Article

The Effect of Different Filament Arrangements on Thermal and Optical Performances of LED Bulbs

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Abstract: The influences on thermal and optical performances of light emitting diode (LED) bulbs with three different filament arrangements are investigated in detail. The average junction temperature, temperature of the surface of the bulb, and luminous flux of three samples all increased with increasing power. The thermal performance test results show that between the average junction, temperature and power were linear. The junction temperatures of the three samples at a power of 3.5 W were 102.48, 98.46, and 88.88 °C. The optical performance test results revealed that the luminous flux and efficiency in the two vertical filament arrangements were closely related to each other and higher than that of the horizontal filament arrangement. A numerical model of LED filament bulbs was established by the Floefd 17.2 software for analyzing the temperature distribution of the cross section and the gas flow path inside the bulb. The simulation results illustrated that the average temperatures of three samples were 105.88, 101.83, and 96.12 °C. Additionally, the gas flow inside the bulb of the two vertical filament arrangements was subject to forming a thermal cycle during operation work more than that of the horizontal filament arrangement. As a result, the flexible spiral LED filament bulb is feasible as a new light source.

Keywords: thermal; optical; filament arrangement; led filament bulb

1. Introduction

As a new light source, light emitting diodes (LEDs) are regarded as the fourth generation of solid-state lighting sources owing to their advantages of environmental friendliness, energy saving, long lifetime, quick start up, and so on [1–4]. So far, environment protection and energy saving have generated considerable research interest, the white light emitting diodes (WLEDs) have been developed rapidly in the commercial market and widely used in various lighting fields [5–7]. Early devices only provided lighting in one direction and could not meet the requirements for omnidirectional luminescent applications [8–10]. The flexible spiral LED filament bulbs combine the bulb shell of traditional incandescent bulbs with a new LED filament to achieve 360-degree illumination [11,12]. However, there is no effective radiator installed in the limited space, which seriously affects the thermal and optical performance of the filament. The heat generated by the chip is difficult to dissipate from inside of the bulb to the environment [13–16].

The study of the effect of filament overheating, is of great value to the thermal design and management of LED filament bulbs. The properties of phosphors, such as the diameters, shapes, thickness, and concentration, may affect the luminous flux and junction temperature [11,17]. Liu [17] et al. reduced the average junction temperature of the LED filament by optimizing the size of the bulb and the structure of the phosphor. Moreover, heat generated from LED chips is transferred to the surface of the filament by conduction, then transferred to the bulb shell by convection, and finally dissipated to the environment [18,19]. LED filament bulbs mainly rely on convection heat dissipation and have a poor heat dissipation performance [17,20,21]. The previous report put forward several plans.

High thermal conductive materials and high thermal conductive gases are chosen to decrease the average junction temperature of the LED filament [15,22,23]. To increase the flow of gas inside the bulb, Xu [24] et al. used ionic wind to improve the heat dissipation ability of LED filament bulb. It was also necessary to consider the optical and thermal properties with various currents [24–26]. Nevertheless, they did not study the effect of different filament arrangements on the thermal and optical performances, nor did they design and simulate the temperature distribution and gas flow path inside the bulbs, so it was worthwhile to analyze the thermal and optical performances during the operating time.

Hence, the purpose of this paper is to investigate the thermal and optical performances of flexible spiral LED filaments bulbs with three different filament arrangements. The junction temperature, temperature of surface bulb, luminous flux, and luminous efficiency of LED filament bulbs are studied. In addition, for better analysis and understanding of the principle of heat dissipation of LED filament bulbs, simulation models were carried out.

2. Experimental Method

2.1. Flexible Spiral Light Emitting Diode (LED) Filament Bulb Structure

The main work of this paper is to examine the thermal and optical performances of LED bulbs with different filament arrangements. In addition to the driving equipment and the lamp cap, the typical flexible spiral LED filament bulb is mainly composed of two parts: a flexible spiral LED filament with made by aluminum or aluminum alloy and a glass bulb shell with filling air. There are 99 chips evenly distributed on the flexible spiral filament substrate with a length of 26 cm. A few commercially available LED filament bulbs, which rate their voltage at 260 V, were bought from Zhejiang Emitting Optoelectronic Technology Co., Ltd., and tested to obtain valid and reliable data.

As mentioned above, the flexible spiral LED bulbs have three different filament arrangements, namely a horizontal filament arrangement and two vertical filament arrangements with different stretch height, as shown below in Figure 1.

