LED's Luminous Flux Lifetime Prediction Using a Hybrid Numerical Approach

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Abstract

Light-emitting diodes (LEDs) have several advantages over traditional incandescent bulbs and compact fluorescent lamps, such as superior energy efficiency, environmental friendliness, and particularly long lifetime (between 25,000 to 100,000 hours). However, this long lifetime of LED proves inconvenient to manufacturers for conducting reliability tests which require the same amount of time to conclude. To overcome such inconvenience, this paper presents a hybrid numerical approach that combines numerical modeling with analytical analysis to predict the lifetime of LEDs. In this paper, a 60W-equivalent 10W phosphor-converted white LED bulb is studied by two numerical approaches. A one-dimensional (1-D) thermal-resistance circuit analysis and a three-dimensional (3-D) hybrid finite element analysis (FEA) are employed to estimate the LEDs' junction temperature in accord to the data obtained through the experiment. The numerical results showed that both 1-D thermal-resistance circuit and the hybrid FEA model are in agreement with the experiment data, thus invaluable to manufacturers who need to carry out reliability testing. Then the estimated junction temperature is used to determine the LED luminaire's lifetime according to the known LM-80 database and TM-21 method.

1. Introduction

Since the technology breakthrough in fabricating high brightness LED in 1994 [1], LED has become a solid competitor to other traditional general lightings such as incandescent bulbs and compact fluorescent lamps. Overall, LED lighting is a favorable choice due to its superior energy efficiency, environmental friendliness, and particularly long lifetime. Being solid-state lighting (SSL), where there are no moving parts inside the package, LEDs are able to demonstrate operating lifetime's up to 100,000 hours. For LED manufacturers, this long lifetime proves to be inconvenient because the reliability tests require the same amount of time to complete. This issue is also recognized by the U.S. Department of Energy (DOE); according to its LED labeling recommendations, lifetime is recommended but not required to be stated. If it is not stated, at least one of these other options is to be included: lumen depreciation, a warranty, or an estimate based on accelerated testing of components [2]. Due to the time constraint, accelerated lifetime tests (ALTs) where LED lifetime can be determined within a reasonable test period have been considered and developed [3, 4]. However, because high-brightness LED is relatively new and advances at a rapid pace, the reliability research is quite far behind [5-7]. Even so, it is still possible to obtain LED lifetime without the direct measurement thanks to the two standards approved by Illumination Engineering Society (IES): LM-80-08 and TM-21-11. LM-80 is the standard for measuring lumen maintenance of LED light sources, and TM-21 is the method for projecting LED lifetime based on LM-80 data. By using TM-21, the total time required to collect luminous flux data is only 6,000 hours, as opposed to 25,000+ hours of actual LED lifetime. Cai M. *et al* studied the feasibility of this approach with the aid of 3-D FEM (finite element model) and found the predicted LED lifetime was in agreement with the lifetime claimed by the manufacturer [8].

At the p-n junction of the LED, electrical energy is converted into light energy. The conversion efficiency, however, is not 100%, and there is always heat generated as a product of energy loss. So far, as high as 40% of electrical power can be converted to light [9]; this number is expected to be higher as the LED technology becomes more mature. Heat generated inside LEDs must be effectively released out of the system to the environment; otherwise the LED's operating temperature will become higher and higher. Many studies have shown that high operating temperature can damage the LED package in several ways, such as lumen depreciation, die-attach delamination, epoxy degradation, high mechanical stresses due to mismatch of thermal expansion coefficients of materials, decrease of electron-hole recombination efficiency in the active layer, and color shift [5, 6, 10-12]. Any of these effects can reduce the useful LED lifetime significantly. For instance, a 10°C-15°C increase of junction temperature (T_j) can reduce LED lifetime by 50% [13]. Therefore it is crucial to effectively release the heat generated by the light conversion to the environment in order to maintain LED performance.

In order to increase heat flow from the p-n junction to the environment, heat sink must be constructed as a part of the LED structure. The heat transfer process used in a typical LED system is generally a combination of conduction, natural convection, and radiation, which will greatly affect the magnitude of T_j. Since T_j is usually very difficult to be determined by experimental testing, effective methods for thermal analysis of LED systems become necessary.

