

LED Lighting: A Case Study

in Thermal Management

This article examines the thermal management of a light emitting diode (LED)-based lighting system. First, we discuss the environment in which the lighting system will be used. Then, we look at the system's cooling needs and the various analyses used to confirm that the LED thermal requirements are being met. The article concludes with a comparison of the results.

LED-Based Lighting System Requirements

An LED-based lighting system was to be designed to replace a halogen-based downlight. A downlight is typically installed in a hollow opening in a ceiling and provides a concentrated output in the downward direction. A thermal management analysis was needed to properly design a cooling method for the LED system, which had to include a natural convection heat sink. This environment is shown in Figure 1

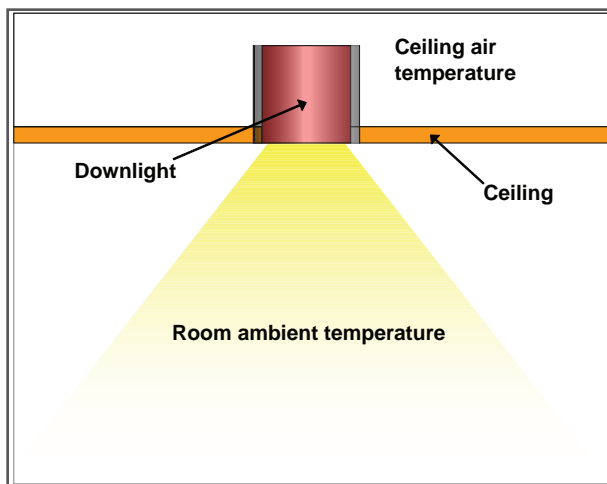


Figure 1. A Typical Downlight Environment.

Product Requirements

The lifetime of an LED relates to its junction temperature and forward current. The new downlight includes three InGaN-based LUXEON cool white K2 LEDs at a forward current of 1000 mA. The maximum operational junction temperature for these cool white LEDs is 150°C [1]. The downlight has a lifetime requirement of 60,000 hours. Figure 2 shows the lifetimes of the cool white LED for different forward currents, junction temperatures, and for the B10, L70 lifetime condition (which implies that for a specific lifetime, 10% of the LEDs are expected to fail at the specified junction temperature and forward current.) The failure criterion is when the light output of the LED has been reduced to 70% of its original light out. To achieve the 60,000 hours lifetime with a B10, L70 condition, the junction temperatures required for specific forward currents are shown in Table 1. From Table 1, with a forward current of 1000 mA, the junction temperature needs to be kept below 124°C to achieve a 60,000 hours lifetime.

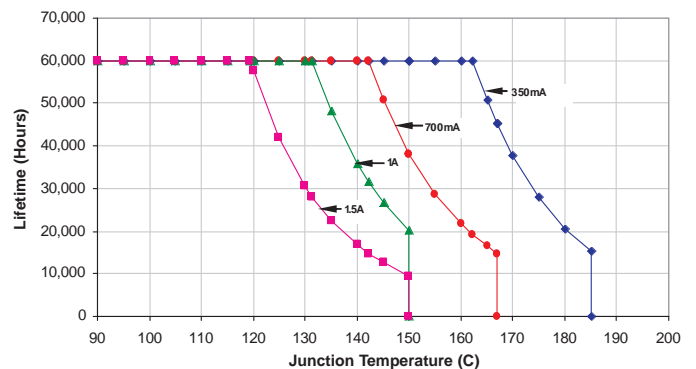


Figure 2. Lifetimes for Different InGaN Versions of the LUXEON K2 LED [2].

Table 1. Required Junction Temperatures of LUXEON K2 LEDs for Specific Forward Currents to Achieve 60,000 Hours Lifetime Under the B10, L70 Lifetime Condition [2].

Forward Current [mA]	Max Junction Temperature [°C]
350	154
700	134
1000	124
1500	112

For this study, in order to achieve a 60,000 hours lifetime the LED junction temperature must be kept under 124°C, with an average year-round temperature of 20°C. Under maximum temperature conditions, the junction temperature must be less than 150°C at an ambient temperature of 40°C.

