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Heat Analysis and Optimal Design of Heat Sink of LED Fish Aggregation Lamp

Chen Shengxiong[1,2] and Zhu Daqing[1,2*]

[1]College of Information Science and Engineering, Huaqiao University, Xiamen 361021, China
[2]Fujian Key Laboratory of Light Propagation and Transformation, Xiamen 361021, China

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A LED fish aggregation lamp is important equipment in the fishing industry, and it plays a role in attracting and gathering fish. To enhance the overall cooling performance of the lamp, reduce the chip temperature and the heat sink mass, and increase the lifetime of the lamp, we design and optimize the heat sink structure. The computational fluid dynamics (CFD) method is used to simulate the heat transfer performance of the heat sink, and three types of heat sink are analyzed. The results show that heat sink III is the most ideal. Then, an orthogonal experimental design (with four factors and four levels) is used to study the effects of the length, thickness, and spacing of the fins and the semicylinder spacing (four factors) on the cooling performance of the heat sink. When only the chip temperature is considered, the test data show that the optimal level combination is $A4B4C2D4$ (A, B, C, and D are four factors, and the numbers are the levels of each factor). When both the chip temperature and the heat sink mass are considered, the optimal level combination is $A3B2C2D4$. The results show that the combination $A3B2C2D4$ is the best when the maximum chip temperature is 66.49 °C and heat sink mass is 3.16 kg.

1. Introduction

As the fourth-generation light source, LED has the advantages of low energy consumption, long lifetime, quick response, and environmental friendliness.[(1)] The LED fish aggregation lamp is important equipment in the fishing industry. It is a high-power LED device and can attract and gather fish by phototaxis. Compared with the traditional metal halide fish aggregation lamp, the LED fish aggregation lamp has the advantages of energy saving, and environmental friendliness, and easier control of light color. However, it suffers from luminous decay and limited lifetime in the current market.[(2)] The main reason is that the heat generated by the chips cannot be dissipated effectively, so that the chip junction temperature becomes too high, resulting in luminous decay and even damage to the lamp. Studies have shown that the luminous efficiency decreases with the increase in the chip junction temperature, and a

*Corresponding author: e-mail: zhudaqing@hqu.edu.cn
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high chip junction temperature can lead to the deterioration of the physical properties of the internal materials, such as phosphor and epoxy resin, and the decrease in the light conversion efficiency of the phosphor layer, which may result in a lower luminous efficiency of the LED.[3] In addition, when the junction temperature increases, the device aging rate also increases, resulting in reduced lifetime.[4] The experimental results show that if the junction temperature is below 65 °C for a long period of time, it will take more than 100000 h for its luminosity to fall to 50%, and its effective working time will be extended to twice as long as the chip temperature decreases by 10 °C.[3] In a nutshell, reducing the LED junction temperature is essential for high-power LED devices. Research studies have shown that the design of the heat sink has a considerable impact on the cooling performance of the lamp.[5] In addition, Culham and Muzychka have shown that cooling performance will be enhanced with an increase in the number of heat sink fins. However, after a certain number, cooling performance decreases with increasing number of fins.[6] Yu *et al*. have shown that optimizing the mass and temperature of the heat sink can improve the cooling performance. It is impossible to optimize both thermal performance and heat sink mass at the same time, and there exists an upper limit to the ratio of weighting factors for obtaining the best cooling performance of the heat sink.[7] Therefore, for the LED fish aggregation lamp, the design of the heat sink has a significant impact on the temperature distribution of the lamp, and the optimization of the heat sink design is critical.

2. Materials and Methods

2.1 Simulation model

A high-power (1000 W) LED fish aggregation lamp is designed. It consists of a conduit, lens, heat sinks, aluminum substrate in a chip on board (COB) packaging and some small components, as schematically shown in Fig. 1. To facilitate the analysis, the model is simplified by removing some components that have little impact on the results. The computational fluid dynamics (CFD) method is used to simulate the effect of the change in the heat sink structure on the chip temperature.