In this paper, both experimental and numerical methods are employed to study junction temperatures of typical LED bulbs. First, a 60W-equivalent 10W phosphor-converted white LED bulb is tested by

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measuring the board temperature during the operating condition. Second, two different numerical models are developed according to the LED bulb's structure. They are a 1-D thermal-resistance circuit model and a 3-D hybrid FEA model, respectively. In the 1-D thermal-resistance circuit, multiple LEDs are mounted to a printable circuit board that is attached to a heat sink. A thermal resistance between LED junction and board is used to find the junction temperature. Second, a hybrid 3-D finite element model is developed. In the FEM, the board, adhesives or solder materials, and heat sink are modeled by 3-D finite elements, while each LED package is modeled by a 1-D element with the diode's thermal resistance. The estimated junction temperature is then used to determine the LED luminaire's lifetime according to the known LM-80 database and TM-21 method.

2. Experimental Procedures

The goal of the experiment is to obtain an accurate temperature reading off of the metal-core printed-circuit board (MCPCB) of an LED light engine to compare to a 1-D analytical model and a 3-D hybrid FEA model.

The LED bulb and the geometry of the light engine after taking the bulb apart can be seen in Figure 1. The bulb used was a typical 10W 120V bulb that fit in an A19 base, and the light engine uses 16 diodes to emit 800 lumens at a color temperature of 2700K. To generate white light, the LEDs adopt phosphor conversion technology with a driver to convert 120V of alternating current to direct current. The driver is housed in the hollow center of the heat sink. As seen in Figure 2, the heat sink configuration found in the bulb test makes no use of fins to create added surface area, instead it relies on a relatively simple hollow-cylindrical shape to create the surface area needed to expel heat and house the driver. It is found that the thermal grease used in the construction of this bulb covered approximately 50% of the surface of the MCPCB that contacted the heat sink.

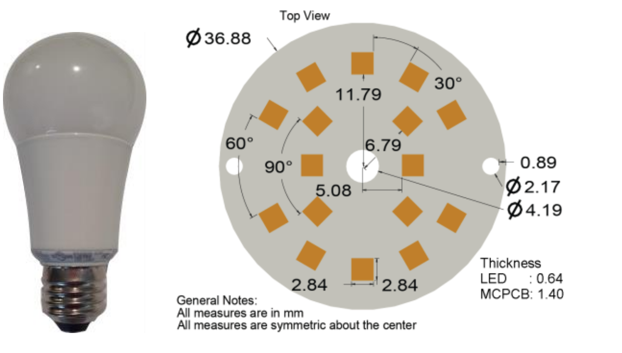

Figure 1. LED bulb and the geometry of its light engine.

To take accurate measurements on the MCPCB at operating condition, a test stand was created to mitigate the heat flow through the base of the lamp. The stand consisted of two A19 lamp bases (as seen in Figure 3) mounted on a generic piece of wood to not inhibit the natural convection generated by the heat flow through the bulbs and heat sinks. Two lamps were tested to achieve consistent test results. The lamp bases were wired in parallel to allow an equivalent voltage to flow through each of them while the bulbs were illuminated. The bulbs were then energized for 24 hours to achieve a steady state condition for the heat throughout the bulb.

