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Research Article

The Study for Saving Energy and Optimization of LED Street Light Heat Sink Design

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LED lamps are characterized by high energy efficiency, high luminance, and long lifespans. However, the heat radiation problem caused by the extra high power shortens the lifespan and reduces the luminous efficiency of such lamps. This study introduced the development of a novel cooling fin structure for LED lamps and compared its performance with those of commercially available products. The objective of the design was to reduce the maximum temperature and temperature difference on the fin, the amount of aluminum required for fin manufacturing, and CO_2 emissions to save energy. The study employed the Taguchi method for experiment planning and used gray relational analysis and principal component analysis to determine the optimal parameter combination for cooling fins. The results showed that the maximum temperature on the fin surface dropped by 2.62°C in environments without forced convection, which indicated improved lighting efficiency. Furthermore, the amount of aluminum used per unit volume for fins was reduced by 15%, which effectively reduced CO_2 emissions during the manufacturing process.

1. Introduction

Light-emitting diodes (LEDs) have been widely used in recent years. Because LED-based lighting sources have the advantages of high luminous efficacy, a long lifespan and do not contain mercury, they have attracted people's attention. Before related regulations were implemented, many manufacturers developed LED-based street lights that received an encouraging response from the emerging market; however, numerous problems have been identified in these lights and remain to be solved, such as heat dissipation problems caused by high power, illumination-related legislation, mechanisms and optical design for light sources, the new requirement for power saving, and high prices. Therefore, the research and development of a low-cost and high-efficiency heat dissipation system can expedite the development of the market for LED illumination, promote LED applications, and achieve the goal of reducing energy consumption and carbon emission.

As shown in Figure 1, the junction temperature of the LED light analyzed in this study was inversely proportional to light output efficiency. As the junction temperature increased from room temperature to 100°C, the light output gradually decreased, resulting in light-induced degradation. Regarding lifespan, when the junction temperature reached approximately 70°C, the lifespan of the LED street light degraded by 75%. Therefore, to enable the light source of an LED street light to achieve optimal performance, the design of fin heat sinks for LED street lights is vital for the improvement of light output efficiency and lifespan extension.

The heat dissipation problem is one of the problems at the LED design. In this study we proposed a design method to replace fins for LED street lights. To be compared between the commercial fins and novel fins. The primary material comprising fin heat sinks for street lights is aluminum alloy, the production process of which typically emits a substantial amount of CO_2. According to the statistics, producing 1 kg of aluminum yields 10.233 kg of CO_2. Therefore, the effective

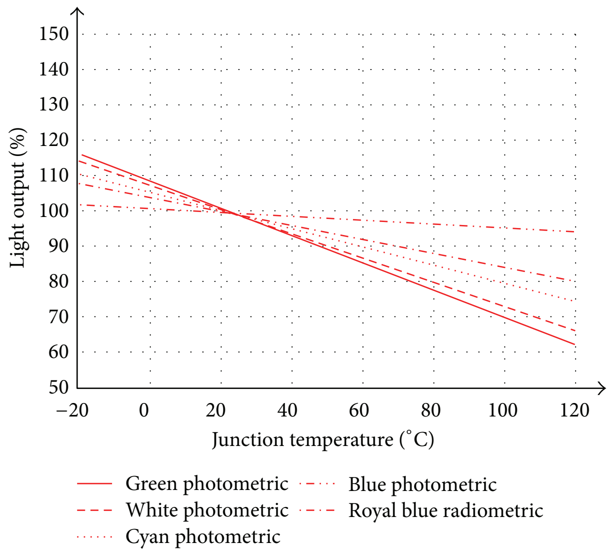

Figure 1: Relationship between the LED junction temperature and light output.

reduction of aluminum in fin heat sinks can reduce the emission of CO_2 and the weight of the fin heat sinks.