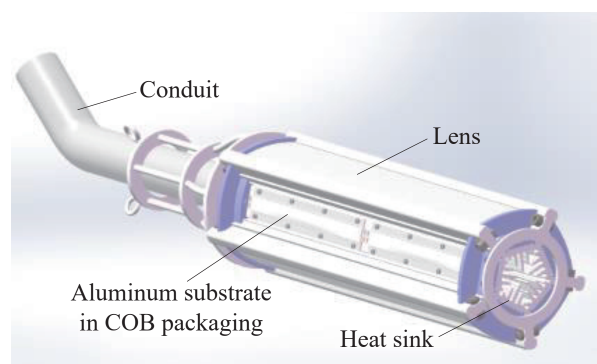

Fig. 1. (Color online) Simulation model of the LED fish aggregation lamp.

The LED fish aggregation lamp that we designed has an aluminum substrate in COB packaging, the simple structure of the COB packaging is shown in Fig. 2.

The thermal conductivity of the epoxy resin is very low, only about 1 W/(m·K). Studies have shown that even if epoxy resin were to have a thermal conductivity of up to 7 W/(m·K), the chip temperature is not much lower than that with epoxy resin having a thermal conductivity of only 0.25 W/(m·K). Thus, heat transfer through the lens can be ignored.(8) The structure and size of the heat sink have been studied and optimized in this work.

2.2 Theoretical analysis

Reducing the thermal resistance of the device can effectively improve its cooling performance, which results in a lower junction temperature and a longer lifetime. To simplify the model and facilitate the analysis, the total thermal resistance of the LED fish aggregation lamp only consists of the thermal resistances of the chips, die attachment adhesive, substrate, thermal grease, and heat sinks. When the materials of every component have been determined, the structure and size of the heat sink are identified as the key factors that affect the cooling performance of the heat sink.

The heat generated by the chips is conducted from the chip to the fins of the heat sink by heat conduction and then dissipated to the environment in accordance with Newton's Law of Cooling,

$$\Phi = Sh(T_s - T_\infty), \tag{1}$$

where Φ is the quantity of convective heat transfer, S is the heat transfer area, h is the convective heat transfer coefficient, T_s is the solid surface temperature, and T_∞ is the ambient temperature.

As seen in Eq. (1), increasing the heat dissipation surface area S and the convective heat transfer coefficient h can increase the quantity of convective heat transfer Φ.(9)

When evaluating the cooling performance of the heat sink, not only the chip junction temperature but also the heat sink mass is considered. At a constant chip heat generation rate, when the chip junction temperature is constant, a smaller heat sink mass is expected. When the

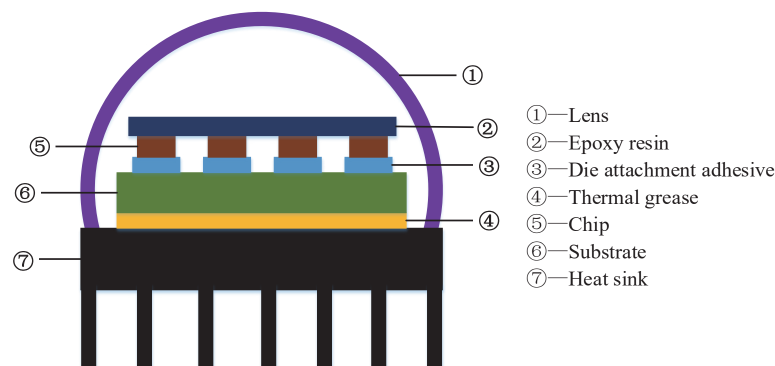

Fig. 2. (Color online) Simple structure of COB packaging.

heat sink mass is constant, a lower chip junction temperature is expected. Thus, we use the heat dissipation factor Q to describe the cooling performance of the heat sink:

$$Q = \frac{\Delta T \times M}{P}, \tag{2}$$

where Q is the heat dissipation factor, ΔT is the difference between the maximum temperature of the device and the ambient temperature, M is the mass of the heat sink, and P is the chip heat generation rate. When Q is lower, the cooling performance is better.[10]