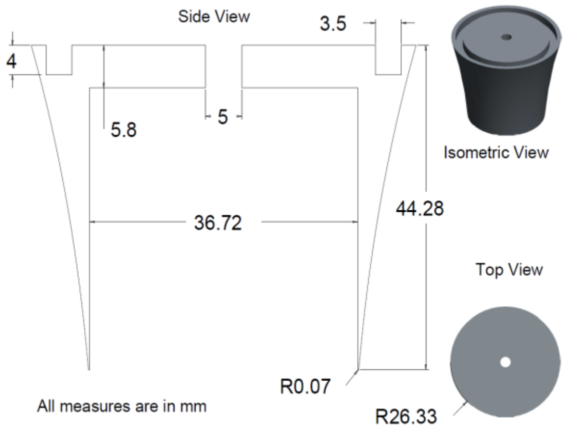

Figure 2. Geometry of Heat Sink

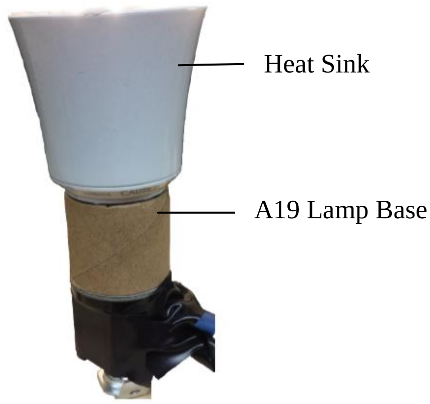

Figure 3. Lamp Base Configuration

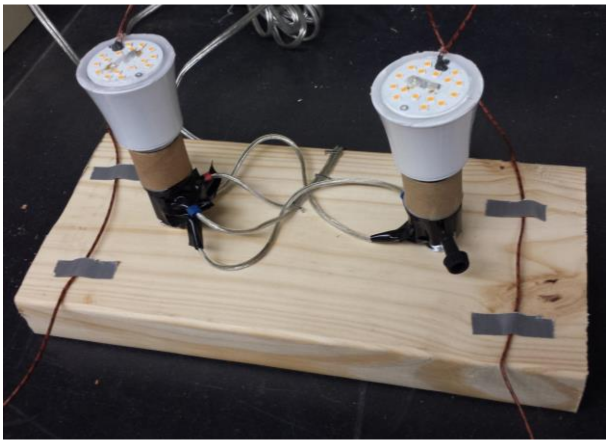

Figure 4. Experimental Test Stand Full View

An infrared (IR) thermometer and a thermocouple were used independently of each other to take the temperature readings on the MCPCB and the heat sink of the bulb. These results can be seen in Table 1. The IR thermometer used was a Dwyer PIR1 with a resolution of ±1°C and the thermocouple used, a Digi-Sense J-Type thermocouple, had a resolution of ±0.5°C. The thermocouple was mounted to the MCPCB using a thermally conductive, electrically insulating epoxy as seen in Figure 6.

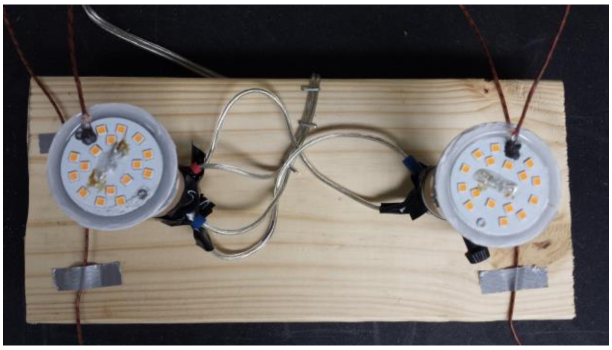

Figure 5. Experimental Test Stand Top View

Figure 6. Location of Thermocouple

Table 1. MCPCB Temperature

Measurement	Bulb 1	Bulb 2
IR Termometer	81	81
Thermocouple	77.4	77.0

3. 1-D Thermal-Resistance Circuit Model

One of the most popular and effective methods used in heat transfer analysis is the 1-D thermal-resistance circuit model. This method models the heat transfer process in a way that is analogous to that of an electrical circuit. It simplifies the heat transfer process from 3-D to 1-D, thus heat can only travel along the path in the circuit. This method is also used in this paper for thermal analysis of the LED packages to determine the junction temperature.

Figure 7 shows a typical LED system that is comprised of a series of LED packages, a metal-core printed-circuit board (MCPCB), a thermal-interface material (TIM), and a heat sink. In this figure, T_j represents the p-n junction temperature inside the LED package; T_b represents temperature at base of the heat sink; and T_p represents the board temperature, which is the measuring point in the experiment part of this study.

