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THERMAL MANAGEMENT BASICS AND ITS IMPORTANCE FOR LED LUMINAIRE PERFORMANCE AND COST.

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LED luminaires are being marketed today as an alternative lighting technology that reduces power consumption and maintenance costs for commercial and residential installations. Thermal management has a significant impact upon the lifetime, performance and cost of an LED luminaire. Without proper application of thermal management design principles, the potential benefits of solid state lighting and its ability to be successfully marketed will be reduced.

LED efficacy (lumens produced per unit of applied electrical power, lm/W) is the single most important light engine characteristic. LED efficacy is reduced as the junction temperature of the device is increased. As the efficacy is decreased, the number of LEDs in a given luminaire required to achieve the desired luminous intensity are increased, along with the cost of materials. The power consumed to achieve the desired luminous intensity is also increased, which in turn increases the operating costs.

Luminous maintenance (change in light output over the life of the LED) is the second most important characteristic. Luminous maintenance is reduced as the LED junction temperature increases. The lower the luminous maintenance figure, the more frequently the light engine will need to be maintained or replaced. This increases the operating cost of the light engine.

Failing to properly manage the LEDs' junction temperature can result in an increase in the dominant wavelength and the correlated color temperature of the luminaires' light output, while causing the device's CRI (color rendering index) to be decreased, meaning the light fixture is less likely to reproduce true colors. There are color-critical applications that are adversely affected by changes in these parameters, such as in color sensing, photography, displays and signage, and cinematography equipment.

The purpose of LED light engines is to reduce the operating and maintenance costs of luminaires. Maintaining a lower junction temperature will further reduce the total cost of ownership of the LED light engine, making thermal management an important part of the luminaire design. There are several parameters of an LED's electrical performance that must be considered in applying proper thermal management to LED light engine design:

Forward voltage of an LED is directly affected by junction temperature: as junction temperature increases, forward voltage decreases. Most of today's LED light engines are powered by a constant current drive circuit. As the forward voltage is decreased, the electrical power is also reduced. This reduced power applied to the LED, combined with lower efficacy caused by the temperature rise, compounds the loss in light output. However, the reduction in light output can be compensated for by selecting a drive current for the light engine with a thermally stabilized junction temperature.

LED power dissipation creates heat inside the LED and increases the junction temperature. As electrical power (a product of the applied forward current and the LED forward voltage) flows through the LED, it is converted to optical power and heat. Because the LED is a closed system, the sum of the optical power and heat is equal to the applied electrical power. A 100 lumen cool white LED will produce about 330mW of optical power for every watt of electrical power dissipated. The remaining 670mW is converted to heat. A benefit of increasing the LED efficacy is converting less electrical power to heat.

The difference between junction temperature and the ambient environment temperature is a product of the LED heat being generated and the thermal impedance of the path from the LED junction to the ambient environment. By lowering the heat or the thermal impedance, the junction temperature will be reduced.

Thermal impedance is a measure of how well the system transfers the heat from the source. For light engines, heat is transferred in a combination of conduction and convection. Conduction is the transfer of heat across solid matter and is dependent upon the thermal characteristic of the solid and its geometry. For material with a given thermal conductivity (k), the amount of heat being transferred through the material (q), the material's effective thickness (L) parallel with the flow of heat, and the effective area of the thermal path (A), the change in temperature from the material boundary (T1) closest to the heat source to the second boundary (T2) is calculated by the following equation derived from Fourier's law of heat conduction:

$$T1 - T2 = \frac{q \bullet L}{k \bullet A}$$

Hence, by maximizing material thermal conductivity (k) and effective surface area of the thermal path (A) and minimizing the length of the thermal path (L), the change in temperature along the thermal path from the first to the second boundary is minimized.

Convection is the transfer of heat from a solid matter boundary to a gas or liquid. Convection is dependent upon the surface area of the boundary and the mobility of the gas or liquid. If the gas or liquid is stationary, the heat transfer is considered to be natural convection. If the gas or liquid is moving, the heat transfer is forced convection. For the solid with an effective surface area (A), the amount of heat being transferred (q), the gas or liquid has a flow-dependent convection heat transfer coefficient (h), which results in a change in temperature from the solid (T_S) to the gas or liquid (T_A). This can be calculated by the following equation derived from Newton's law of cooling:

$$T_S - T_A = \frac{q}{h \bullet A}$$

By maximizing the effective surface area (A) and the convection heat transfer coefficient (h), the change in temperature from the solid boundary to the gas or liquid temperature is minimized.