2.3 Thermal simulation

As shown in Fig. 3, a single heat sink has one long, two medium, and two short fins. The medium and short fins are symmetrical with the long fin. Three types of heat sink are named "heat sink I", "heat sink II", and "heat sink III". In heat sink II, external semicylinders are added on both sides of heat sink fins to increase the heat dissipation surface area, and in heat sink III, concave semicylinders are added on both sides of heat sink fins to increase the heat dissipation surface area, as shown in Fig. 3. A, B, C, D, and E denote the length, thickness, and spacing of the fins, and the spacing and radius of the semicylinder, respectively, and their values are listed in Table 1. For structure 1, the long, medium, and short fins are 17, 10, and 3 mm. Similarly, for structure 2, the long, medium, and short fins are 19, 12, and 3 mm. In Table 1, we denote the value of A by the length of the long fin.

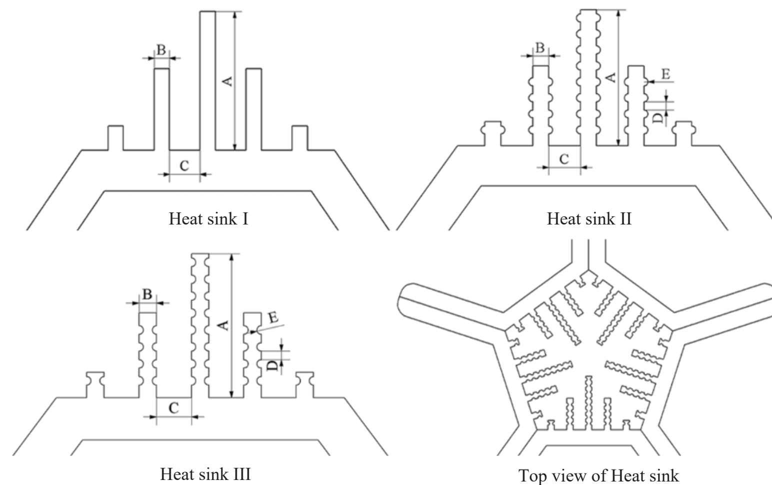

Fig. 3. Types of heat sink.

Table 1
Heat sink sizes.

Structure	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
1	17	2.0	4.0	1.0	0.5
2	19	2.5	3.5	2.0	0.5

Simulation test conditions are as follows: GaN chip with thermal conductivity of 30 W/(m·K); aluminum substrate with axial and radial thermal conductivities of 100 and 2 W/(m·K), respectively; thermal conductivity of thermal grease is 2.3 W/(m·K); heat sink is made of ADC12 die-cast aluminum material with thermal conductivity of 96 W/(m·K) and density of 2700 kg/m^3. Since only the heat transfer between the chip and the heat sink is considered, the remaining components are treated as thermal insulation material. In the CFD method, when the heat sources are set, since the LED chips are solids, we can set the chips as solid heat sources, the total power is 1000 W, and photoelectric conversion efficiency is 20%. Thus, the heat generation rate is 800 W. The simulation condition is that the lamp is 20 m below the water surface; the initial temperature of the external environment is 20.05 °C, and the pressure is 201105 Pa.

For structure 1, while keeping *A*, *B*, *C*, *D*, and *E* unchanged, three sets of tests were carried out to determine the effect of the heat sink type on the chip temperature, by the CFD method. Then, we could determine which type was the best. However, it was possible that one type of heat sink was the best in structure 1 but not the best in structure 2. For example, even if heat sink III was the best in structure 1, it may not be the best in structure 2. Therefore, for structure 2, three sets of tests were also carried out. The reason why three sets of tests were carried out for both structures 1 and 2 was to eliminate the chance that the cooling performance of one type of heat sink was the best in any structure.