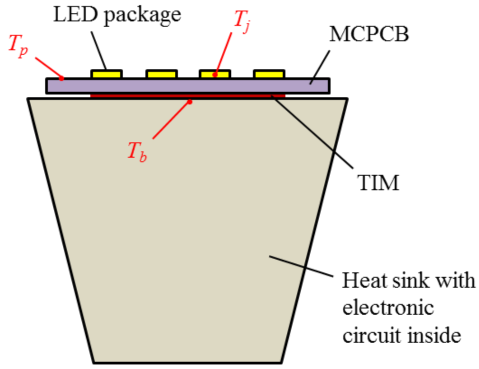

Figure 7. Schematic structure of the LED bulb

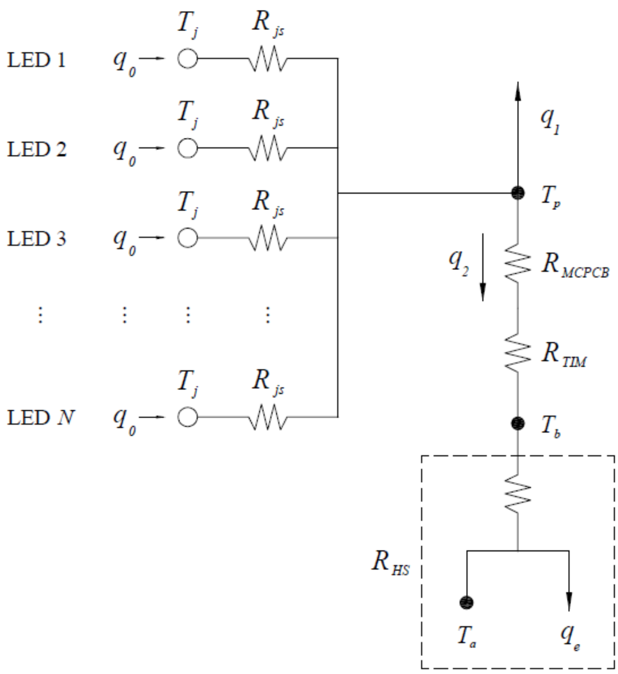

Figure 8. 1-D thermal-resistance circuit model of the LED bulb

In Figure 8, a 1-D thermal-resistance circuit model is developed according to the general structure of a LED bulb. The model indicates that the junction temperature T_j can be affected by the following factors: the heat rate generated at p-n junction (q_0), thermal resistance between p-n junction and MCPCB (R_{js}), thermal resistance of MCPCB (R_{MCPCB}), thermal resistance of TIM (R_{TIM}), and thermal resistance of heat sink R_{HS}. To calculate R_{MCPCB} and R_{TIM}, a general formula is used:

$$R_{conduction} = \frac{t}{kA} \tag{1}$$

where $R_{conduction}$ is thermal resistance (°C/W); t is thickness of material (m); k is thermal conductivity of material (W/m°C); and A is cross-sectional area of the material (m^2).

In the case of R_{js}, its value cannot be calculated directly using equation (1). This is because the structure inside LED package is considered proprietary information and is not generally known to public. Also, each LED manufacture may use different LED chips, setups, and packaging so the value of R_{js} has to come directly from the manufacturer. Usually, this number can be obtained from the LED product information published by the manufacturer. Based on the published information, the value of R_{js} can be as low as 2.5°C/W up to 40°C/W [14-18].

The input heat rate q_0 for each LED module can be determined by the equation below:

$$q_0 = \frac{P_L \eta_D (1-\eta_L)}{N} \tag{2}$$

where P_L is the power of the LED bulb (W); η_D is the driver efficiency of the LED bulb; η_L is the energy conversion efficiency of the LED; N is the total number of LED packages in the LED bulb. The total heat rate can be divided into two parts as:

$$Nq_0 = q_1 + q_2 \tag{3}$$

in which q_1 is heat rate released to the environment through the top section of LED bulb, and q_2 is heat rate that flows to the bottom section of the LED bulb. By defining p_{qt} as the ratio of q_1 to total heat rate, one has

$$q_1 = p_{qt} N q_0 \tag{4}$$

and

$$q_2 = (1-p_{qt}) N q_0 \tag{5}$$

According to Figure 8, the junction temperature (T_j) can be expressed as

$$T_j = q_0 R_{js} + T_p \tag{6}$$

with board temperature T_p determined by

$$T_p = T_b + q_2 (R_{MCPCB} + R_{TIM}) \tag{7}$$

where T_b is the temperature of heat sink base. In order to find T_j, one must determine T_b first. Generally, the energy equation for solving the heat rate across a heat sink can be written as:

