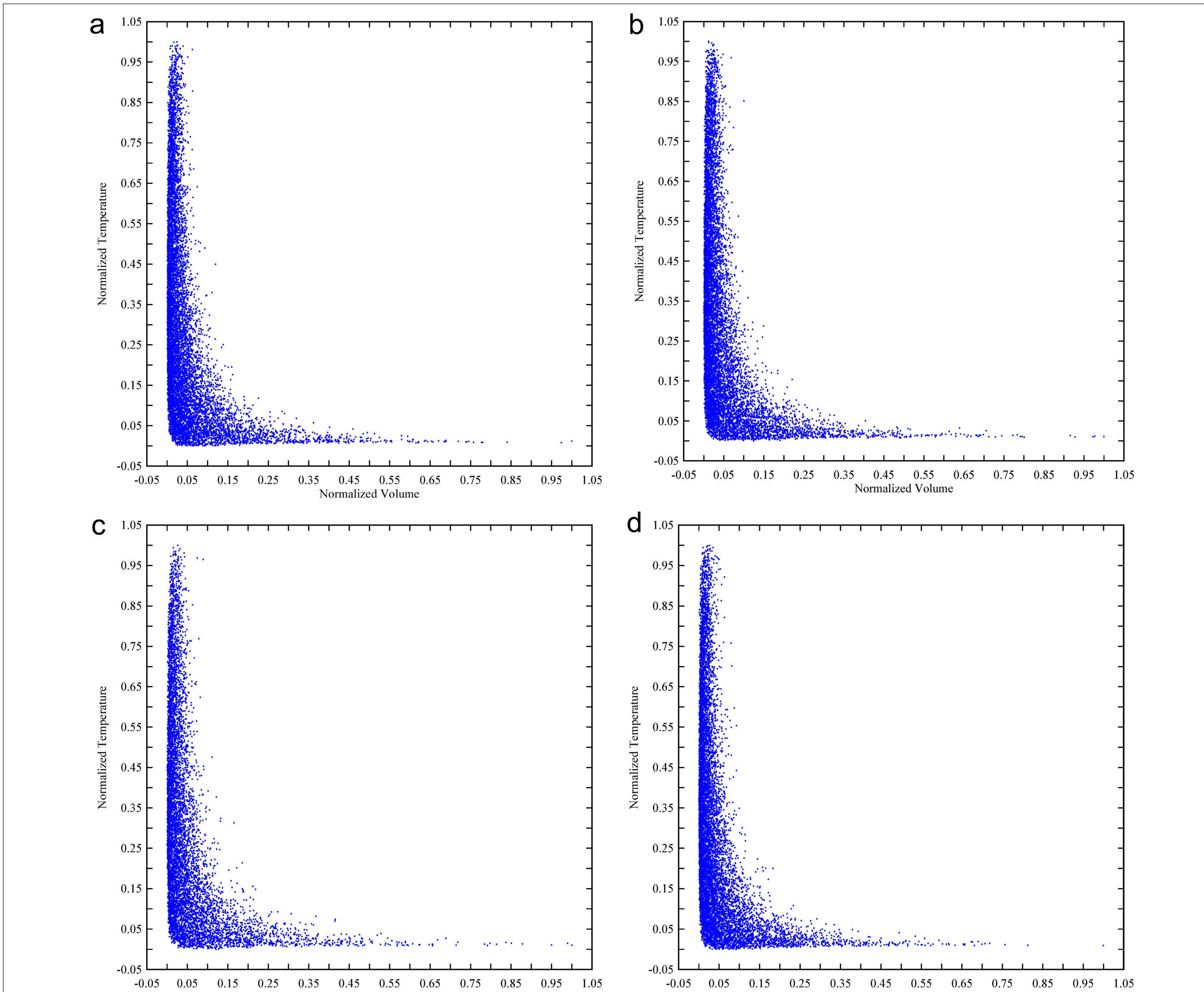

Fig. 8. The Pareto front at different LED power: (A) 15 W, (B) 25 W, (C) 35 W, and (D) 40 W.

$$T_{e,opt} = 0.0007371 P_{LED} + 585.6 \times exp(-P_{LED}) - \frac{0.0001636}{P_{LED} - 29.63} + \frac{0.1716}{P_{LED}} - \frac{8.861}{10^6} P_{LED}^2 - \frac{\frac{2.582 P_{LED} exp(-P_{LED})(P_{LED} + 2.701)(P_{LED} + 0.1089)}{(2000 P_{LED} exp(P_{LED}) - 2000 P_{LED} + 15500}}{10^5 (exp(P_{LED}) - 1)} - 0.0183 \quad (7)$$

$$T_{e,opt} = 0.0007371 P_{LED} + 585.6 \times exp(-P_{LED}) - \frac{0.0001636}{P_{LED} - 29.63} + \frac{0.1716}{P_{LED}} - \frac{8.861}{10^6} P_{LED}^2 - \frac{\frac{2.582 P_{LED} exp(-P_{LED})(P_{LED} + 2.701)(P_{LED} + 0.1089)}{(2000 P_{LED} exp(P_{LED}) - 2000 P_{LED} + 15500}}{10^5 (exp(P_{LED}) - 1)} - 0.0183 \quad (8)$$