As shown in Fig. 4(a), in the three types of heat sink, the chip temperature of heat sink I is lowest, and that of heat sink III is the highest. Similarly, the mass of heat sink III is the smallest, and that of heat sink II is the largest. As shown in Fig. 4(b), in the three types of heat sink, the chip temperature of heat sink I is the lowest, and that of heat sink II is the highest. Similarly, the mass of heat sink III is the smallest, and that of heat sink II is the largest.

Compared with heat sink I, heat sink III increases the heat transfer area, but the chip temperature increases slightly. The reason may be that the thermal resistance of the fins from the bottom to the top increases and the heat transfer distance of the semicylindrical surface to

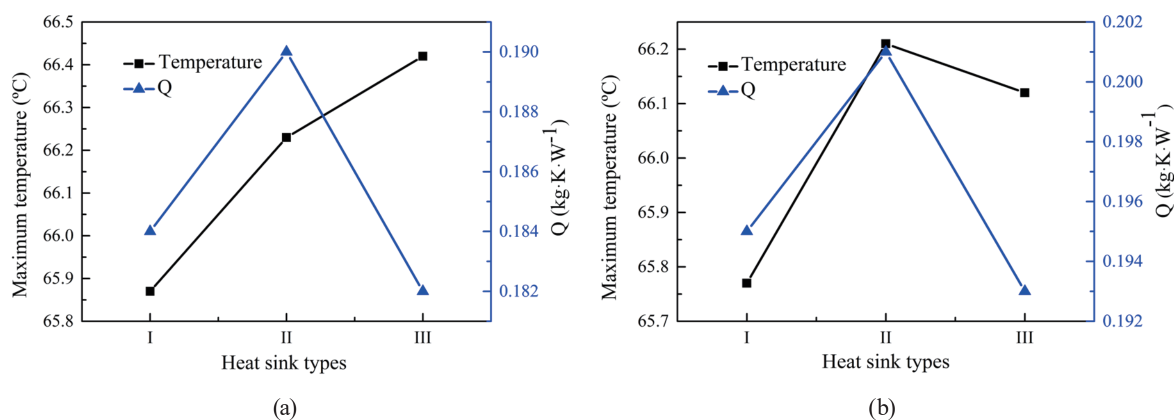

Fig. 4. (Color online) Effects of heat sink type on temperature and factor *Q* of structures (a) 1 and (b) 2.

the area where the flow velocity is large also increases, resulting in a decrease in the cooling performance. Similarly, compared with heat sink I, heat sink II also increases the heat transfer area, but the spacing between adjacent fins decreases, resulting in a decrease in the convective heat transfer coefficient. According to Eq. (1), a decrease in the convective heat transfer coefficient results in a decrease in the quantity of convective heat transfer. Thus, the chip temperature increases slightly.

As shown in Fig. 4(a), the maximum chip temperature of heat sink III is only 0.55 °C higher than that of heat sink I, and the mass is 0.08 kg lighter than that of heat sink I. According to Eq. (2), the Q factors of heat sinks I and III are 0.184 and 0.182 kg·K·W^{-1}, respectively. The Q factor of heat sink III is smaller and its comprehensive cooling performance is better.

As shown in Fig. 4(b), the maximum chip temperature of heat sink III is only 0.35 °C higher than that of heat sink I, and the mass is 0.06 kg lighter than that of heat sink I. The heat dissipation factors Q of heat sinks I and III are 0.195 and 0.193 kg·K·W^{-1}, respectively. The Q factor of heat sink III is smaller and its comprehensive cooling performance is better.

In addition, the installation of lamps becomes more difficult and the cost becomes higher with an increase in the heat sink mass. When the mass increases, fishing operation also becomes more difficult. Through the above two simulation tests, it is most reasonable to choose heat sink III for the LED fish aggregation lamp.

