Thermal Management of High Brightness LEDs at the System Level

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Bridgelux

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LEDs for Illumination – a paradigm shift

• Traditional incandescent light sources are very inefficient, however most of the wasted heat energy is radiated from the bulb

• LED light sources are very efficient, however most of the wasted heat energy is conducted from the package
System Energy Equation

- Electrical Input to System
- Electrical Input to Array
- Driver Efficiency
- Light
- Optical Losses
- Heat
LED arrays vs. LED emitters – Thermal Perspective

- **Different thermal resistance**
  - In application, Bridgelux arrays have one less thermal interface that emitters
  - The thermal path (distance and thermal conductivity) are different due to different package construction

- **Different die to die spacing**
  - Smaller surface area for same lumen output with arrays
  - More concentrated heat source with arrays

- **Materials compatibility - coefficient of expansion**
  - Arrays use compatibility materials and wire bonding technology ‘pre-engineered’
  - Emitters users must consider substrate materials and solder joint properties ‘customer engineered’
Importance of Thermal Management

Most problems in an LED lighting solution are caused by poor thermal management.
Importance of Thermal Management

- Flux changes with temperature  
- Vf changes with temperature  
- Color changes with temperature  

To optimize the performance of a luminaire, proper thermal management is essential.

The effect of case temperature on the LED operation **AT LUMINARE OPERATING TEMPERATURE** must be considered before finalizing the design.
System Margins – Example

System Specification: Energy Star

<table>
<thead>
<tr>
<th></th>
<th>Best Case Scenario</th>
<th>Typical Case Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>575 lm Minimum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40 lm/W Minimum</td>
<td></td>
<td></td>
</tr>
<tr>
<td>15 W Maximum</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Driver Efficiency</strong></td>
<td>80%</td>
<td>75%</td>
</tr>
<tr>
<td><strong>Optical Efficiency</strong></td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Thermal Efficiency</strong></td>
<td>90%</td>
<td>85%</td>
</tr>
<tr>
<td><strong>Guard Band</strong></td>
<td>0%</td>
<td>5%</td>
</tr>
<tr>
<td><strong>Array Efficacy</strong></td>
<td>60 lm/W</td>
<td>75 lm/W</td>
</tr>
</tbody>
</table>

There are MULTIPLE ways to achieve target specification. The best designs aim to optimize ALL aspects.
Thermal Design Process

From the system requirement specification

1. Determine physical dimension constraints & aesthetic goals
2. Determine temperature constraints
3. Determine orientation
4. Calculate the power
5. Consider passive or active airflow designs
6. Select thermal interface material
7. Calculate system thermal resistance
8. Design heat sink
9. Perform computer simulation of design – verify within design limits
10. Build prototype
11. Test prototype – verify within design limits
1. Thermal Design Process: Physical Dimensions

Is there a pre-determined size?

Is the design intended for drop-in replacement of current fixture?

2. Thermal Design Process: Temperature Constraints

**Efficacy considerations:**
- Light output decreases with temperature

**Lifetime:**
- Lifetime decreases with increased temperatures
- Bridgelux recommends maintaining a Tcase below 70°C

**Color shift:**
- CCT shifts slightly with temperature variations

**Ambient:**
- An accurate ambient temperature assumption is critical to proper thermal design
### 3. Thermal Design Process: Orientation

<table>
<thead>
<tr>
<th>Fin Orientation</th>
<th>Illustration</th>
<th>Guideline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical</td>
<td><img src="image" alt="Vertical Illustration" /></td>
<td>100%</td>
</tr>
<tr>
<td>Horizontal</td>
<td><img src="image" alt="Horizontal Illustration" /></td>
<td>85%</td>
</tr>
<tr>
<td>Horizontal Down</td>
<td><img src="image" alt="Horizontal Down Illustration" /></td>
<td>60%</td>
</tr>
<tr>
<td>Vertical (Inside a 6 x 7 x 7 in³ Non-Conducting Box)</td>
<td><img src="image" alt="Vertical Non-Conducting Box Illustration" /></td>
<td>_</td>
</tr>
</tbody>
</table>

Rule of Thumb:
The thermal management system should be designed for 85% of the total LED array input power

\[ Q = (V_f \cdot I_f) \cdot 0.85 \]

- \( Q \) is the thermal power dissipated (approximately the heat that needs to be managed)
- \( V_f \) is the forward voltage of the device
- \( I_f \) is the current flowing through the device

**CAUTION:** Other heat generating sources (i.e. Driver) may need to be considered and added into the total heat load.
### 4. Thermal Design Process: Typical Application Power Ranges

<table>
<thead>
<tr>
<th>Application</th>
<th>Bulbs</th>
<th>Down Light</th>
<th>Street Light</th>
</tr>
</thead>
<tbody>
<tr>
<td>LED Power Range</td>
<td>4 – 15W</td>
<td>12 – 50W</td>
<td>50 – 200W</td>
</tr>
</tbody>
</table>

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In thermal design, SURFACE AREA should be defined as the sum of all thermally conductive surfaces which are exposed to the ambient environment.

When relying on natural convection to transfer heat to the ambient, the minimum required surface area for an aluminum heat sink is 10 in\(^2\) per watt (or 64.5 cm\(^2\) per watt) of dissipated power.