$$L_{opt} = 0.01325 P_{LED}^2 - \frac{6.73 P_{LED} + 6.73 exp(0.1007 P_{LED}) + \frac{19.98}{P_{LED}} - 17.1}{2 P_{LED} + \frac{12.34}{P_{LED}} + 0.8301} - \frac{18.96}{P_{LED} - 7.437} - \frac{128.3}{P_{LED}} - 0.8112 P_{LED} + \frac{3.317 P_{LED}^2 (exp(1) + exp(0.384 P_{LED}))(P_{LED} - exp(1.034 - 1.034 P_{LED}))}{exp(1) - P_{LED} + exp(P_{LED} + 0.000184)} + 22.83 \quad (9)$$

$$H_{L,opt} = 0.004973 exp(0.1425 P_{LED}) - 0.5069 P_{LED} + 2.663 exp\left(exp\left(P_{LED}^2 exp(-P_{LED})(P_{LED} - 3.076)\right)\right) - \frac{35.09}{P_{LED}} + 0.01666 P_{LED}^2 - 0.0002167 P_{LED}^3 - 0.3286 \quad (10)$$

$$T_{c,opt} = 0.03567 P_{LED} exp(-0.0007227 P_{LED}^2) - 0.9634 exp(0.0003621 P_{LED}^2) - 0.05585 P_{LED} + \frac{0.0006208}{0.2523 P_{LED} + 0.2368} - \frac{0.5544 P_{LED}}{exp(P_{LED}) + 344.8} - \frac{0.04506}{P_{LED}} - \frac{2.39}{P_{LED}^2} + 0.001501 P_{LED}^2 - \frac{3.602}{exp(P_{LED}) + 344.8} + 1.105 \quad (11)$$

$$r_{2,opt} = 9.663 P_{LED} + 895.3 exp\left(-\frac{9.214}{P_{LED}}\right) - \frac{7.951 P_{LED}^2}{P_{LED} - 5.266} + \frac{3151 exp\left(exp\left(-\frac{5.949}{P_{LED}}\right)\right)}{P_{LED} + 6.459} + \frac{3435}{P_{LED}} - 0.01127 P_{LED}^2 - 959.7 \quad (12)$$

$$\left(\frac{r_2}{r_1}\right)_{ratio} = 0.0268 P_{LED} - 1525 exp\left(\frac{1}{P_{LED}}\right) - \frac{26.4 \exp(P_{LED})}{\exp(1.076 P_{LED}) - \frac{\exp(1)}{2}} - 106.6 P_{LED}^2 \exp(-P_{LED}) + \frac{1792}{P_{LED}} + 1520 \quad (13)$$

Table I shows the results of the optimum points for some capabilities of the LED lamp. The last two columns of the table indicate an increase in efficiency and a decrease in the proposed heat sink volume compared to the sinks with fixed-section fins. It should be noted that the efficiency in the base model is about 0.32, and in the table, the improvement rate compared to this value is listed. In fact, in Table I, using analytical correlations without the need for optimization, the power of the LED lamp has been entered into analytical formulas (based on optimization results), and optimal geometrical variables for thermal wells have been obtained.

IV. CONCLUSION

The present paper presents an analytical formulation to determine a heat sink's optimum geometry with concave fins for LED lamp use. Accordingly, the heat sink's optimum geometry was determined for different capacities of the LED lamp using the numerical and coupled solution with COMSOL and MATLAB software. The optimization MOPSO method was used to minimize the electronic chip's surface temperature and the volume of the thermal sink. Finally, with the database of optimal points and the genetic planning tool, the analytical relations were created to calculate the optimum geometry at the arbitrary power of the LED lamp. Using these analytical equations, the heat sink's optimal geometry can be determined without any numerical solution and optimization. The results indicated that new fins increased efficiency and improved the heat sink volume compared to the heat sink with fixed cross-sections. Based on the results, increasing the outer radius of the proposed heat sink and the fins' length and width reduces the electronic chip's temperature significantly and increases the volume. Further, the minimum and maximum thicknesses have opposite effects on the objective functions; one decreases the temperature and increases the volume and vice versa.

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Nomenclature

General			
C_p	Specific Heat Capacity	T_c	Minimum Thickness of Fins
El	Elenbaas Number	T_e	Maximum Thickness of Fins
K	Thermal Conductivity	***U***	Velocity
L	Length of Heat Sink's Channel	w_c	Width of Heat Sink's Channel
Nu	Nusselt Number	Greek Letters	

P	Power Produced by the LED Lamp	β	Volume Expansion Coefficient
Pr	Prandtl number	ρ	Density
q	Heat rate	ν	Kinematic viscosity
R	Radius ratio	Subscripts	
R^2	Outer radius of heat sink	opt	Optimum
T	Temperature	amb	Ambient

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