Figure 1. Three different filament arrangements of flexible spiral light emitting diode (LED) bulbs. (1) Horizontal filament arrangement with a stretch height of 3 cm. (2) Vertical filament arrangement with a stretch height of 3 cm. (3) Vertical filament arrangement with a stretch height of 5 cm.

2.2. Experimental Measurement

To obtain the thermal and optical data, two experiments were done. In one experiment, the average junction temperature, temperature of the surface bulb and thermal resistance of three different filament arrangements were measured by instrument (LED-T300B, as shown in Figure 2a) with an accuracy of ± 0.15 °C from LEETS Lighting Shanghai Co., Ltd., which is based on the forward voltage method. Figure 2b shows the thermocouples attached to the surface of the vertically placed bulb. The relationship between the temperature and power of these LED devices was recorded at steady state and is shown in Figure 3. The temperature was measured by at least two thermocouples during the operation, so the data is the mean value. In another experiment, the optical performance of these LED devices, including luminous flux and luminous efficacy, was tested through an integrating sphere from the EVERFINE corporation, with the results as shown in Figure 4.

Figure 2. (a) Junction temperature testing instrument (LED-T300B). (b) LED filament bulb with thermocouple.

Figure 3. Temperature performances of three different filament arrangements: (a) Junction temperature under different powers. (b) Steady state process of junction temperature at a power of 3.5 W. (c) Temperature of surface bulb. (d) Thermal resistance.

Figure 4. Luminous flux (a) and luminous efficiency (b) of the three different filament arrangements under different powers.

2.3. Simulation Model

A 3-D computational model was established to enable a more intuitive observation and analysis of the temperature distribution and the gas flow of inside the bulb. Figure 5 shows the multi-block unstructured meshes which was generated by FLOEFD 17.2 software in all the domains. The computational model is composed of 3842886 grids for thermal behavior simulation. Some hypotheses completing the numerical model were made as shown below:

- (1) Wires are neglected in the simulation model.
- (2) The thermophysical properties of each material are independent of temperature.
- (3) All the material interfaces in the spiral flexible LED filament are perfectly connected.
- (4) The thermal radiation of the LED filament can be ignored owing to its small contact area.
- (5) The GaN chip is a volume heat source with a power of 2.45 W.
- (6) The laminar flow was three dimensional and steady.
- (7) The ideal gas flow was used to compute the densities of gases, whose other physical characteristics of gas depend on temperature and pressure.
- (8) The ambient temperature is set at 20 °C.

Figure 5. Mesh of the numerical simulation model.

The major thermal physical parameters of LED filament bulbs were shown in Table 1. At present, the efficiency of LED converting input power into heat is 70%–80% [17,27,28], so the total heat dissipation rate is 2.45 W when the power is 3.5 W for the thermal design. The simulation results of

temperature distribution and gas flow path of three different filament arrangements are shown in Figure 6.

Table 1. Thermal physical parameters of LED filament bulbs.

Item	Thermal Conductivity	Reference
LED chip	150	[7,12,13]
Substrate (Al)	237	[13,16]
Phosphor	0.3	[7,11]
Glass bell	0.9	[15,16]

Figure 6. Temperature distribution of three different filament arrangements.

3. Results and Discussions

In order to illustrate that the thermal and optical performances of three different filament arrangements of flexible spiral LED bulbs, the average junction temperature, temperature of the surface bulb, and thermal resistance were measured for analyzing the effects on heat dissipation. The luminous flux and luminous efficacy were also measured to analyze the optical characteristics. Furthermore, the design and simulation of three different filament arrangements was carried out to analyze the temperature distribution and the gas flow inside the bulb. Due to the different filament arrangements, the LED filament bulbs exhibit different thermal and optical properties.

3.1. Temperature Performance of LED Filament Bulbs

Figure 3 shows the temperature performance of three different filament arrangements at different power levels. Both experiments were carried out at room temperature of 20 °C. As shown in Figure 3a, the average junction temperature of three different arrangements has a wide gap, which all increased with increasing power and are linear. The temperature–power coefficients of the sample 1, 2 and 3 are 22.87, 22.24, and 22.10 K/w, respectively. Table 2 lists the linear fitting expressions of the three different filament arrangements. The linearity is the absolute difference between the actual value and the theoretical value divided by the actual value, and the formula is $\delta = (\Delta Y / Y) \times 100\%$. As given in Figure 3b, the average junction temperature at a power of 3.5 W for the three different filaments is 102.48, 98.46, and 88.88 °C, respectively.

Table 2. Linear fitting results of three different filament arrangements.

