Journal of Electronics and Sensors
Review Article

Optimum Composition of Vacuum Content in a Spiral-Like Flexible Chimney-Based LED Bulb1

Wang W[1], **Wang z**[1], **Xu Y**[3], **Su X**[3], **Zhang M**[3], **Zhang C**[1], **Li** Y[1], **Wu** H*[4], **Shi** M[1], **Yang** B[1], **Li** Y[2], **Zou** J*[1]

[1]School of Science, Shanghai Institute of Technology, P. R. China
[2]School of Materials Science and Engineering, Shanghai Institute of Technology, P. R. China
[3]Yantai Huachuang intelligent Equipment Co., Ltd., China
[4]School of Engineering Innovation, Shanghai Institute of Technology, P. R. China

Received: 15 November 2020 **Accepted:** 20 November 2020 **Published:** 24 November 2020

***Corresponding authors:** Jun Zou. School of Science, Shanghai Institute of Technology, P. R. China. **Email:** zoujun@sit.edu.cn.
Hong Wu. School of Engineering Innovation, Shanghai Institute of Technology, P. R. China.
E-mail: wuhong@sit.edu.cn

Abstract:

This paper introduced the gas flow and optimization of a spiral-like flexible chimney-based LED bulb by a combined mathematical and experimental study. A mathematical model of spiral flexible LED bulb considering nature convection, radiation and heat transfer was established by the FLOEFD software based on the finite element method (FEM), and was also compared with the experimental result. The effect of chimney-self based and vacuum content on the thermal performance of a bulb was studied. A thermal resistance model was proposed for analytical model. Compared with the filament with a stretch height of 3cm, the chimney effect can reduce the average junction temperature of filament by 6.38 °C (through the experiment) and 6.48 °C (through the simulation) respectively. The results revealed that the chimney effect has a huge impact on the gas flow in the bulb. The cause of the phenomenon is that flexible LED filament can improve the gas flow by changing self-shape instead of other cooling device. A vacuum content was introduced in the bulb and composition was optimized by using analytical model. The filament temperature in optimized bulb could decrease 6 0C than full filled with helium.

Keyword: Spiral-like Flexible LED Filament; Chimney-Effect; Vacuum Content; Thermal Arrangement

Introduction

As an attractive illumination source, the white light emitting diodes (WLEDs) have a great speed of development in recent years [1-3]. Chinese government affirms that one-third of power consumption could be saved if LEDs acting as a domain illumination source [4]. The lifetime of LEDs are 9-10 times while the energy consume is only about 75% than fluorescent lights [5]. So far, LEDs are being considered the fourth generation of light sourced [6]. However, the junction temperature of LEDs should not exceed 110 degrees for fear of shorten lifetime, shifted wavelength, lower luminous efficiency and so on [7]. The first enemy of LED is the heat owing to the material of semiconductor [8], so the thermal management of LEDs of great value. 45% of the input electrical energy is converted into heat owing to the power conversion efficiency of LED chips is about 55% [9]. For many advanced cooling systems, such as heat-pipe cooling [10], liquid cooling [11], ionic wind cooling [12-14], as well as heat sink cooling [15], have been used to manage the thermal property of high-power LEDs.

Xiao et al [10] firstly designed an automatic cooling device which integrated with a microcontroller, heat pipes and Fan. Lai et al [11] investigated an active liquid cooling solution of such LEDs in an automotive headlight application. Dong et al [12] developed a heat sink with ionic wind which using wire to parallel-none-stretched-electrodes as a new cooling device. Chen et al [13] employed ionic wind to augment heat transfer of a LED mounted on a substrate and found that the thermal resistance for the negative polarity is lower than that for the positive one. Wang et al [14-15] studied the application of ionic wind produced by corona discharge to cool a LED car headlamp and demonstrated that the ionic wind could decade the red shifting of the chromaticity coordinates as well as the radiant power.