2.4 Orthogonal experimental design

Then, four factors, namely, the length, thickness, and spacing of the fins and the semicylindrical spacing (A, B, C, and D, respectively), that affect the maximum chip temperature and mass of the heat sink, are analyzed by the orthogonal experiment. The semicylindrical radius of 0.5 mm remains unchanged. While keeping the short fin length of 3 mm constant, we change the lengths of the long and medium fins, as shown in Table 2. The results of the orthogonal experimental design are shown in Table 3.

The numbers 1, 2, 3, and 4 are the levels of each factor, and the numbers in parentheses are the actual values of that level. For example, 1(13), 2(15), 3(17), and 4(19) of factor A means that factor A has four levels, and the actual values of each level are 13, 15, 17, and 19 mm. $k1$, $k2$, $k3$, and $k4$ are the averages of the results for each level of each factor. For example, for factor A, $k1$, $k2$, $k3$, and $k4$ are the averages of the results for the levels of 13, 15, 17, and 19 mm. The results of the data analysis of maximum chip temperature are shown in Table 4.

The analysis of variance can distinguish the differences among the test results of each level of each factor owing to the different levels of factors or test errors, and can estimate the sizes of test errors. The basic idea is to decompose the total variation of the data into the variation

Table 2
Fin lengths.

Serial numbers (mm)	1	2	3	4	5	6	7
Long fins (mm)	11	13	15	16	17	18	19
Medium fins (mm)	4	6	8	9	10	11	12
Short fins (mm)	3	3	3	3	3	3	3

Table 3
Orthogonal experimental design.

Test serial numbers	*A* (mm)	*B* (mm)	*C* (mm)	*D* (mm)	Maximum chip temperature (°C)	Heat sink mass (kg)
1	1(13)	1(1.5)	1(3.0)	1(0.5)	68.41	2.93
2	1	2(2.0)	2(3.5)	2(1.0)	67.57	3.04
3	1	3(2.5)	3(4.0)	3(1.5)	67.96	3.12
4	1	4(3.0)	4(4.5)	4(2.0)	67.69	3.12
5	2(15)	1	2	3	67.42	2.99
6	2	2	1	4	67.03	3.10
7	2	3	4	1	67.25	3.10
8	2	4	3	2	66.87	3.20
9	3(17)	1	3	4	66.94	3.04
10	3	2	4	3	66.78	3.15
11	3	3	1	2	66.40	3.26
12	3	4	2	1	66.68	3.35
13	4(19)	1	4	2	67.15	3.06
14	4	2	3	1	66.57	3.16
15	4	3	2	4	66.12	3.35
16	4	4	1	3	66.45	3.47

Table 4
Results of data analysis of maximum chip temperature.

Level average	Factor			
	A	*B*	*C*	*D*
$k1$	67.91	67.48	67.07	67.23
$k2$	67.14	66.99	66.95	67.00
$k3$	66.70	66.93	67.09	67.15
$k4$	66.57	66.92	67.22	66.95
Comparison	$k4 < k3 < k2 < k1$	$k4 < k3 < k2 < k1$	$k2 < k1 < k3 < k4$	$k4 < k2 < k3 < k1$

caused by factors or test errors, and F statistics is constructed; then, the F test is carried out to determine whether the effects of factors are significant. If the F value is larger than the F critical value, the factor is considered to have a significant effect on the test results; otherwise, the factor is considered to have no significant effect on the test results.

As shown in Table 5, the F values of factors *A* and *B* are larger than the F critical value; thus, factors *A* and *B* have a significant effect on the test results. However, the F values of factors *C* and *D* are smaller than the F critical value and thus, factors *C* and *D* have little effect on the test results. Thus, the order of the factors *A*, *B*, *C*, and *D* is $A > B > D > C$, sorted by the significance of the factors on the test results.