Thermal Management Analysis

The lifetime and maximum temperature conditions were determined previously; now, a thermal management analysis is applied to each condition. This is a confidence level analysis performed to build in safety margins for all unknowns in all engineering phases. The analysis comprises three sections: analytical, numerical (CFD) and experimental.

1. Analytical analysis
 - a. Based on the unknowns in the analysis and shortcomings of empirical and experimental correlations, assumptions made in order to do the analysis
2. Numerical or CFD analysis
 - a. Unknowns and assumptions made in order to do the analysis
 - b. Shortcomings in the numerical code
3. Experimental
 - a. Incorrect thermocouple placement
 - b. Variations in thermocouple response
 - c. Errors in velocity probe calibration
 - d. Power input measurement

Equation 1 is used for the confidence level analysis, where T_j is the required junction temperature and CFL is the

confidence level being applied. Additionally, $T_{j,condition}$ is the specified junction temperature and $T_{reference}$ is the reference or ambient temperature. The temperature difference between the required junction temperature and the reference temperature, $\Delta T_{condition}$, is used when comparing different conditions.

$$\frac{T_j - T_{reference}}{T_{j,condition} - T_{reference}} = \frac{\Delta T_{condition}}{T_{j,condition} - T_{reference}} \leq CFL \quad (1)$$

Table 2. Confidence Factor Level, CFL, for Different Types of Analyses.

Type of Analysis	CFL
Analytical	80%
Numerical	80% to 85%
Experimental	90%

A confidence level of 90% is used in this study. Re-arranging Equation 1 yields Equation 2. Applying the lifetime conditions to Equation 2 determines the temperature difference for the lifetime condition.

$$\Delta T_{condition} = CFL \times (T_{j,condition} - T_{reference}) \quad (2)$$

$$\Delta T_{lifetime} = 0.9 \times (124 - 20) = 93.6 \text{ K} \quad (3)$$

The maximum temperature difference can also be determined, as shown in Equation 4.

$$\Delta T_{maximum} = 0.9 \times (150 - 40) = 99 \text{ K} \quad (4)$$

From Equations 3 and 4, the lifetime condition is the most severe condition. Re-arranging Equation 1 yields Equation 5, which, applied to the lifetime condition, gives us Equation 6.

$$T_j = CFL \times (T_{j,condition} - T_{reference}) + T_{reference} \quad (5)$$

$$T_j = 0.9 \times (124 - 20) + 20 = 113.3 \text{ }^\circ\text{C} \quad (6)$$

Therefore, the junction temperatures to be determined by different analyses must be less than 113.3°C at an ambient of 20°C.

Analytical Analysis

As a starting point, an LED junction temperature of 108°C is assumed, with a required forward current of 1000 mA. The usable light tool [3] gives a light efficiency of 9.4% and electrical power dissipation, P_e , of 3.53 W. The light efficiency is the ratio of the light power, P_l that the LED emits to the electrical power input, P_e . This is also given by Equation 7, which can be re-arranged in the form shown in Equation 8.

$$\eta_l = P_l / P_e \quad (7)$$

$$P_l = \eta_l P_e \quad (8)$$

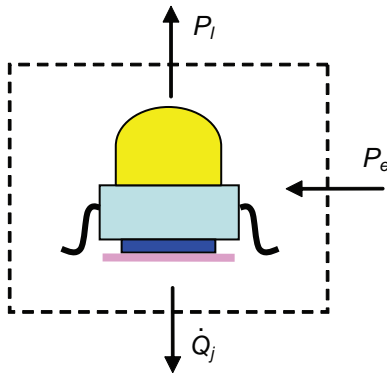


Figure 3. Control Volume Around an LED.