Item	Linear Fitting	Linearity (δ)
Sample 1	$Y = 22.87X + 22.44$	1.05%
Sample 2	$Y = 22.24 X + 21.34$	1.07%
Sample 3	$Y = 20.09X + 19.50$	1.16%

The average junction temperature of sample 1 was increased by 4.08% and 15.30% compared with sample 2 and 3. This is because when the filament bulb is placed vertically, it is more difficult for a horizontal filament arrangement to form convection within the bulb. Additionally, the heat source volume of samples 1 and 2 is larger than that of sample 3. Figure 3c shows the temperature of the surface of the bulb of the three different filament arrangements rising slowly with increasing power. Figure 3d shows the thermal resistance characteristics of the three different filament arrangements at different power levels. Thermal resistance decreases slowly with the increase of power. This is because the thermal power consumption of LED filament bulbs increases with the increase of power. According to the expression of thermal resistance and power:

$$R_{th} = \frac{T_j - T_a}{P} \quad (1)$$

where T_j is the junction temperature of the LED filament, and T_a is the temperature of the surface bulb. As can be seen, the thermal resistance of sample 3 is the lowest compared to sample 1 and 2, which is attributed to good convection heat dissipation. Generally, it can be concluded that the lower junction temperature and thermal resistance is associated with the vertical filament arrangement with a stretch height of 5 cm.

3.2. Illuminance Performance of LED Filament Bulbs

Figure 4 shows the optical performance of three different filament arrangements with increasing power. The luminous flux and luminous efficacy of LED filament bulbs were all considered. The luminous flux of LED filament bulbs increases with the increase of power. However, the luminous efficacy is opposite to the luminous flux, and decreases with the increase of power. The luminous flux and efficacy of sample 1 at all input powers is lower than that of the others owing to its high junction temperature and poor heat dissipation. Without appropriate heat dissipation, the junction temperature of the chip increases with the increase of power, which seriously reduces the efficiency of the photoelectric conversion of the chip. In addition, the luminous flux and efficacy curves of sample 2 and 3 are very closely related to each other and higher than that of sample 1, indicating that the vertical filament arrangement seems to be effective for the illuminance performance of flexible spiral LED filament bulbs.

3.3. Simulation Results of LED Filament Bulbs

Figure 5 shows the multi-block unstructured meshing which was generated by FLOEFD 17.2 software in all the domains. The simulation results of the three different filament arrangements are shown in Figure 6. The simulation average junction temperatures of the three different filament arrangements are 105.88, 101.83, and 96.12 °C, and the error with the actual results of the three different filaments arrangement are 3.21%, 3.31%, and 7.53% respectively. Therefore, these models are available.

The left-hand of Figure 7 illustrates the temperature distribution of cross sections of LED filament bulbs. As can be seen, the heat of samples 2 and 3 is mainly concentrated on the top end of the filament due to the filament formed by the geometry of the chimney prompting heat convection, and that of sample 1 concentrated on the middle of the filament due to the lack of thermal cycling inside the bulb. The intermediate figures in Figure 7 illustrate the gas flow path inside the bulb of three different filament arrangements. The plume of heated gas rose from the bottom of the bulb shell, then turned downward along the inner surface of the bulb shell, and then arrived at the top part of bulb shell. Comparing sample 2 with sample 3, we find that the thermal cycling path inside the bulb is relatively longer and symmetrical resulting in a large aspect ratio of heat source volume, further promoting natural convection to improve heat dissipation performance [19]. Moreover, the heat of sample 1 rises from both ends of the filament to the top of the bulb and falls along the inner surface of the bulb shell, but it is difficult to pass through the filament to form a thermal cycle in limited space.

Figure 7. The cross-section temperature distribution and the gas flow path of three different filament arrangements (a–c) of LED bulbs.

Based on the above experiment and simulation, the orientation of the bulb has an important influence on the junction temperature [24]. As shown in Figure 8, when the direction of gravity was the same as the direction of the filament, the bulb has the lowest junction temperature and exhibits excellent convective heat dissipation performance. The LED filament bulb with a stretch height of 5 cm has the lowest temperature in all three directions. The results show that the heat source formed by the filament was smaller and easier to release heat.

Figure 8. The junction temperature of LED filaments in various measuring orientations. (a) Measuring orientations of LED filament bulb; (b) Simulation results of three different filament bulbs.