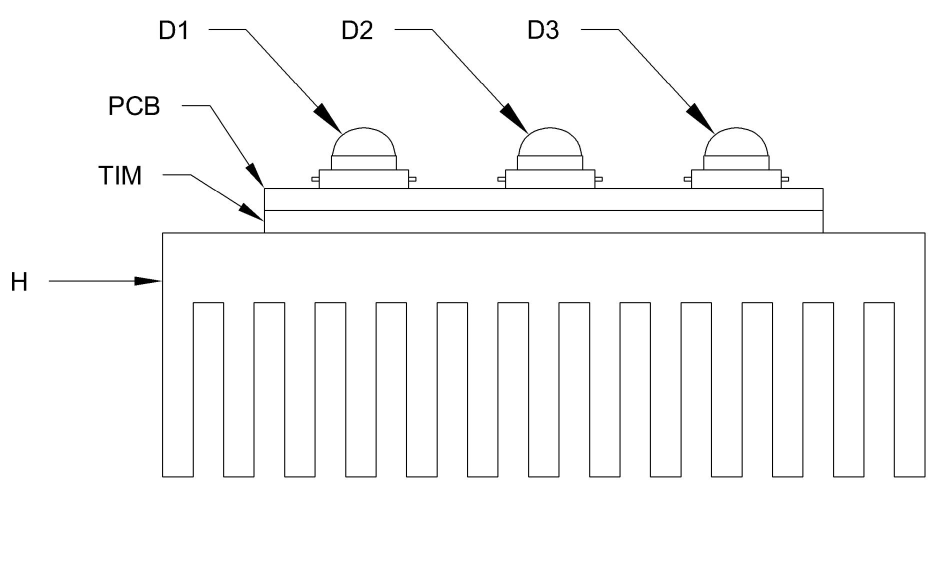
Applying these thermal conduction and convection methods to the design of the luminaire, the LED junction temperature can be maintained to minimize the operating and maintenance costs. The usual limits to the thermal design are physical constraints and fixture cost.
The electrical power being dissipated by an LED is a product of the forward voltage and forward current. For a 100-lumen LED, approximately 33% of the electrical power is converted to optical power, while the other 67% becomes heat. The heat transfer in the LED package begins at the LED junction and most of it flows through the bottom of the die, the die attach material, the lead frame, to the solder joint. The thermal path from the die through the package encapsulant to the ambient environment typically has a higher thermal resistance compared with the path to the solder joint. Therefore, most of the high power LED packages have a thermal pad that may or may not be electrically isolated from the LED. The thermal pad is normally attached to the circuit board with solder. There are designs with the thermal pad attached to the circuit board with thermally conductive material or the thermal pad attached to the heat sink with thermally conductive material.

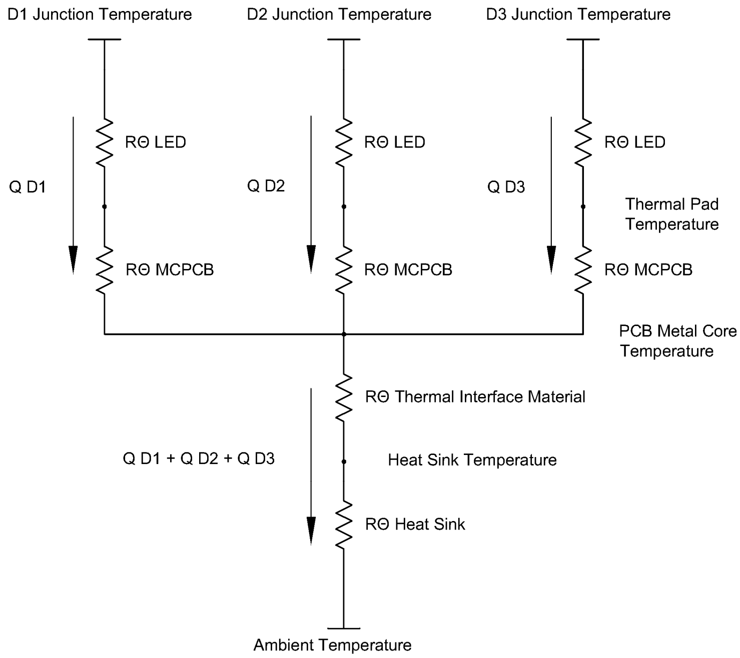
LED manufacturers should list the thermal resistance of the LED package for the path from the junction to this thermal pad. The temperature difference between the thermal pad and the junction is a product of the thermal power and the thermal impedance of the LED package.

There are a number of circuit board materials and constructions that minimize thermal impedance. Many FR4 circuit boards have thermal vias placed next to the thermal pads to conduct heat to the side opposite the LEDs. Metal core circuit boards, such as Optotherm®, are constructed using copper foil laminated to an aluminum plate. The dielectric between the copper foil and aluminum has a thermally conductive fill that is thin enough to provide low thermal impedance yet still offers high electrical isolation between the circuit and aluminum cladding.