Consider the control volume around the LED in Figure 3. The electrical power input, P_e enters the control volume while the heat dissipated, \dot{Q}_j and the light power, P_l leave the control volume. Applying an energy balance to the control volume yields Equation 10.

$$\sum E_{in} = \sum E_{out} \quad (9)$$

$$P_e = P_l + \dot{Q}_j \quad (10)$$

Re-arranging Equation 10 yields Equation 11:

$$\dot{Q}_j = P_e + P_l \quad (11)$$

Substituting Equation 8 into 11 yields Equation 12. Re-arranging Equation 12 gives Equation 13:

$$\dot{Q}_j = P_e - \eta_l P_e$$

$$\dot{Q}_j = P_e (1 - \eta_l) \quad (13)$$

Because all other values of Equation 13 are known, the heat dissipated by the LED can be calculated.

$$\dot{Q}_j = 3.53 \times (1 - 0.094) = 3.2 \text{ W} \quad (14)$$

Standard FR-4 boards can be used for LEDs with up to 0.5 W of dissipation, but metallic substrates are required for higher levels [4]. Because the LED heat dissipation is 3.2 W, a metal core board type PCB was used. Figure 4 is a sketch of the LED junction to heat sink. It shows each material that the heat from the LED must transfer through before it reaches the heat sink. Figure 4 also provides a thermal resistance diagram based on the sketch. The resistances are considered to be in series.

The metal core board's spreading resistance, $R_{metalcore}$ can be determined using the spreading resistance calculation method explained in [5]. The effective in-plane thermal conductivity can be calculated using Equation 15, as described in [6]:

where t is the total thickness of the PCB, $t_{c,i}$ and $t_{g,i}$ are the

$$k_{p,e} = \frac{\sum_{i=1}^{N_c} k_c t_{c,i} + \sum_{i=1}^{N_g} k_g t_{g,i}}{t} \quad (15)$$

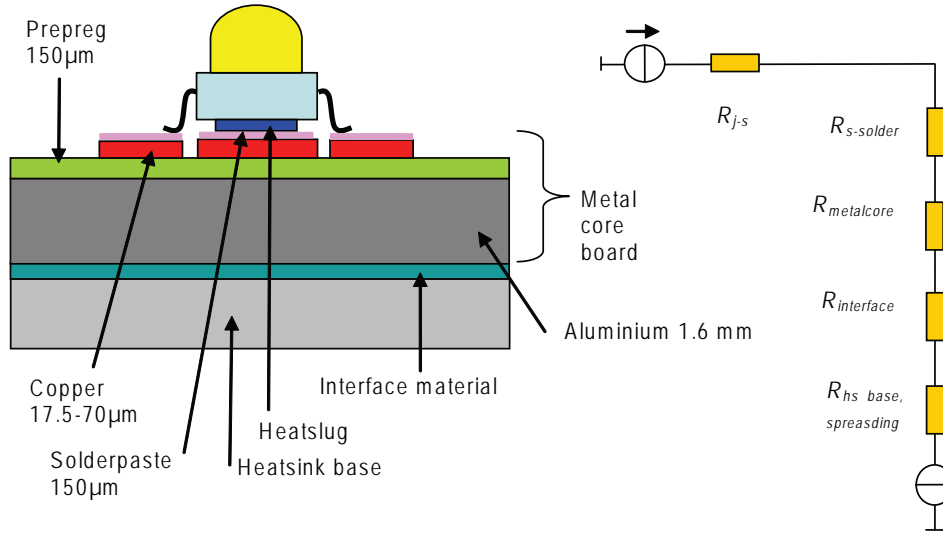


Figure 4. Heat Sink-to-LED Junction and Corresponding Thermal Resistance Diagram.

thicknesses of the copper and glass-epoxy or prepreg/dielectric layers, and k_c and k_g are the thermal conductivities of the copper and glass-epoxy, respectively.

Equation 15 can be modified to accommodate the PCB's aluminum layer, as shown in Equation 16. Additionally, the coverage percentage of each layer can be taken into account by the factor β_p ,

$$k_{p,e} = \frac{\sum_{i=1}^{N_c} \beta_i k_c t_{c,i} + \sum_{i=1}^{N_g} \beta_i k_g t_{g,i} + \beta_{AL} k_{AL} t_{AL}}{t} \quad (16)$$

where t_{AL} is the aluminum thickness and k_{AL} is the thermal conductivity of the aluminum.

The PCB's material properties are shown in Table 3. Using the spreading resistance calculation and effective in-plane thermal conductivity methods previously mentioned, along with the PCB's material properties, the spreading resistance in the metal core board was calculated as $R_{metalcore} = 1 \text{ K/W}$.