4. Conclusions

This paper investigated the thermal and optical performances for examining heat transfer characteristics of LED bulbs with three different filament arrangements, which including a horizontal arrangement and two vertical arrangements with different stretch heights. The average junction temperature, temperature of surface bulb, thermal resistance, luminous flux, and efficiency of these devices were measured and compared. The average junction temperature of three different filament arrangements all increases with rises of power and are linear. The junction temperature of sample 1 and sample 2 at a power of 3.5 W were improved by 47.24% and 10.78% compared with sample 3 at -90° . The luminous flux of the three different filament arrangements also increases with increasing power, but the thermal resistance and luminous efficiency of three different filament arrangements decreased due to the increased power consumption. Meanwhile, the optical characteristics of samples 2 and 3 are close to each other and higher than that of sample 1, indicating that the vertical filament arrangement has the best thermal and optical performances.

Simulation models of the LED bulbs with three different filament arrangements were built to analyze the temperature distribution of the cross section and air flow path of the inner bulb. The simulation of average junction temperature of three different filament arrangements were 120.99, 101.83, and 96.12 °C. Compared to sample 1, the gas inside the bulbs of samples 2 and 3 is subject to forming a thermal cycle. From the results of the analysis, the vertical filament with a stretching height of 5 cm showed excellent thermal and illuminance performance characteristics. The presented results may serve as a guide in the heat dissipation design of high-power LED filament bulbs.

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References

1. Luo, X.; Hu, R.; Liu, S.; Wang, K. Heat and fluid flow in high-power LED packaging and applications. *Prog. Energy Combust. Sci.* **2016**, *56*, 1–32. [\[CrossRef\]](#)