2. Literature Review

Numerous parameters may influence the heat dissipation effect of fin heat sinks. Kim et al. [1] compared plate-fin and pin-fin heat sinks and determined that the heat dissipation performance of plate-fin heat sinks was superior to that of pin-fin heat sinks when wind velocity was high and the fins were short. Conversely, with low wind velocity and long fins, the pin-fin heat sinks exhibited superior heat dissipation performance compared with that of the plate-fin heat sinks. Sahiti et al. [2] compared the performance of airfoil-shaped streamline fins developed by the National Advisory Committee for Aeronautics and drop-shaped fins with that of elliptic, circular, and square pin fins under various conditions. And Chang and Lees [3] show a novel compound heat transfer enhancement (HTE) measure. It combines deepened scales and pin-fin array to strengthen cooling. Moreover, because of the trend of product weight reduction, numerous studies have investigated designs for the weight reduction of fin heat sinks such as hollow or perforated fin heat sinks. Tony Tan et al. [4] present hollow geometry introduced inside the rectangular fins and used three kinds of hollow geometries (circular, rectangular, and trapezoidal). The results show that the "hollowed" fins have better heat dissipation efficiency compared to the solid fins. And Elshafei [5] compared solid and hollow circular pin fins and investigated the influence of the thickness of hollow pin fins on the temperature difference among the fins. The result revealed that the hollow pin fins exhibited a comparatively small temperature difference and light weight, compared with that of the solid pin fins. Additionally, as the thickness of the hollow pin fins increased, the temperature difference decreased. In recent years, the design optimization of quality characteristics has become required in the field of engineering. Sahin et al. [6, 7] applied the Taguchi method to design perforated rectangular and circular fin heat sinks, which achieved optimal heat dissipation performance. They reported that the heat dissipation efficiency was influenced the most by wind velocity, followed by the fin height and fin spacing.

3. Experimental Design and Operation

A lighting test was first conducted on the sample to measure the temperature distribution among the fins and the highest temperature of the fins. Subsequently, a computer-aided simulation was conducted by using ANSYS software; the simulation result was compared with the actual measurement result to confirm that the errors in the simulation result were within the tolerance range. Therefore, the new fin heat sink was further simulated. The LED light source used as a reference sample comprised 50 Cree XLamp XR-E LEDs (2.5 W/diode). The material of the fin heat sink was A6061 aluminum alloy; the heat transfer coefficient was 0.154×10^{-3} W/mm°C. Because the fin heat sink was symmetrical, only half of the heat sink was used in the simulation to reduce the calculation time. The reference sample and simulation result were compared. The highest and lowest temperature of the base of the sample heat sink were 47.8°C and 36.8°C, respectively, whereas those of the heat sink base in the simulation were 45.7°C and 36.7°C, respectively. The errors between the two results regarding the highest and lowest temperature were 4.4% and 0.3%, which were within the tolerance range of 5%. In addition, based on the room temperature at 24°C and outdoor temperature at 22°C, the heat transfer coefficient (h) for the indoor environment was 10×10^{-6} W/mm°C and that for the outdoor environment was 25×10^{-6} W/mm°C. In addition, the total surface area and the material weight of the reference sample were 138 000 mm^2 and 921.3 g, respectively. The amount of CO_2 generated from the production of fins was 9.4 kg.

4. Design of a Novel Fin Heat Sink for Street Lights

4.1. Type Area Simulation Parameters for the Model of Street Light. The power consumption of the reference sample street light was 125 W, which was low compared with other types of street lights. To expand the application range of the newly designed fin heat sink, the power consumption was increased to 180 W in the design of the new fin heat sink. Specifically, various wattages were applied to the reference sample for the simulation, and the results were compared. When the power consumption of the reference sample was 125 W, the highest temperature of the fins was 45.6°C. When the power consumption was increased to 180 W, the highest temperature increased to 55.1°C (increasing by 9.5°C)

4.2. Optimization Analysis of the New Fin Heat Sink. In this section, the influence of numerous parameters on the heat dissipation performance of the fin heat sink is examined.

Table 1: Parameter and parameter levels of the novel fin heat sink.

Control parameters	Parameter levels			
	Level 1	Level 2	Level 3	Level 4
Fin type	Rectangular plate	Trapezoidal plate	Square pin	Circular pin
Fin spacing (mm)	10	14	—	—
Fin arrangement	Parallel	Staggered	—	—
Fin height (mm)	40	50	—	—
Thickness of heat sink base (mm)	5	10	—	—

Table 2: Performance comparison between the new hollow fin heat sink and reference sample.