Natural air cooling is much more reliable, environmental, and economic than active cooling systems. Abdelmlek [16] studied the number and arrangement of LED-chips on the heat-sink owing to the different effect of junction temperature. Later, the same group also investigated the optimization of different chip size, disposition on different substrate [17]. These authors also proposed a new thermal resistance model to precise estimate the junction and phosphor temperature, which proves the feasibility of the estimated model [18]. Chen et al discussed the phenomenon about overestimation of phosphor temperature in high-power LEDs by thermocouple [2]. Park investigated the chimney design of a radial heat sink [19]. Park and his group [20, 21] investigated the effect of a radial heat sink with a chimney for LED downlights. The cooling efficiency could up to 20%. Feng [22] et al introduced a gas mixture in the LED bulb and optimized its composition. It was found that the lowest temperature of 360 K of the LED bulb filled with a mixture of 74% helium and 26% xenon. A correlation which could predict the effect factor determined by the geometric factors and installation angle was proposed. Luo et al details reviewed the heat and fluid flow problems in LED packaging process in recent years [23]. Shen et al studied the orientation effects on natural convection heat dissipation of rectangular fin heat sinks mounted on LEDs [24]. It may result in an abnormal of the light intensity a reduction in the lifetime of LED lights as well as the worse of the bulb [25, 26].

The properties of thermal dissipation are also very important in LED bulbs. Many researchers have done something about it. For example, Feng et al found that the higher thermal conductivity of filling gas, the less junction temperature change would be [27].

This paper studied a novel flexible spiral-like LED filament bulb, which could optimize gas flow mechanism through self-shape changing. The mathematical model including heat conduction, radiation and convection were computed through numerical simulation results. A thermal resistance model concerning bulbs was proposed to analysis the average temperature of LED filament. A vacuum content was introduced in the bulb and its percentage was optimized through analytical model.

Term			
ρ	density	C_P	Specific heat
η	Viscosity	λ	Thermal conductivity
I	Radiation intensity	$\vec{r}$	Position vector
$\vec{s}$	Direction vector	σ	Stefan-Boltzmann constant
a	Absorption coefficient	σs	Scattering coefficient
n	Refractive index of each heat	Q	Total heat transfer rate

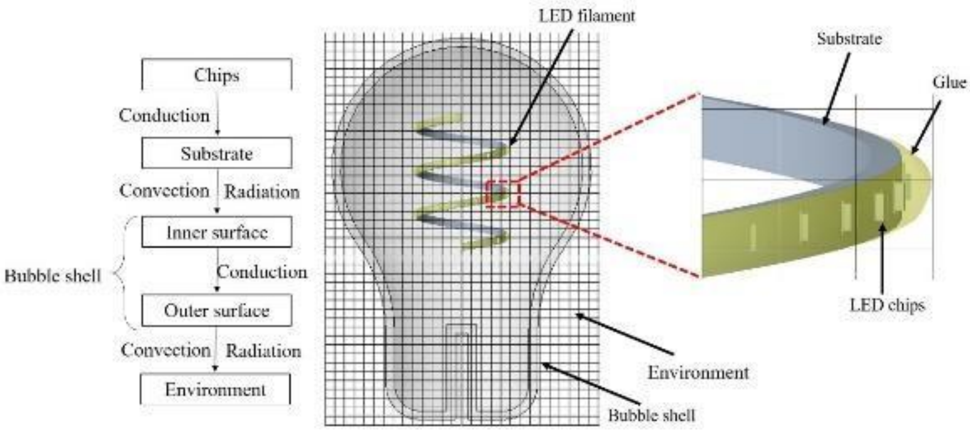
	Transfer medium		
$Tglass,in$	Average temperatures of inner surface of bubble shell	Tglass,out	Average temperatures of outer surface of bubble shell
$Afile$	Wetted surface area of filament	hin	Heat transfer coefficient inside bulb
$C1$	0.5611, empirical coefficients of Nu-Ra correlation inside bulb	n1	0.225, empirical coefficients of Nu-Ra correlation inside bulb
$Aglass,out$	Outer surface area of bubble shell	hout	Average heat transfer coefficient on the outer surface of bulb
$C2$	0.4428, empirical coefficients of Nu-Ra correlation outside bulb	n2	0.2527, empirical coefficients of Nu-Ra correlation outside bulb
$Qrad, in$	Radiation heat transfer rate from filament to bubble shell	Qrad,out	Radiation heat transfer rate from bubble shell to environment
σ	5.67×10-8 $w/m2K2$ Stefan-Boltzmann constant	εfile	emissivity
$X12$	0.644 view factor from the filament to the inner surface of bubble shell	εglass	emissivity
$Aglass$	Average of inner and outer surface areas of bubble shell	δ	Thickness of bubble shell
ni	Mole fraction of species i	λglass	Thermal conductivity of glass
β	Volumetric thermal expansion coefficient	φij	Binding factor of species i and j
ΔT	Average temperature different between filament and inner surface of bulb shell	l	Characteristic length (filament height & bulb diameter)