If we expect a lower chip temperature, the optimal level combination is A4B4C2D4 on the basis of Table 3. At this point, the lengths of the long, medium, and short fins are 19, 12, and 3 mm, respectively; the fin thickness is 3.0 mm, the fin spacing is 3.5 mm, and the semicylindrical spacing is 2.0 mm. However, when both the junction temperature and the heat sink mass are considered, the combination *A*4*B*4*C*2*D*4 is not necessarily the most ideal. As shown in Figs. 5–8, small red circles are the average values of each level of factors and small black squares are the actual values of each level of factors. The data in Figs. 5–8 were taken from Table 3. However, we are concerned about the trend of the average values, and the

Table 5
Analysis of variance.

Factor	Sum of square of deviations	Degrees of freedom	F value	F critical value	Significance
A	4.36	3	51.32	9.28	High significance
B	0.86	3	10.12	9.28	Significance
C	0.15	3	1.72	9.28	No significance
D	0.21	3	2.45	9.28	No significance
Error	0.09	3	—	—	—

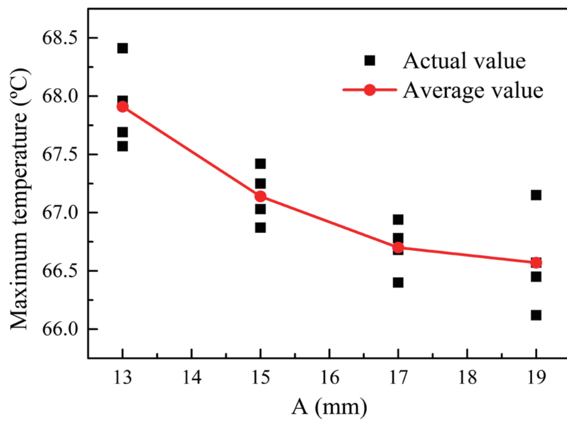

Fig. 5. (Color online) Effect of fin length on maximum chip temperature.

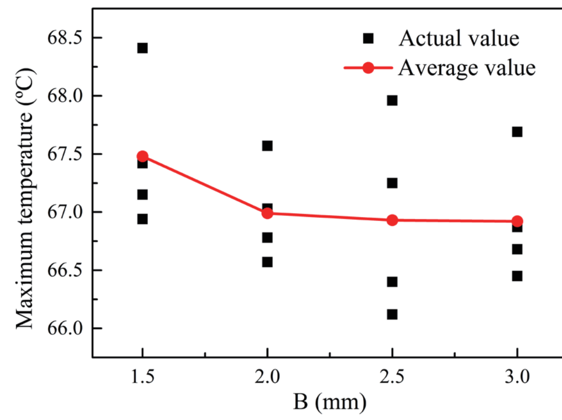

Fig. 6. (Color online) Effect of fin thickness on maximum chip temperature.

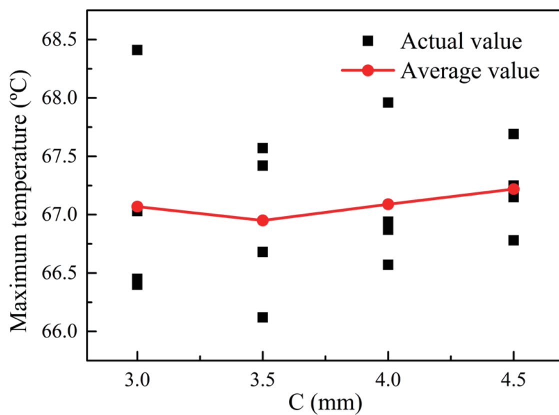

Fig. 7. (Color online) Effect of fin spacing on maximum chip temperature.

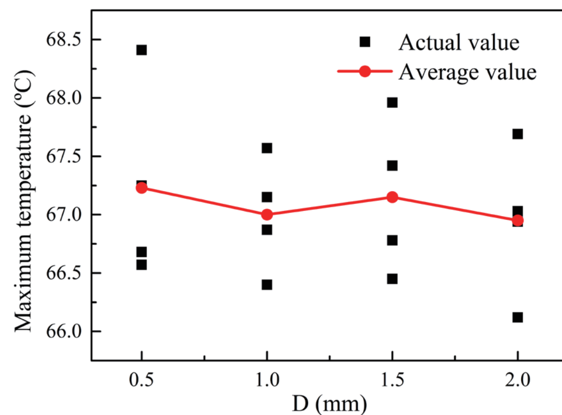

Fig. 8. (Color online) Effect of semicylindrical spacing on maximum chip temperature.

following is based on the trend of the average values to explain the simulation results.