$$\frac{d^2T}{dx^2} + \left(\frac{1}{A_c}\frac{dA_c}{dx}\right)\frac{dT}{dx} - \left(\frac{1}{A_c}\frac{h_{eff}}{k}\frac{dA_s}{dx}\right)(T - T_a) = 0 \tag{8}$$

where T is temperature (°C) at position x; A_c is the cross-sectional area of heat sink (m^2); A_s is the surface area of heat sink (m^2); h_{eff} is the effective convection coefficient (W/m^2°C); k is thermal conductivity of heat sink; and T_a is the air temperature. In this study, the geometry of heat sink, which is as shown in Figure 2, is simplified as a hollow-cylindrical shape with average diameter (cross-section area and perimeter are constants).

The temperature of heat sink base (T_b) is involved as one boundary condition for solving equation (8):

$$T(x=0) = T_b \tag{9}$$

Since there is also some heat flowing into lamp socket at x=L (L is the length of heat sink), the other boundary condition for equation (8) is:

$$-kA_c \left.\frac{dT}{dx}\right|_{x=L} = q_e \tag{10}$$

where q_e is the heat flowing into lamp socket. The importance of q_e for obtaining reasonable T_j will be discussed later in the numerical studies.

Solving equation (8) yields a relationship between q_2 (the heat rate that flows into heat sink) and T_b, which is

$$q_2 = C_1 q_e + C_2 (T_b - T_a) \tag{11}$$

with

$$C_1 = \frac{2\exp\left(\sqrt{\frac{h_{eff}A_s L}{kA_c}}\right)}{\left[\exp\left(2\sqrt{\frac{h_{eff}A_s L}{kA_c}}\right)+1\right]} \tag{12}$$

and

$$C_2 = \sqrt{\frac{h_{eff}A_s kA_c}{L}}\tanh\sqrt{\frac{h_{eff}A_s L}{kA_c}} \tag{13}$$

As a special case, if the heat rate that flows to lamp socket is zero, or q_e = 0, equation (11) will turn into the traditional equation of heat sink with adiabatic end ($dT/dx|_{x=L}$ = 0). One can also calculate the thermal resistance of heat sink ($R_{HS\text{-}env}$) by

$$R_{HS-env} = \frac{T_b - T_a}{q_2 - q_e} \tag{14}$$

Note that with the coefficient C_1 having its value close to 1 (see Table 3), equation (11) can be approximated into

$$q_2 \cong q_e + q_{HS-env} \tag{15}$$

where $q_{HS-env} \cong C_2(T_b - T_a)$. This relationship is in agreement with the thermal resistance of heat sink to the environment introduced in equation (14) where heat rate released to the environment through heat sink, or $q_{HS\text{-}env}$, can be estimated using equation (15).

In summary, T_j can be determined by equations (6), (7), and (11) if q_2 is known. The value of q_2 can be estimated by equations (2) and (5). However, the values of p_{qt}, η_D, and η_L may vary with manufacturers. Therefore, sensitivity studies are needed to investigate the effects of these variables.

In this paper, the 1-D thermal-resistance circuit method described previously is employed to perform thermal analysis of the selected LED bulb at normal operating condition. Thermal properties of materials are as shown in Table 2. A sensitivity-study approach is conducted in order to handle the diversity of the following variables:

1. LED driver efficiency η_D : (80%-90%);
2. LED light conversion efficiency η_L : (30%-40%);
3. The ratio of heat released from top section of LED bulb (p_{qt});
4. The heat released into lamp socket (q_e);

5. R_{js} (2.5°C/W-40°C/W); and
6. Effective convection coefficient (h_{eff}).

Different combinations of the above variables are investigated, resulting in three different cases which are as shown in Table 3. Case 1 represents the condition where the combination of LED variables would result in low junction temperature. Case 2 represents the condition where the natural convection coefficient is low, and radiation heat transfer process at heat sink is not considered. In Case 3, the normal operating condition of the LED is studied.