2. Krames, M.R.; Shchekin, O.B.; Mueller-Mach, R.; Mueller, G.O.; Zhou, L.; Harbers, G.; Craford, M.G. Status and future of high-power light-emitting diodes for solid-state lighting. *J. Disp. Technol.* **2007**, *3*, 160–175. [\[CrossRef\]](#)
3. Jang, D.; Park, S.; Lee, K.S. Thermal performance of a PCB channel heat sink for LED light bulbs. *Int. J. Heat Mass Transf.* **2015**, *89*, 1290–1296. [\[CrossRef\]](#)
4. Peng, Y.; Li, R.; Wang, S.; Chen, Z.; Nie, L.; Chen, M. Luminous Properties and Thermal Reliability of Screen-Printed Phosphor-in-Glass-Based White Light-Emitting Diodes. *IEEE Trans. Electron. Dev.* **2017**, *64*, 1114–1119. [\[CrossRef\]](#)
5. Weng, C.J. Advanced thermal enhancement and management of LED package. *Int. Commun. Heat Mass Transf.* **2009**, *36*, 245–248. [\[CrossRef\]](#)
6. Montoya, F.G.; Peña-García, A.; Juaidi, A.; Manzano-Agugliaro, F. Indoor lighting techniques: An overview of evolution and new trends for energy saving. *Energy Build.* **2017**, *140*, 50–60. [\[CrossRef\]](#)
7. Shyu, J.C.; Hsu, K.W.; Yang, K.S.; Wang, C.C. Orientation effect on heat transfer of a shrouded LED backlight panel with a plate-fin array. *Int. J. Heat Mass Transf.* **2013**, *42*, 51–54. [\[CrossRef\]](#)
8. Park, S.J.; Jang, D.; Yook, S.J.; Lee, K.S. Optimization of a chimney design for cooling efficiency of a radial heat sink in a LED downlight. *Energy Convers. Manag.* **2016**, *114*, 180–187. [\[CrossRef\]](#)
9. Chi, W.H.; Chou, T.L.; Han, C.N.; Yang, S.Y.; Chiang, K.N. Analysis of Thermal and Luminous Performance of MR-16 LED Lighting module. *IEEE Trans. Compon. Packag. Technol.* **2010**, *33*, 713–721. [\[CrossRef\]](#)
10. Huang, B.J.; Tang, C.W. Thermal-electrical-luminous model of multi-chip polychromatic LED luminaries. *Appl. Therm. Eng.* **2009**, *19*, 3366–3373. [\[CrossRef\]](#)
11. Li, S.; Chen, H.; Tan, S.C.; Hui, S.R.; Waffenschmidt, E. Power Flow Analysis and Critical Design Issues of Retrofit Light-Emitting Diode (LED) Light bulb. *IEEE Trans. Power Electron.* **2014**, *30*, 3830–3840. [\[CrossRef\]](#)
12. Liu, Z.Y.; Liu, S.; Wang, K.; Luo, X.B. Studies on Optical Consistency of White LEDs Affected by Phosphor Thickness and Concentration Using Optical Simulation. *IEEE Trans. Compon. Packag. Technol.* **2010**, *33*, 680–687. [\[CrossRef\]](#)
13. Liu, S.M.; Chen, C.F.; Chou, K.C. The design and implementation of a low-cost 360-degree color LED display system. *IEEE Trans. Consum. Electron.* **2011**, *57*, 289–296. [\[CrossRef\]](#)
14. Park, S.J.; Jang, D.; Lee, K.S. Thermal performance improvement of a radial heat sink with a hollow cylinder for LED downlight application. *Int. J. Heat Mass Transf.* **2015**, *89*, 1184–1189. [\[CrossRef\]](#)
15. Feng, W.; Feng, B.; Zhao, F.; Shieh, B.; Lee, R. Simulation and optimization on thermal performance of LED filament light bulb. In Proceedings of the 2015 12th China International Forum on Solid State Lighting, Shenzhen, China, 2–4 November 2015; pp. 88–92.
16. Wang, L.P.; Li, W.B.; Xu, Y.C.; Yang, B.B.; Shi, M.M.; Zou, J.; Li, Y.; Qian, X.L.; Zheng, F.; Yang, L. Effect of different bending shape on thermal properties of flexible LED filament. *Chin. Phys. B* **2018**, *27*, 430–436.
17. Liu, J.; Xu, C.; Zheng, H.; Liu, S. Numerical Analysis and Optimization of Thermal Performance of LED filament Light Bulb. In Proceedings of the 2017 IEEE 67th Electronic Components and Technology Conference (ECTC), Orlando, FL, USA, 30 May–2 June 2017; pp. 2243–2248.
18. Luo, X.B.; Mao, Z.M.; Liu, S. Thermal design of a 16W LED bulb based on thermal analysis of a 4W LED bulb. In Proceedings of the Electronic Components & Technology Conference, Las Vegas, NV, USA, 1–4 June 2010; pp. 1906–1911.
19. Petroski, J. Advanced natural convection cooling designs LED bulb systems. *J. Electron. Packag.* **2014**, *136*, 041005. [\[CrossRef\]](#)
20. Tran, N.T.; Shi, F.G. Studies of phosphor concentration and thickness for phosphor-based white light-emitting-diode. *J. Lightwave Technol.* **2008**, *26*, 3556–3559. [\[CrossRef\]](#)
21. Yang, X.F.; Liu, J.; Chen, Q.; Shen, Y.P.; Liu, H.Z.; Lai, G.Q. A low temperature Vulcanized transparent silane modified epoxy resins for LED filament bulb package. *Chin. J. Polym. Sci.* **2018**, *36*, 114–121. [\[CrossRef\]](#)
22. Yu, X.; Xie, B.; Shang, B.; Chen, Q.; Luo, X. A Cylindrical Tuber Encapsulant Geometry for Enhancing Optical Performance of Chip-on-Board Packaging Light-Emitting Diodes. *IEEE Photonics J.* **2016**, *8*, 1–9. [\[CrossRef\]](#)
23. Li, B.; Baik, Y.J.; Chan, B. Enhanced natural convection heat transfer of a chimney-based radial heat sink. *Energy Convers. Manag.* **2016**, *108*, 422–428. [\[CrossRef\]](#)
24. Xu, C.; Zhang, Z.; Chu, J.; Wu, J.; Lei, X.; Zheng, H.; Liu, S. Thermal dissipation enhancement of LED filament bulb by ionic wind. In Proceedings of the International Conference on Electronic Packaging Technology, Wuhan, China, 16–19 August 2016; pp. 1212–1215.

25. Rao, F.; Ge, Z.C.; Zhu, J.L. Effect of Temperature and Current on luminous Efficiency of High-Power LED. *Adv. Mater. Res.* **2012**, *347*, 310–315. [[CrossRef](#)]
26. Wang, L.P.; Zou, J.; Yang, B.B.; Li, W.B.; Li, Y.; Shi, M.M.; Zhu, W.; Zhang, C.Y.; Wang, F.C.; Lin, Y.J. Optical and electrical properties of a spiral LED filament. *J. Semicond.* **2018**, *39*, 024003. [[CrossRef](#)]
27. Vairavan, R.; Sauli, Z.; Retnasamy, V.; Ismail, R.C.; Nor NI, M.; Nadzri, N.S.; Kamarudin, H. High power LED thermal and stress simulation on copper slug. In Proceedings of the Uksim International Conference on Computer Modelling & Simulation, Cambridge, UK, 10–12 April 2013; pp. 294–298.
28. Jang, D.; Park, S.J.; Yook, S.J.; Lee, K.S. The orientation effect for cylindrical heat sinks with application to LED light bulb. *Int. J. Heat Mass Transf.* **2014**, *71*, 496–502. [[CrossRef](#)]

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