Material	Coverage [%]	Conductivity [W/m·K]	Thickness [µm]
Copper	50	385	70
Dielectric	100	3	150
Aluminum	100	180	1600

The other thermal resistance needs are as follows:

1. $R_{s-solder}$ is the thermal resistance in the solder under



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Table 3. PCB Material Properties.

the LED slug. It is 146 μm thick with a thermal conductivity of 50 W/m·K and an area of 22.5 mm². This results in a thermal resistance of 0.13 K/W.

2. The interface resistance is assumed to be 0.2 K/W. This is comparable to the resistance of Chomerics T405-R thermal interface material.
3. The spreading in the heat sink base, $R_{hs\ base, spreading}$ is assumed to be zero.
4. The junction-to-heat slug thermal resistance of the LED is 9 K/W [1].

Consider the thermal resistance in the heat transfer path from the junction to the heat sink base shown in Figure 4. These resistances are considered to be in series, and the junction-to-heat sink resistance is the sum of the individual resistances. Using Fourier’s law of heat conduction in a one-dimensional differential form, the heat transfer rate between the junction and the heat sink can be expressed by Equation 17. Because the required lifetime junction temperature, the heat dissipated by the LED, and the thermal resistance from the junction to heat sink are known, Equation 17 can be rearranged to calculate the heat sink temperature, Equation 18.

$$\dot{Q}_j = \frac{T_j - T_{hs}}{R_{j-hs}} \quad (17)$$

$$T_{hs} = T_j - \dot{Q}_j R_{j-hs} \quad (18)$$

$$T_{hs} = 113.3 - 3.2 \times 10.3 = 80.34 \text{ } ^\circ\text{C} \quad (19)$$

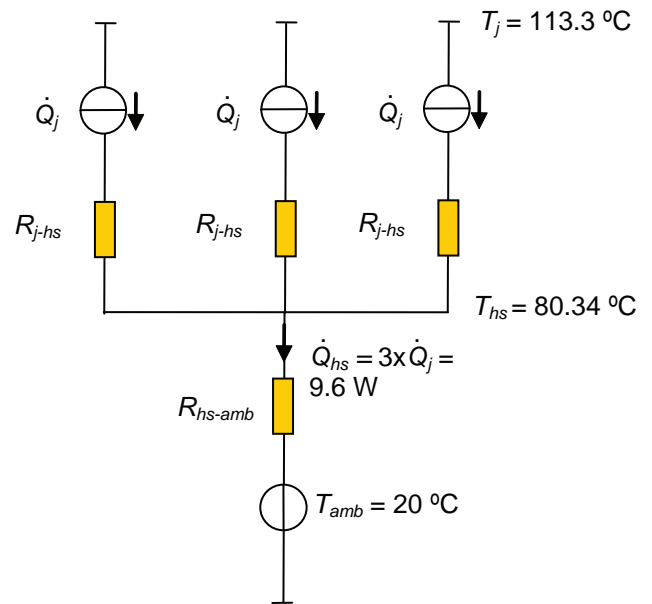
Because there are three LEDs on the heat sink, the sink must be able to transfer 3 x 3.2 W = 9.6 W from a heat sink temperature of 80.34°C to an ambient of 20°C. Using the thermal resistance diagram shown in Figure 5, the thermal resistance from the heat sink to ambient can be calculated using Equation 21. From Equation 22, the heat sink thermal resistance must be less than 6.28 K/W or the heat sink must be able to dissipate 9.6 W at a temperature difference of 60.34 K.

$$\dot{Q}_{hs} = \frac{T_{hs} - T_{amb}}{R_{hs-amb}} \quad (20)$$

$$R_{hs-amb} = \frac{T_{hs} - T_{amb}}{\dot{Q}_{hs}} \quad (21)$$

$$R_{hs\ amb} = \frac{80.34 - 20}{9.6} = 6.28 \text{ K/W} \quad (22)$$

Figure 5. Thermal Resistance Diagram of LED Junction to Ambient.



Ambient.

For the analytical simulation, two methods available to determine the heat sink thermal resistance. The first is to refer to the heat sink’s data sheet, which, in this study, shows that 9.6 W can be dissipated at a 56.3K temperature difference (see Figure 6.) This is less than the required 63.4 K temperature difference.