Often, the circuit board is attached to the heat sink to increase the heat transfer from the luminaire to the ambient environment. A larger heat sink surface area will result in a lower thermal impedance. To maximize the heat flow from the PCB to the heat sink, a thermal interface material (TIM) is placed between the two components. The TIM can be a grease, epoxy, or pad that fills in the gaps that occur due to surface roughness or warpage.

Determining the LED junction temperature based upon the ambient environment temperature and the thermal resistance of the components along the thermal path are analogous to electric circuit analysis. The temperature is represented by voltage, the heat transfer represented by current, and the thermal resistance represented by electrical resistance. For designs with multiple LEDs, thermal paths are in parallel with each other until the paths are connected to a common point. For FR4 circuit boards with thermal vias, the thermal paths become common at the next element connected to the boards. For metal core circuit boards, the thermal paths become common at the metal core.



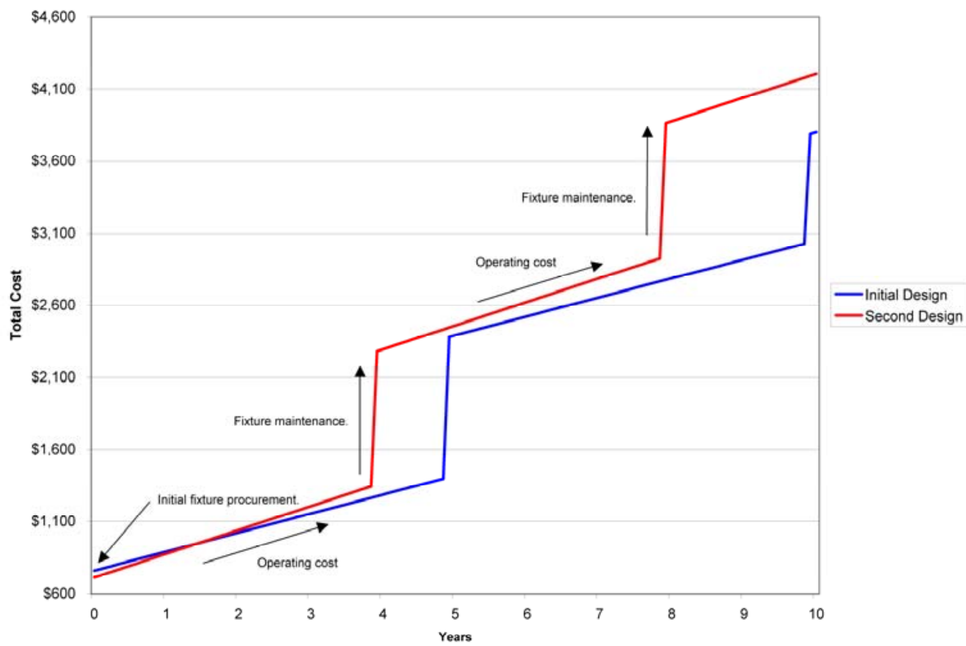


The example above shows a number of opportunities to reduce the effective thermal path resistance. The constraints to the thermal design are typically size of the heat sink and cost associated with the thermal components. If there is not enough volume for the appropriate surface area and airflow to allow natural convection, the design may require forced convection to achieve the desired thermal resistance. The heat may be transferred to a more suitable location that has the appropriate volume and airflow. Heat pipes can serve this purpose effectively.

The total cost of the luminaire, including procurement, operating and maintenance costs, needs to be considered when making design decisions. A decision to reduce the size and cost of the heat sink while at the same time increasing the power consumption to deliver the same amount of light may have the effect of reducing the device's luminous maintenance, which in turn may cause the total cost of the fixture to be higher.

For example, a 100 watt, $750 fixture will cost $657 to operate for five years (24 hours/day) at $.15/KW-H. At the end of the five-year lifespan, the cost to replace the fixture is estimated to be $225 for labor and equipment. If the heat sink design is altered to reduce the procurement cost to $700 but the LED junction temperature is increased such that the power consumption is now 125 watts to produce the same amount of light, the operating cost is necessarily higher [need this calculation].

A second result of the higher junction temperature is the decrease in luminous maintenance, requiring the fixture to be replaced in four years instead of five. The procurement cost of the fixture may have been reduced, but the cost of operating and maintaining the fixture quickly overcomes that savings.



As new LED luminaire designs are created and optimized, their efficacy and luminous maintenance will be the key performance parameters that influence operating costs and maintenance costs. Proper design will balance these factors with the material cost. By evaluating all of the components along the thermal path and understanding how to minimize the effective thermal resistance for every component, the designer will ensure a relatively low junction temperature, resulting in a luminaire that is thermally efficient, with a long operating life and low maintenance costs – in other words, a highly marketable alternative lighting technology.