Mathematical Simulation

Boundary conditions, computational domain and governing equations

A 3D simulated model was designed to optimize the vacuum content of the bulb based on the thermal resistance model. Heat conduction, convection and radiation was involved from the chip to the environment respectively. The transfer path is shown in (Figure 1). In solid domains, we could use standard heat conduction equation for heat conduction, for example, chip to filament and bubble shell from inside to outside surface. The buoyancy force term and Naiver- Stokes equation were considered for thermal convection inside the bubble shell [22]. Since the surface area of the filament is very small, the thermal radiation generated by the filament is negligible. The numerical simulation model has been introduced in [9].

Figure (1): Mesh of numerical simulation model



For the above numerical simulation model, the governing equations as shown below [22, 26]: The continuity equation goes as follows:

$$\nabla \cdot (PV) = 0 \quad (1)$$

The momentum equation is:

$$p\frac{D_v}{D_t} = -\nabla p + \theta\nabla^2 V + F(for\ z - direction\ F\ = -p.q) \quad (2)$$

The energy equation is:

$$PC\frac{D_T}{P_{D_t}} = \nabla.(\omega\nabla \mathrm{T}) + \frac{D_P}{D_t} \quad (3)$$

Solid region energy equation:

$$\nabla.(\omega\nabla \mathrm{T}) + S_h = 0 \quad (4)$$

There are five sub-domains in the computational domain, i.e., LED chip, filament (substrate, glue and chips), bubble shell, gas vacuum inside the bulb and ambient condition. The thermal physical properties of each sub-domain were shown in (Table 1) [9], which was used to calculate the above governing equation. The LED chips were regarded as volumetric heat source with a 70%-80% efficiency of conversion into heat [9, 27]. The imposed volume heat source was 2.45W, which uniformly distributed on 99 chips.

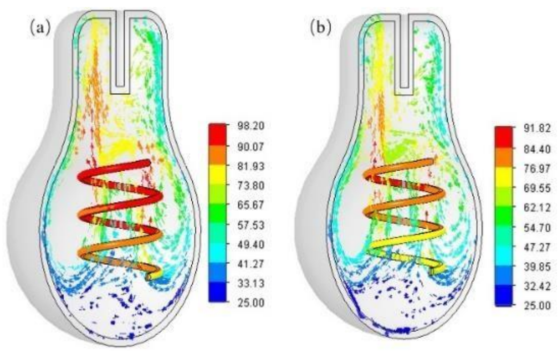
Table (1): thermal physical properties of sub-domain

Domain	Thermal conductivity $w/(m \cdot k)$
LED chips	150
Substrate (Al)	237
Glue	0.3
Glass	0.9
Inner gas	Eq. (34)
Outer gas	0.02

Mathematical results

(Figure 2) shows the mathematical results of model, which include the numerically predicted streamlines and the gas flow path of air and helium inside the bulbs respectively. The input electrical power is 3.5 W. The environment temperature was set at 25°C . The highest temperature of the bulb in the left was 98.20°C, while the right was 91.82°C, As can be seen from (Figure 2). According to the temperature distribution, the heat is concentrated at the top of the bulb because the gas heats up. Air has a lower thermal conductivity than helium, so the gas in Fig. 2(a) flows denser and faster than that in Fig. 2(b). In general, the vacuum content of the bulb has a great influence on the junction temperature of LED filament.