As shown in Fig. 5, the maximum chip temperature gradually decreases as the fin length increases. When the fin length is less than 17 mm, the temperature decreases markedly, and when the fin length is greater than 17 mm, the temperature reduction slows down. The reason is that as the fin length increases, the heat transfer area becomes larger, thus, the maximum chip temperature drops. When the fin length is increased to 17 mm, although the heat transfer

area becomes larger with increasing length, the space in the central portion of the heat sink becomes smaller, resulting in a decrease in fluid speed, and in turn, the reduction of the maximum chip temperature slows down. Moreover, when the fin lengths are 17 and 19 mm, the heat sink masses are 3.20 and 3.26 kg, with a difference of 0.06 kg, while the maximum temperatures of the chip are 66.70 and 66.57 °C, respectively, with a difference of only 0.13 °C. When the lengths are 17 and 19 mm, the corresponding heat dissipation factors Q are 0.187 and 0.190 kg·K·W^{-1}, thus, when the length is 17 mm, the factor Q is smaller. By comprehensive consideration, selecting the fin length of 17 mm is more reasonable.

As shown in Fig. 6, similar to fin length, the maximum chip temperature gradually decreases as the fin thickness increases. When it is less than 2.0 mm, the temperature decreases markedly. When it is greater than 2.0 mm, the temperature reduction slows down. The reason is that as the fin length increases, the heat transfer area becomes larger. When the fin thickness is increased to 2.0 mm, although the heat transfer area becomes larger with the increase in thickness, the space in the central portion of the heat sink becomes smaller, resulting in the slowing down of temperature reduction. Moreover, when the fin thicknesses are 2.0 and 3.0 mm, the heat sink masses are 3.11 and 3.29 kg, with a difference of 0.18 kg, while the maximum chip temperatures are 66.99 and 66.92 °C, with a difference of only 0.07 °C; the corresponding heat dissipation factors Q are 0.182 and 0.193 kg·K·W^{-1}. Therefore, compared with the thickness of 3.0 mm, the thickness of 2.0 mm is preferred. Thus, selecting the fin thickness of 2.0 mm is more ideal.

As shown in Fig. 7, the maximum chip temperature first decreases and then increases as the fin spacing increases. With the fin spacing of 3.5 mm, the temperature is lowest, 66.95 °C. The reason is that as the fin spacing increases, the speed of the fluid among the fins increases. When the fin spacing increases to 3.5 mm, the further increase in the spacing makes the space in the central portion of the heat sink become too large, which results in a decrease in the number of fins. Thus, the heat dissipation area is reduced and the temperature increases. In a nutshell, it is important to choose the appropriate fin spacing. Here, the best fin spacing is 3.5 mm, whereby the maximum chip temperature is lowest, 66.95 °C, and the mass of the heat sink is 3.18 kg.

As shown in Fig. 8, the semicylindrical spacing has an effect on the thermal resistance of fins from the bottom to the top and the space between the fins. When the semicylindrical spacing is small, the thermal resistance of the fins is large, and the space in the central portion of the heat sink is also large. As a result, the water velocity and convective heat transfer coefficient decrease. When the spacings are 1.0 and 2.0 mm, the chip temperature is relatively low. At this point, the heat sink masses are 3.14 and 3.15 kg, with a difference of only 0.01 kg, and the temperatures are 67.00 and 66.95 °C, with a difference of only 0.05 °C. Correspondingly, the heat dissipation factors Q are 0.184 and 0.185 kg·K·W^{-1}. For the spacings of 1.0 and 2.0 mm, there is almost no difference in the mass of the heat sink and Q, and chip temperature is lower when the semicylindrical spacing is 2.0 mm. Thus, it is ideal to choose a semicylindrical spacing of 2.0 mm.