Performance	Fin heat sinks		
	Reference sample	Novel hollow fin heat sink	Gains
Highest temperature in an outdoor environment (°C)	40.1	37.5	Decreased by 6.5%
Total surface area (mm^2)	138000	313270	Increased by 127%
Material weight (g)	921.3	782.4	Decreased by 15%
The amount of CO_2 emission (kg)	9.4	8	Decreased by 15%

Adequate parameter levels were determined for analysis. An excessive number of design parameters for fin heat sinks could have caused the experiment to be complicated and time consuming. Therefore, in this study, the fin length and thickness were fixed and integrated with fin shape to produce a newly designed parameter. In the experiment, five parameters were used as control factors: fin type, fin spacing, fin arrangement, fin height, and the thickness of the heat sink base. The parameters and parameter levels are listed in Table 1. And we fixed the fin length and thickness. This is because we want to keep the fins area and volume of distribution. This is related to two objectives of this paper, to reduce material and production costs. The experiment for the design optimization of the new fin heat sink involved a total of five parameters. Except for the fin type, which was a four-level parameter, the other parameters comprised only two levels. In addition, an interaction effect existed among the parameters. Therefore, L_{32} and L_9 were used as the inner and outer orthogonal arrays, respectively, for the optimization experiment. After the optimization analysis, the new fin heat sink produced based on the optimal combination of parameter levels was compared with the reference sample. According to the comparison result, the highest temperature of the new fin heat sink was 1.4°C lower than that of the reference sample. However, the production of new fins required an additional 770.3 g of aluminum alloy, resulting in an additional 7.9 kg of emitted CO_2.

4.3. Optimization Analysis of the Novel Hollow Heat Sink. To optimize the efficiency of the novel fin heat sink and reduce the amount of aluminum used, optimization was conducted for a second time to improve the structure of the first novel fin heat sink developed. Specifically, the structures of the four types of fins applied to the first fin heat sink were modified, as shown in Figure 2. By adopting a hollow structure, the amount of materials used to produce a single fin decreased, and the exposure of the fin to the air increased. Additionally, the thickness of the heat sink base was adjusted from 5 mm to 3 mm and from 10 mm to 5 mm. By performing optimization analysis for a second time, a hollow fin heat sink was produced based on the optimal combination of parameter levels and was compared with the reference sample; the comparison result is summarized in Table 2. The highest temperature of the new hollow fin heat sink was 2.6°C lower than that of the reference sample. The amount of aluminum material used for producing the hollow fin heat sink was 138.9 g less than that used for the reference sample, resulting in a reduction of 1.4 kg in CO_2 emission during the production of fins.

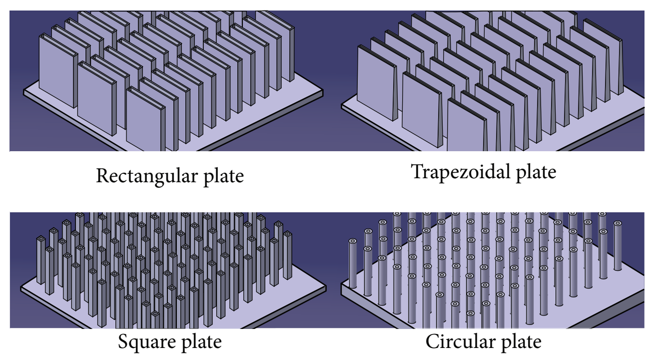

Figure 2: Types of hollow fin heat sinks.

4.4. Examination of Hollow Fin Thickness. The new hollow fin heat sink successfully achieved cost reduction and the improvement of heat dissipation efficiency; the achievement can be mainly attributed to the hollow structure of the fins. Because of the hollow structure, the contact area of the fins with the air increased, and the amount of material used to produce the fins decreased, leading to a reduction in cost and fin weight. The optimization analysis used in this study revealed that the heat dissipation performance of the hollow fin heat sink was superior to that of the solid fin heat sink. This

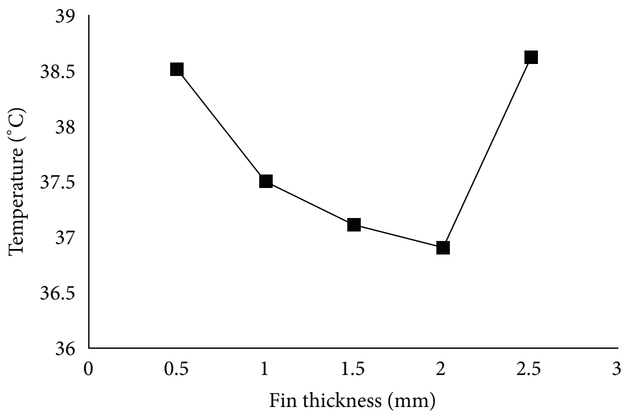

Figure 3: Relationship between the thickness of hollow fins and the highest temperature of the fins.