Table 2. Thermal Properties of Materials

Component	k(W/m°C)	R(°C/W)	R''(°C·m²/W)
LED package	-	2.5-40	-
MCPCB	54	0.025	-
TIM	-	0.035	1.85×10^{-5}
Heat Sink (Al)	216	17*	-

* h_{eff} = 12 W/m²°C

Table 3. Results of Sensitivity Study

Variable	Case 1	Case 2	Case 3
Total power (W)	10	10	10
Number of LED, N	16	16	16
Ambient (°C), T_a	25	25	25
Driver efficiency	0.8	0.9	0.8
LED efficiency	0.4	0.3	0.4
% heat to top	20	10	20
Heat rate (W), q_e	0.77[a]	0[b]	0.81
R_{js} (°C/W)	2.5	40	40
h_{eff} (W/m²°C)	12	5	12
Heat rate (W), Nq_0	4.8	6.3	4.8
Heat rate (W), q_1	0.96	0.63	0.96
Heat rate (W), q_2	3.84	5.67	3.84
C_1 in equation (11)	0.97	0.99	0.97
C_2 in equation (11)	0.06	0.02	0.06
$R_{HS\text{-}env}$ (°C/W)	17	40	17
MCPCB (°C), T_p	77.7	252.9	77[c]
Base HS (°C), T_b	77.5	252.6	76.7
Junction (°C), T_j	78.5	268.7	89

[a] 20% of q_2
[b] Heat flow to lamp socket is set to be zero
[c] T_p measured in experiment

By analyzing the results in Table 3, it is found that the most sensitive parameter is the effective convection coefficient (h_{eff}) whose little change in its value could significantly affect the junction temperature (T_j). For other parameters, they do not affect junction temperature as much as h_{eff} does, as can be seen in Case 1 and Case 3. Without the influence of h_{eff}, the junction temperature from Case 1 and Case 3 are very similar to each other, only varying by 10°C. Case 3 is different from Case 1 and Case 2 in that instead of designate a certain amount of heat to transfer to lamp socket (q_e), the actual board temperature (T_p) is used to signify the normal operating condition of the LED, then q_e is determined by equation (11). Under the normal operating condition, or Case 3, heat generated at p-n junction is released to the environment through the three exits as follows: 20% through top part of LED bulb (q_1), 63% through surface area of heat sink ($q_{HS\text{-}env}$), and 17% through lamp socket (q_e). These results confirm that majority of heat in the LED system is released through the heat sink as to be expected. The junction temperature at normal operating condition is calculated to be 89°C, which is consistent to the acceptable range of the operating junction temperature by the LED industry [19,20].

4. Hybrid 3-D Finite Element Model

Besides the 1-D thermal-resistance circuit model discussed previously, a hybrid finite element method is also implemented in ANSYS to estimate the junction temperature. Unlike traditional FEM that considers internal structures of LED module, our method assumes that heat flow transfers only in one direction (thickness direction) through each LED module. Therefore, each LED module can be modeled as 1-D thermal resistor similar to previous 1-D thermal circuit analysis. In the meantime, convectional 3-D thermal analysis is still applied to all the other components of LED lamb, including heat sink, MCPCB, thermal paste, and air. There are several advantages of this hybrid method, such as reducing the efforts of numerical modeling on complex LED structures, fully considering 3D effects of heat sink, and offering convenience for parameter sensitivity studies.

Figure 9 shows the mesh of the LED bulb based on the hybrid FEA method. As it can be seen, each LED module is modeled as only one element, while the other components are still discretized into regular 3-D elements with much finer mesh size. Material properties of LED modules and other components for FEA analysis are listed in Table 4, which are also used in Case 3 of the 1-D thermal-resistance circuit model.

Table 4. Material Properties for FEA Analysis. Units: k, W/m°C ; R, °C/W.

Properties	LED	MCPCB	Heat Sink	Thermal Paste	Air
k	2.07	54	216	20.20	0.026
R	40.0	0.025	/	0.035	/

As shown in Figure 10, three boundary conditions are applied in the FEA modeling: a natural convection on exterior surface of heat sink, a heat flow of 3.84W through top surface of LED modules, and a heat flow of 0.81W from the heat sink base. These boundary conditions are also consistent with the previous 1-D thermal-resistance circuit analysis.