The second method is to use an analytical model of the heat sink (whose part number is ATSEU-077B-C4-R0.) The results of the analytical analyses are shown in Table 4.

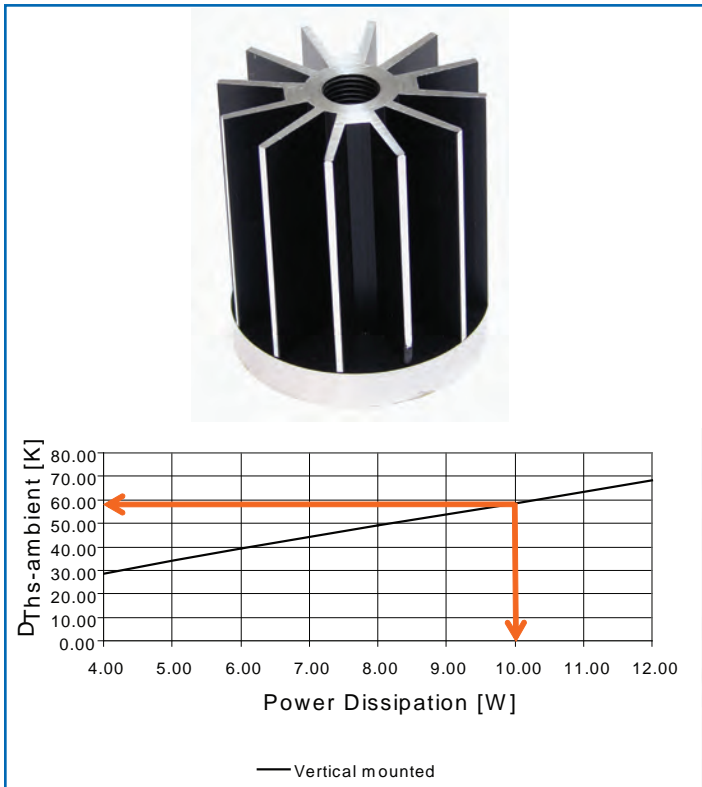


Figure 6. Experimental Results using the ATSEU-077B-C4-R0 Heat Sink.

Numerical Results

Based on the analytical results, a model of the downlight was created. It was simulated in a free air environment. The boundary conditions for a free air environment are discussed in [7]. The results of the numerical analysis are shown in Table 4.

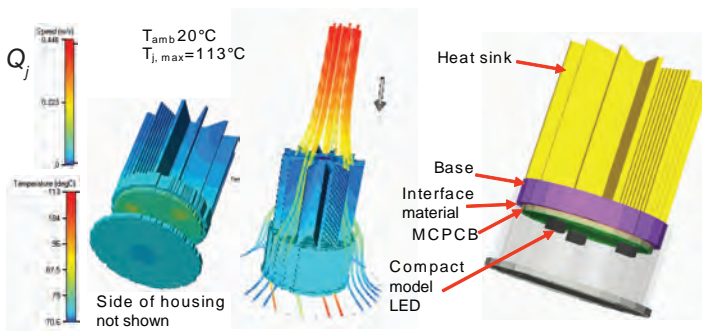


Figure 7. Numerical Results of the Downlight Analysis.

Experimental Results

An experimental model of the downlight was manufactured

and tested. This was done in order to verify the results of the analytical and numerical analyses. The LEDs were calibrated using the forward voltage method, also referred to as the electrical method. In the forward voltage method, the LED is calibrated at a sense current. Thereafter, the LED is tested at the required forward current of 1000 mA. When steady-state has been reached, the junction voltage at the sense current is measured and the junction temperature can be calculated from the calibration curve. A detailed example of the forward voltage/electrical test method is given in [8].