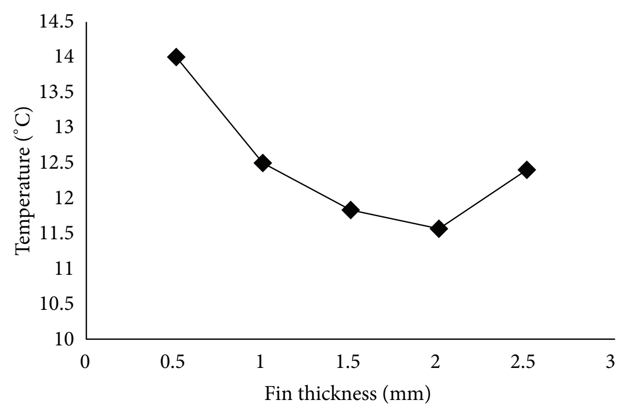

Figure 4: Relationship between the thickness of hollow fins and the temperature difference among fins.

section provides a discussion on the thickness of the hollow fins.

This study targeted a rectangular plate-fin heat sink. The width of the fins was set at 5 mm; therefore, the thickness of the hollow fins was set at 0.5 mm, 1 mm, 1.5 mm, 2 mm, and 2.5 mm (i.e., the thickness of the solid fins). Heat-flow analysis was conducted in an outdoor environment; the influences of the various levels of fin thickness on quality characteristics were compared. Thus, the optimal thickness of the hollow fins was obtained. According to Figures 3 and 4, the highest temperature and the temperature difference exhibited by the hollow fins were both lower than that exhibited by the solid fins. The lowest values were achieved when the fin thickness was 2 mm. Regarding the temperature difference, when the fin thickness was greater than 1 mm, the total volume of the hollow fins exceeded that of the reference sample. Therefore, the analysis of hollow fin thickness verified that optimal performance can be achieved when the fin thickness is 1 mm. In other words, the hollow fin heat sink possessed the advantages of satisfactory heat dissipation performance and low production cost.

5. Conclusion

The purpose of this study was to develop a robust design for fin heat sinks based on existing fin heat sinks used for LED street lights. By reducing the highest temperature of the fins, the temperature difference among the fins, the use of aluminum materials, and the emission of CO_2, the goal of reducing carbon emission and energy can be achieved. By conducting optimization analysis twice, the following conclusions were derived.

(a) The significant control factors that influenced multiple quality characteristics of the fin heat sinks were fin type, the thickness of the heat sink base, and fin spacing, ordered in a descending sequence from high to low degrees of influence. The total contribution rate was 92.45%. Furthermore, fin type had a contribution rate of 57.87% and, therefore, was the most influential control factor. The optimal parameter for novel fin heat sink: hollow rectangular plate, thickness of the heat sink base is 5 mm, fin arrangement is staggered, fin height is 50 mm, and fin spacing is 10 mm.

(b) The verification experiment revealed that the predicted values and the experimental values obtained by optimizing the grey relational grade twice were similar. All the experimental values of the grey relational grade were within the 95% confidence interval, demonstrating that the experiment was successful and reliable.

(c) The novel hollow fin heat sink produced after performing optimization analysis twice was compared with the reference sample in an outdoor environment. According to the comparison result, the highest temperature, the amount of aluminum usage, and the amount of CO_2 emission in the production of the new hollow fin heat sink were 2.62°C, 138.9 g, and 1.4 kg, respectively, all of which were lower than those of the reference sample. Additionally, the difficulty of producing the new fin heat sink decreased because of its simple appearance.

(d) When the novel hollow fin heat sink was applied to a 180 W street light, the highest temperature of the fins was 46.8°C, which was lower than the highest temperature exhibited by the reference sample applied to a 125 W street light (48.3°C). Therefore, the novel hollow fin heat sink designed in this study can be applied to an LED light source with high wattage.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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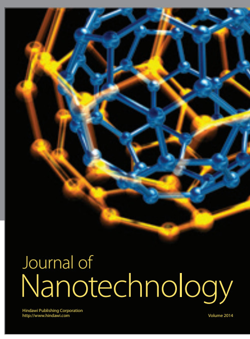

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