In a nutshell, the optimal level combination is $A3B2C2D4$. Then, taking the optimal level combinations $A3B2C2D4$ and $A4B4C2D4$ as test parameters, two simulation tests are carried

Table 6
Optimal level combinations.

Level combinations	Maximum chip temperature (°C)	Heat sink mass (kg)
*A*4*B*4*C*2*D*4	66.11	3.48
*A*3*B*2*C*2*D*4	66.49	3.16

out. The simulation results are shown in Table 6.

As shown in Table 6, the chip temperature of level *A*4*B*4*C*2*D*4 is lower than all the temperatures in Table 3. Moreover, the chip temperature of level *A*3*B*2*C*2*D*4 is 0.38 °C higher than that of level *A*4*B*4*C*2*D*4, however, the mass of the heat sink is 0.32 kg smaller than that of level *A*4*B*4*C*2*D*4.

Considering that the price of the ADC12 die-cast aluminum material is about 17050 RMB per ton, the mass of 0.32 kg can save 5.46 RMB. Assuming that there are 100 lamps on a fishing boat, one can save 546 RMB. However, the temperature increases by 0.38 °C and the service lifetime is reduced by about 164 h.

According to Eq. (2), the Q values of levels *A*4*B*4*C*2*D*4 and *A*3*B*2*C*2*D*4 are 0.200 and 0.183 $kg{\cdot}K{\cdot}W^{-1}$, respectively. Thus, the Q of level *A*3*B*2*C*2*D*4 is smaller and selecting level *A*3*B*2*C*2*D*4 is more reasonable. At this point, the lengths of the long, medium, and short fins are 17, 10, and 3.0 mm, respectively, the fin thickness is 2.0 mm, the fin spacing is 3.5 mm, and the semicylindrical spacing is 2.0 mm.

3. Conclusions

In the present research, the CFD method was used to simulate the cooling performance of a heat sink of a LED fish aggregation lamp. The structure of the heat sink was optimized, and three types of heat sink were analyzed. The results showed that heat sink III is the most ideal. Then, on the basis of heat sink III, the effects of the length, thickness, and spacing of the fins and the semicylindrical spacing on the cooling performance and mass of the heat sink were studied. Next, the optimal level combinations *A*4*B*4*C*2*D*4 and *A*3*B*2*C*2*D*4 were obtained through the orthogonal experimental design. The maximum chip temperature, mass of the heat sink, and heat dissipation factor Q were compared between the two level combinations. The results showed that the level of combination *A*3*B*2*C*2*D*4 was better. At this point, the lengths of the long, medium, and short fins were 17, 10, and 3.0 mm, respectively, the fin thickness was 2.0 mm, the fin spacing was 3.5 mm, the semicylindrical spacing was 2.0 mm, the maximum chip temperature was 66.49 °C, and the mass of the heat sink was 3.16 kg. The cooling performance of the overall lamp was enhanced by optimizing the structure of the heat sink. These results will be of great significance in promoting the popularization of the LED fish aggregation lamp and the development of the fishing industry. Moreover, the CFD method can be applied to the thermal analysis of sensor applications.

Acknowledgments

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About the Authors

Chen Shengxiong received his B.S. degree from China Three Gorges University, China, in 2015. Snice 2015, he has been studying at Huaqiao University for his M.S. degree. His research interests are in lighting technology and application of LED.

Zhu Daqing received his B.S. degree from Peking University, China, in 1987 and his M.S. and Ph.D. degrees from the Huazhong University of Science and Technology (HUST), China, in 1996 and 2000, respectively. From 2002 to 2009, he was an associate professor at HUST. Since 2009, he has been an associate professor at Huaqiao University, China. His research interests are in solid-state lighting.