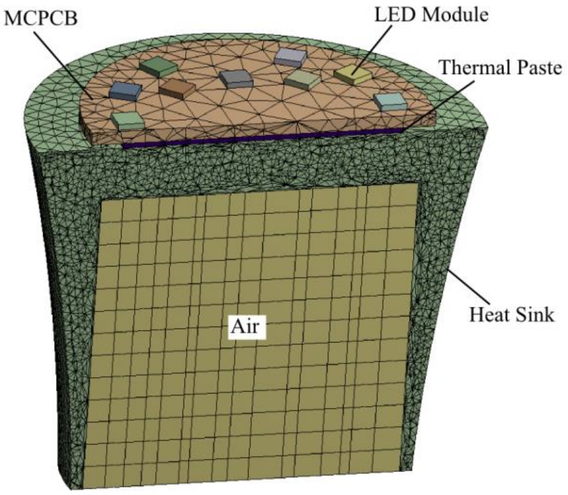

Figure 9. A hybrid FEA model (half) for simulting themermal performance of LED bulb.

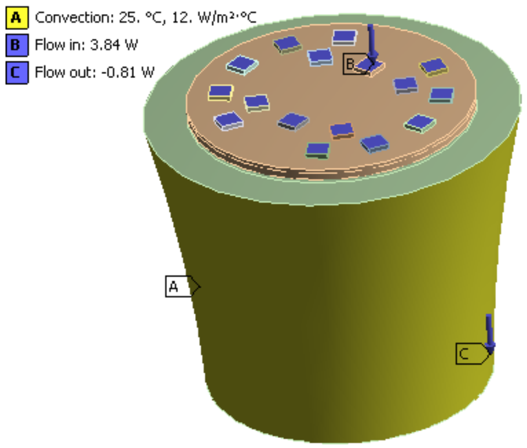

Figure 10. Boundary conditions: A) convection at the exterior of heat sink; B) heat flow through LED; and C) heat flow out of heat sink from bottom.

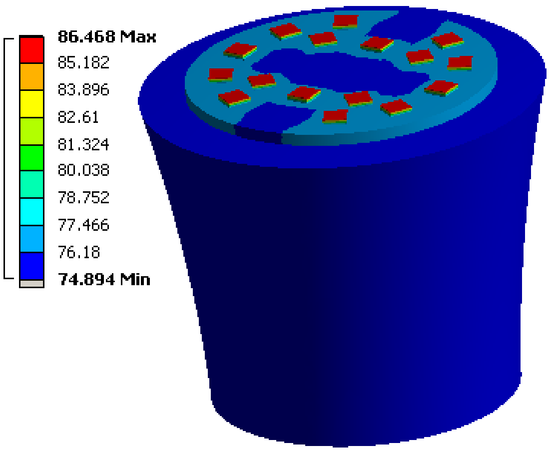

Figure 11. Computed temperature profile from hybrid FEA analysis. Unit: ^{o}C.

Figure 11 shows computed temperature distribution of the whole model at its steady state. The junction temperature, which is at the top of each LED module, is around 86.5^{o}C, about 2.5^{o}C lower than the 1-D thermal-resistance circuit analysis (See Table 3, Case 3). Temperatures profiles for MCPCB and heat sink are as shown in Figure 12 and Figure 13, respectively. Generally, the temperature of MCPCB is relatively uniform due to its high thermal conductivity of the material, and agrees well with the experimental measurement (77^{o}C). The lowest temperature is found at the bottom of heat sink, which is equal to 74.9 ^{o}C. Based on the results of the hybrid FEA model, it can be seen that the heat sink designed for the LED bulb is effective in distributing the heat generated by the LED modules. Comparing to the 1D thermal-resistance model, the hybrid FEA model is more accurate, and the efforts to build the model are also much less than standard FEA modeling.