Figure (2a): Air-filled LED filament bulb **(2b):** Helium-filled LED filament bulb



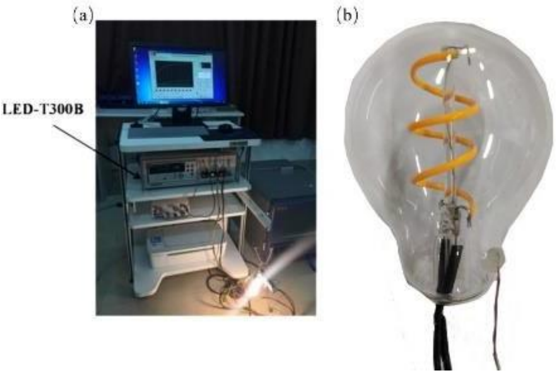
Experiments and setup

To verify the mathematical simulation model, the junction temperature of LED filament bulb was tested. (Figure 3)shows the prototype of flexible spiral LED filament bulb produced processing, which included a glass bubble shell and a spiral LED filament distributed on 99 LED chips.

Figure (3): Conceptual of a self-chimney spiral LED bulb

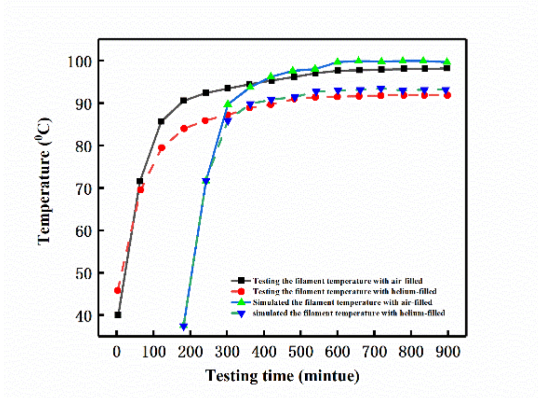
As shown in (Figure 4(a)), the average PN-junction temperature, temperature of the surface bulb was measured by instrument (LED-T300B) in a closed environment, which use Voltage-Current method. The 15-mA direct current power supply was used to light bulbs. A thermocouple was paste to measure the temperature on the other surface of bulb shell, as shown in (Figure 4(b)).

Figure (4): Experimental set up: **(a)** PN junction temperature testing instrument (LED-T300B) **(b)** Tested spiral LED bulb



As shown in Fig. 5, the dashed line was the PN junction temperature of air-filled LED filament bulb and the curve was the PN junction temperature of helium-filled LED filament bulb. The slope of the curve slowed down gradually with the test time or number of iterations. It shows the temperature of the filament with air-filled is higher than that of helium-filled, which is correspond with mathematical simulate results and experiment test.

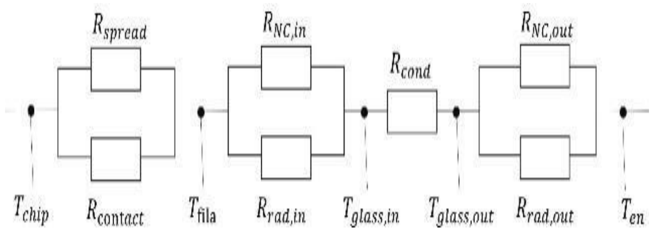
Figure (5): The PN junction temperature of the filament with air-filled and the filament with helium- filled.



Thermal resistance network model

There are four basic steps of the heat transfer: (1) from chips to filament; (2) from filament to bubble shell; (3) from the inside to the outside surface of bubble shell; (4) from outer surface of the bubble shell to the environment. Each step is closely related to one or more thermal resistance model.

Figure (6) Schematic diagram of thermal resistance model for spiral chimney-based LED bulb



There may be a thermal contact resistance at the interface between chips and filament in step 1, as well as a spreading thermal resistance exist when heat transferred from chips to filament [22, 29]. It is hard to exact analyze the spreading thermal resistance owing to the complex structure of filament and the uneven distribution of chips on the filament. Besides, the thermal resistances concerning from chip to filament were not covered in this discussed thermal resistance network. Therefore, the suggested model is just capable of predict the average filament temperature. It should be emphasized that the main function of the thermal model is to discover the optimum vacuum content for LED bulbs. To this end, it is enough to select the average filament temperature other than the chip temperature. The optimum vacuum content was determined by the average filament temperature. In general, the average temperature of the filament was related to convection cooling. The lower the average filament temperature, the better the cooling effect of the bulb, and the worse it is.