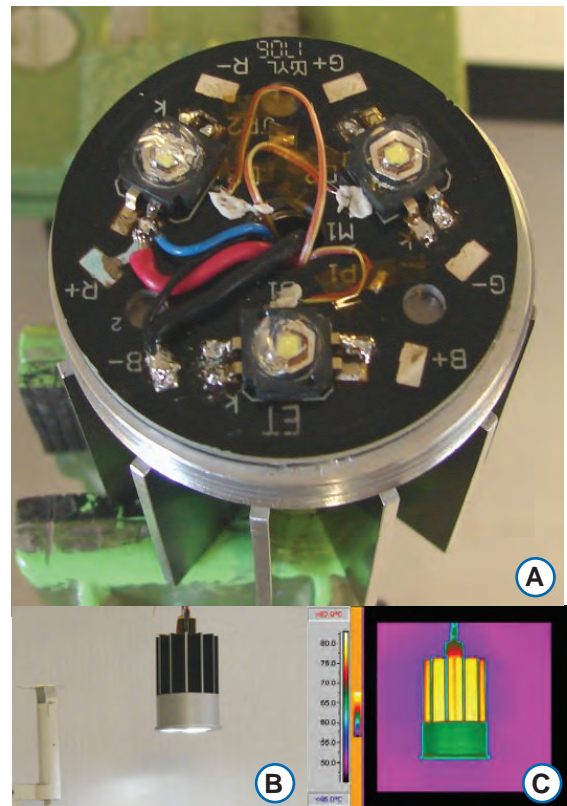


Figure 8. Images of the Experimental Analysis showing the LEDs (a), the Experimental Set Up (b) and an Infrared Picture of the Lighting System (c).

Comparing the Analytical, Numerical and Experimental Results

Table 4 summarizes the analytical, numerical and experimental results for the LED lighting system. The table shows that the results obtained using the different methods are within 10% of each other and have a high confidence level. The maximum temperature difference calculated for the CFD results is 93 K. Further, the experimental results

Table 4. Comparison of the Analytical, Numerical and Experimental Data, Normalized to an Ambient Temperature of 20°C.

Parameter	Units	Analytical, with experimental hs-data	Analytical, only	CFD	Experimental
$T_{ambient}$	°C	20	20	20	20
$I_{forward}$	mA	1000	1000	1000	1000
Light efficiency	%	9%	9%	9%	9%
$P_{dissipated, total}$	W	9.6	9.6	9.6	9.6
$T_{heatsink base}$	°C	68	76	75	71
T_{board}	°C	73	81	84	78
$T_{j, led}$	°C	102	110	113	107
Comparison of methods	%	95%	103%	105%	100%
ΔT_{j-amb}	K	82	90	93	87
Less than the required temperature difference of 93.6K		TRUE	TRUE	TRUE	TRUE

have a temperature of 87 K. Both of these results are below the required 93.6 K for the lifetime condition. Therefore, the analyses have shown that the LED-based downlight system satisfies the lifetime temperature condition. The LED-based downlight lighting system end product is shown in Figure 9.



Figure 9. LED-based Downlight Whose Cooling Solution was Developed by ATS Europe B.V.

Summary

This article explains the development of an LED-based downlight system. The LED lighting system uses 3 LUXEON K2 LEDs at a forward current of 1000 mA. The article discusses analytical, numerical and experimental analysis methods. A comparison of the different analysis results are

given. For reliability, it is recommended that at least two independent results be obtained, and that these not differ by more than 20%.

References:

1. Luxeon K2 Technical data sheet, DS51, <http://www.philipslumileds.com/pdfs/DS51.pdf>, September 2009.
2. Luxeon K2 Reliability Datasheet RD06, <http://www.philipslumileds.com/pdfs/RD06.pdf>, September 2009.
3. Future Electronics, Usable Light Tool, www.futurelightingsolutions.com.
4. Petroski, J., Thermal Challenges in LED Cooling, Electronics Cooling Magazine, November 2006.
5. Spreading Thermal Resistance: Its Definition and Control, Qpedia eMagazine, September 2007.
6. Shabany, Y, Component Size and Effective Thermal Conductivity of Printed Circuit Boards, I THERM, 2002.
7. Boundary Conditions for Natural Convection CFD Simulations, Qpedia eMagazine, June 2009.
8. Hulett, J. and Kelly, C., Measuring LED Junction Temperature, <http://www.photonics.com/Content/ReadArticle.aspx?ArticleID=34316>, September 2009/