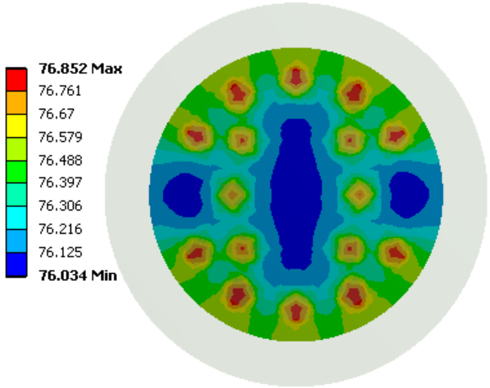

Figure 12. Calculated temperature ditribution of MCPCB surface from hybrid FEA analysis. Unit: ^{o}C.

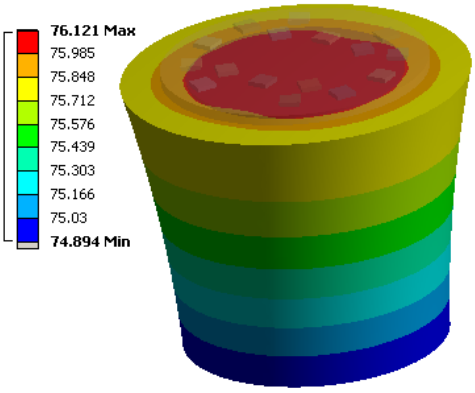

Figure 13. Calculated temperature profile of heat sink from hybrid FEA analysis. Unit: ^{o}C.

5. Discussions and Conclusions

In this paper, two methods in thermal analysis of a typical 10W LED bulb are discussed. The results from the sensitivity study of 1-D thermal-resistance circuit method suggest that the most sensitive parameter is the effective convection coefficient (h_{eff}). Either using too low of a value for h_{eff} or too high of a value for h_{eff} could result in incorrect data pertaining to the operating conditions of the LED because the calculated junction temperature would be too far off from the actual junction temperature. At normal operating condition, the analysis gives a junction temperature of 89°C, which is as expected for a typical functioning LED by the lighting industry.

As the second method, the hybrid 3-D FEA models each LED package by a 1-D thermal resistor with the estimated thermal resistance R_{js} while the board, adhesives or solder materials, and heat sink are modeled by 3-D finite elements. The reason behind using the 1-D element for LED package is because each LED manufacturer uses different LED chips, configurations, and packaging, which is the information that is not distributed publicly; only the thermal resistance between p-n junction and board, or R_{js}, is published. At normal operating condition, the results from the hybrid 3-D FEA show that the junction temperature (T_j) is 86.5^{o}C, which is only 2.5^{o}C lower than the one determined by the 1-D thermal-resistance circuit method. Overall, the results from the hybrid 3-D FEA method and the 1-D thermal-resistance circuit method are in good agreement, indicating that the performance of the 1-D thermal-resistance circuit method can be as good as the hybrid 3-D FEA method. However, this does not mean that the 1-D thermal-resistance circuit model can completely replace the 3-D FEA method in all situations. The agreement of their results in this paper can be a result of the simplicity of both LED system and the shape of heat sink. Should a more complicated LED system be considered, their results are possible to be in less agreement. In which case, 3-D FEA method should be considered over the 1-D thermal-resistance circuit method due to its realization of heat transfer in three dimensions, which is what actually happens in the real application. For thermal analysis to yield reasonable results, regardless of the method, a good understanding of the parameters, especially h_{eff}, is necessary.

Based on our study, the hollow-cylindrical heat sink is considered to perform well for a 10W LED bulb since it can lower LED's junction temperature to be below 90^{o}C, which is the temperature range that is considered to be good operating junction temperature by the LED industry. However, as implied by the sensitivity study, hollow-cylindrical heat sink would not perform well in a higher power LED bulb, where heat sink with more surface area and more complicated shape should be considered.

Since the relationship between the lifetime of LED package and the junction temperature is known due to the fact that all LED light sources are already tested for luminous maintenance at the component level. The present work provide a way to predict the lifetime based on the maximum junction temperature of LED products, instead of running lumen maintenance test at system level to extrapolate the lifetime.

The DOE cautions that this does not directly translate into a complete measurement of lifetime for a luminaire or lamp which may depend on other failure mechanisms [DOE SSL R&D Manufacturing Roadmap].

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