The chip-to-environment thermal resistant network was shown in (Figure (6), which ignore the thermal resistance between the chips and filament. Convection and radiation are mainly involved when heat transferred from filament to the bubble shell in step 2, associated with the convective resistance RNC,in and a radiative resistance Rrad,in respectively. There is only heat conduction from inner surface to the outer surface of the bubble shell, corresponding to conductive resistance Rcond. In the end , heat transferred from the bubble shell to the environment through natural convection and radiation, associated with convective resistance RNC,out and a radiative resistance Rrad,out respectively.

There are 2 processes of heat transferred from filament to the bubble shell: first from the filament to the gas inside the bubble, and from the gas inside the bubble to the bubble shell. Each step-in line with a boundary layer either at the filament or the inside surface, However.

The total thermal resistance was defined on account of temperature difference between filament (Tfila) to environment (Ten) [30, 31], as:

$$R_{tot} = \frac{T_{fila} - T_{en}}{Q} \tag{5}$$

The total thermal resistance could be described as the sum of thermal resistances inside the bulb via the bubble shell, together with outside the glass based on the thermal resistance network, as [22, 30, 31]:

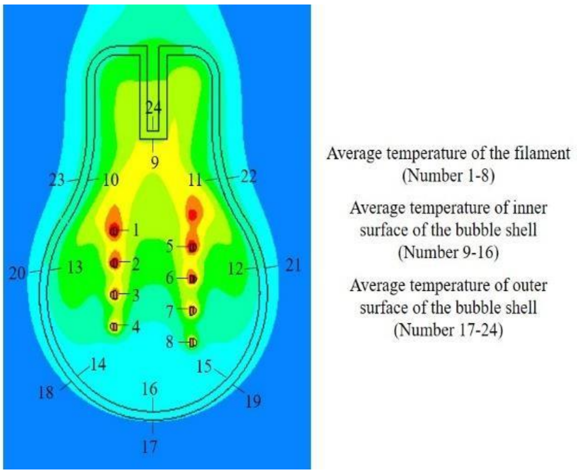
$$R_{tot} = R_{in} + R_{cond} + R_{out} \tag{6}$$

Where, $R_{in} = \frac{T_{fila} - T_{glass,in}}{Q}$ (7)

$$R_{cond} = \frac{T_{glass,in} - T_{glass,out}}{Q} \tag{8}$$

$$R_{out} = \frac{T_{glass,out} - T_{en}}{Q} \tag{9}$$

Figure (7): LED bulb surface temperature collection point



As shown in (Figure 7), this is the simulated section diagram of LED filament bulb. Eight point were collected on the surface temperature of the filament, the inner surface temperature of the bubble shell, and the outer surface temperature of the bubble shell respectively. The average temperature of the filament (T_{fila}) is the average of the sum of temperatures from 1 to 8, the average temperature of inner surface of the bubble shell ($T_{glass,in}$) is the average of the sum of temperatures from 9 to 16, the average temperature of outer surface of the bubble shell ($T_{glass,out}$) is the average of the sum of temperatures from 17 to 24.

Optimum composition of vacuum content in the bulbs

One could improve heat convection inside the bulb to prompt the thermal performance. An effective way is through optimizing the vacuum content to optimize the comprehensive effect between convection and radiation. The concentration of helium increases from 60% to 100% with each 5% increase. With the filament temperature fixed to be 88.56 °C, the optimum composition was found to be 96% helium and 4% vacuum in mole fraction, as shown in (Table 2). The density of helium is positive proportional to the formula weight, while the thermal conductivity is inversely proportional to the formula weight. Helium has the lowest formula weight in all inter gases, so the higher the helium content, the better the convection effect. Besides, the higher the vacuum, the better the radiation effect. Thus, a mixture of helium and vacuum could achieve a balance between natural convection and radiation. All the simulation was done using the same bubble shell model, and the optimum composition might vary with the geometric of bulb.

Table (2): The filament temperature and total thermal resistance of LED bulb for different vacuum.

T_{fila}(°C)	R_{tot} (°C/W)	Helium (%)	Vacuum (%)
106.15	32.13	60	40
104.28	31.59	65	35
102.11	31.02	70	30
100.39	30.5	75	25
98.56	30.11	80	20
95.24	29.58	85	15
93.93	29.06	90	10
90.03	28.66	95	5
88.56	28.4	96	4
91.82	28.53	100	0

Conclusions

The effects of self-chimney-based filament LED bulb were studied by experiment and simulation. Various vacuum content effect on the gas flow of LED filament light bulb was also investigated. The deviation between the simulation and experimental results was only 3 °C and the simulated trend is corresponded with experimental results. Considering natural convection, radiation and conjugated domain, the deviation was reasonable. An analytical model and thermal resistance model of LED bulb was also discussed. It was found natural convection play the leading role on heat performance. In addition, when the optimum mixture gas was used as filling gas instead full filled with helium, the filament temperature could decrease 4°C, which is cost saving in practice.

Highlights

1. The chimney effect has a huge impact on the gas flow in the bulb.
2. The gas flow of the bulb was investigated by mathematical and experimental.
3. A thermal resistance model for spiral flexible LED bulb was proposed.
4. A vacuum content was introduced in the bulb and composition was optimized by using analytical model.

Acknowledgements:

The work was supported by the Science and Technology Planning Project of Zhejiang Province, China (2018C01046), Enterprise-funded Latitudinal Research Projects (J2016-141), (J2017-171), (J2017-293), (J2017-243).

References

1. C Y Guan, J Zou, Q C Chen, et al. Effect of different bonding materials on flip-chip LED filament properties [J]. APPL SCI., Nov. 10, pp. 47, 2020.
2. Q Chen, Y Ma, X Yu, et al. phosphor temperature overestimation in high-power light-emitting diode by thermo couple [J]. IEEE T ELECTRON DEV., vol. 64, no. 2, pp. 463-466, 2017.
3. Z Y Liu, S Liu, K Wang, et al. Studies on optical consistency of white LEDs affected by phosphor thickness and concentration using optical simulation [J]. IEEE T COMPON PACK T., vol. 33, no. 4, pp. 680-687, 2010.
4. X B Luo, T Cheng, W Xiong, et al. Thermal analysis of an 80 W light-emitting diode street lamp [J]. IET OPTOELECTRON., Nov. 5, pp. 191-196,

2007.
5. B L Ahn, C Y Jang, S B Leigh, et al. Effect of LED lighting on the cooling and heating loads in office building [J]. APPL ENERG., vol. 133, no. 6, pp. 1484-1489, 2014.
6. L P Wang, W B Li, Y C Xu, et al. Effect of different bending shape on thermal properties of flexible LED filament [J]. CHINESE PHYS B., Nov. 27, pp. 430-436, 2018.
7. J Petroski. Advanced Natural Convection Cooling Designs for Light-emitting Diode Bulb Systems [J]. J ELECTRON PACKAGING., vol. 136, no. 4, pp. 041007, 2014.
8. S Chhajed, Y Xi, Y L Li, et al. Influence of junction temperature on chromaticity and color-rendering properties of trichromatic white-light sources based on light emitting diodes [J], J APPL PHYS., vol. 97, no. 5, pp. 054506-08, 2005.
9. W Wang, J Zou, Q Y Zheng, et al. The effect of different filament arrangement thermal and optical performances of LED bulbs [J]. APPL SCI., Nov. 10, pp. 1-10, 2020.
10. C Xiao, H Liao, Y Wang, et al. A novel automated heat-pipe cooing device for high-power LEDs [J]. APPL THERM ENG, 2016.
11. Y Lai, N Cordero, F Barthel, et al. Liquid cooling of bright LEDs for automotive applications [J]. APPL THERM ENG., vol. 29, no. 5-6, pp. 1239-1244, 2009.
12. H S Dong, S H Baek, S K Han. Development of heat sink with ionic wind for LED cooling [J]. INT J HEAT MASS TRAN., Nov. 93, pp. 516-528, 2016.
13. I Y Chen, M Z Guo, K S Yang, et al. Enhanced cooling for LED lighting using ionic wind [J]. INT J HEAT MASS TRAN., vol. 57, no. 1, pp. 285-291, 2013.
14. J Wang, Y X Cai, X H Li, et al. Experimental study on optical-thermal associated characteristics of LED car lamps under the action of ionic wind [J]. MICROELECTRON RELIAB., Nov. 82, pp. 113- 123, 2018.
15. V A F Costa, A M G Lopes. Improved radial heat sink for led lamp cooling [J]. APPL THERM ENG., vol. 70, no. 1, pp. 131-138, 2014.
16. K B Abdelmlek, Z Araoud, R Ghnay, et al. Effect of thermal conduction path deficiency on thermal properties of LEDs package [J]. APPL THERM ENG., Nov. 102, pp.251-260, 2016.
17. K B Abdelmlek, Z Araoud, K Charrada, et al. Optimization of the thermal distribution of multi-chip LED package [J]. APPL THERM ENG., Nov. 126, pp. 653-660, 2017.
18. Y Ma, R Hu, X Yu, et al. A modified bidirectional thermal resistance model for junction and phosphor temperature estimation in phosphor-converted light-emitting diodes [J]. INT J HEAT MASS TRAN, Nov. 106, pp. 1-6, 2017.
19. S J Park, D Jang, S J Yook, et al. Optimization of a chimney design for cooling efficiency of a radial heat sink in a LED downlight [J]. ENERG CONVERS MANAG., Nov. 114, pp. 180-187, 2016.
20. B Li, Y J Baik, B Chan. Enhanced natural convection heat transfer of a chimney-based radial heat sink [J]. ENERG CONVERS MANAG., Nov. 108, pp. 422-428, 2016.
21. S J Park, K S Lee. Orientation effect of a radial heat sink with a chimney for LED downlights [J]. INT J HEAT MASS TRAN., Nov. 110, pp. 416-421, 2017.
22. S S Feng, S Y M Sun, H B Yan, et al. Optimum composition of gas mixture in a novel chimney-based LED bulb [J]. INT J HEAT MASS TRAN., Nov. 115, pp. 32-42, 2017.
23. X B Luo, R Hu, S Liu, et al. Heat and fluid flow in high-power LED packaging and applications [J]. PROG ENERG COMBUST., Nov. 56, pp. 1-32, 2016.
24. Q Shen, D Sun, Y Xu, et al. Orientation effects on natural convection heat dissipation of rectangular fin heat sinks mounted on LEDs [J]. INT J HEAT MASS TRAN., vol. 75, no. 16, pp. 462-469, 2014.

25. B J Huang, C W Tang, M S Wu. System dynamics model of high-power LED luminaire [J]. APPL THERM ENG., vol. 29, no. 4, pp. 609-616, 2014.
26. D Jang, S J Park, K S Lee, et al. Thermal performance of a PCB chance heat sink for LED light bulbs [J]. INT J HEAT MASS TRAN., Nov. 89, pp. 1290-1296, 2015.
27. W Feng, B Feng, F Zhao, et al. Simulation and Optimization on Thermal Performance of LED Filament Light Bulb [C] // SSLCHINA. 2015, pp. 88-92.
28. X B Luo. Z Mao, S Liu. Thermal design of a 16W LED bulb based on thermal analysis of a 4W LED bulb [C] // Electronic Components and Technology Conference. IEEE, 2010, pp. 1906-1911.
29. T Yuge. experiments on heat transfer from spheres including combined natural and forced convection [J]. J ENHANC HEAT TRANSF., vol. 82, no. 3, pp. 214-220, 2014.
30. S S Feng, T Kim, T J Lu. Thermal Resistance Analysis of Pin-Fin Heat Sinks Under Nonuniform Impingement Heating [J]. J THERMOPHYS HEAT TR., vol. 25, no. 1, pp. 119-129, 1971.
31. R C Reid, T K Sherwood, R E Street. The Properties of Gases and Liquids [M]. McGraw-Hill*, 1977.
32. Y Q Chang, Z D Cao, Z X Zhao, et al. Calculation method for thermal properties of multi-component gas [J]. J CHIN SOC MECH ENG, vol. 30, no. 10, pp. 772-776, 2010.

Citation: Jun Zou, Hong Wu, Wei Wang et al. (2020), Shanghai Institute of Technology, P. R. China. J Electron Sensors; 3(1): 1-09

DOI: **10.31829-2689-6958/jes2020-3(1)-113**