CAUTION!!!
Without airflow, a heat sink fin is rendered useless.
3. Thermal Design Process: Radial Heat sinks

- Radial heat sinks allow for good airflow when lamps are placed in a vertical orientation.
- Utilizing a radial design can improve the efficiency of a thermal system and reduce cost.
5. Thermal Design Process: Airflow

Key Concepts

- A smaller source size leads to increased airflow
- Smaller source leads to a smaller heat sink core
- Heat sink cost reduction

LED Array

LED Emitter
5. Thermal Design Process: Forced Convection

KEY CONCEPTS:

- Physical dimension reduction
- Material volume reduction
- Cost parity with for high wattage systems

<table>
<thead>
<tr>
<th></th>
<th>HS1</th>
<th>HS2</th>
<th>SJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{s-a, C/W}$</td>
<td>0.63</td>
<td>0.75</td>
<td>0.63 &amp; 0.75</td>
</tr>
<tr>
<td>Mass, g</td>
<td>2,392</td>
<td>1,435</td>
<td>606</td>
</tr>
<tr>
<td>Volume, cm$^3$</td>
<td>5,012</td>
<td>3,007</td>
<td>1,714</td>
</tr>
</tbody>
</table>
5. Thermal Design Process: Forced Convection

- Forced convection, aka “Active”, thermal systems increase airflow
- Increased airflow increases the convection properties of a system
- The result is a much smaller surface area requirement

A heat pipe is a heat transfer mechanism that combines the principles of both thermal conductivity and phase transition to efficiently manage the transfer of heat between two solid interfaces.

Heat Pipe Thermal Cycle
1. Working fluid evaporates to vapor absorbing thermal energy.
2. Vapor migrates along cavity to lower temperature end.
3. Vapor condenses back to fluid and is absorbed by the wick, releasing thermal energy.
4. Working fluid flows back to higher temperature end.

Bridgelux in-house testing confirms the thermal simulation above.
5. Thermal Design Process: Active and Passive Cooling

- **Passive Copper**
- **Heat pipes (Limited Airflow)**
- **Passive Aluminum**
- **Rectangular Extrusion**
- **Fan Cooling**
- **Liquid Cooling**

Above this line, consider active cooling systems. Thermal Dissipation vs. Cost.

- **“A Thermal Interface Material or Mastic (aka TIM) is used to fill the gaps between thermal transfer surfaces, such as between microprocessors and heat sinks, in order to increase thermal transfer efficiency.”**

- For all products except RS Array series products, flatness of the back surface of the LED Array is maintained at < 0.1 mm across the LED Array. For RS Array Series products, flatness is maintained at < 0.25 mm across the LED Array. A standard flatness for a manufactured heat sink is around 0.05 mm.
### 6. Thermal Design Process: Interface Material Comparison

<table>
<thead>
<tr>
<th>Pad</th>
<th>Thermal Adhesive</th>
<th>Thermal Grease</th>
<th>Thermal Grease Based Pad</th>
<th>Phase Changing Materials</th>
<th>Thermal Tape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative Thermal Conductivity</td>
<td>Various</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Electrical Isolation</td>
<td>Various</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Various</td>
</tr>
<tr>
<td>Cost</td>
<td>High</td>
<td>Med/High</td>
<td>Low</td>
<td>Low/Med</td>
<td>High</td>
</tr>
<tr>
<td>Manufacturability</td>
<td>Custom stamping of rolls</td>
<td>Screen Printing / Messy</td>
<td>Screen Printing / Messy</td>
<td>Custom stamping of rolls</td>
<td>Custom stamping of rolls</td>
</tr>
<tr>
<td>Reliability</td>
<td>Good</td>
<td>Good</td>
<td>Potential Long Term Silicone Oil Bleed</td>
<td>Potential Long Term Silicone Oil Bleed</td>
<td>Unproven: Thermal Cycling</td>
</tr>
<tr>
<td>Attachment</td>
<td>None</td>
<td>Permanent</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Other Concerns</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Thermal Cycling</td>
</tr>
<tr>
<td>Recommended for Evaluation</td>
<td>High</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>Low</td>
</tr>
</tbody>
</table>
Heat sinks can be defined by the thermal resistance required to maintain a specified array case temperature with knowledge of:

- Thermal power
- Thermal resistance of system
- Ambient temperature

\[ R_{\text{system}} = \frac{\left( T_{\text{case}} - T_{\text{ambient}} \right)}{Q} \]

- \( R_{\text{system}} \) is the thermal resistance from the case of the array to the ambient side of the heat sink.
- For a well assembled luminaire, \( R_{\text{system}} \) is approximately the same as thermal resistance of the heat sink.
- \( T_{\text{case}} \) is the required case temperature of the array.
- \( T_{\text{ambient}} \) is the ambient temperature of the environment.
- \( Q \) is heat flow.

**LED Array**

\[ R_{\Omega ja} = R_{\Omega j-c} + R_{\Omega c-h} + R_{\Omega h-amb} \]

**LED Emitter**

\[ R_{\Omega ja} = R_{\Omega j-e} + R_{\Omega e-c} + R_{\Omega c-h} + R_{\Omega h-amb} \]
Many heat sink companies produce heat sink products (extrusions and castings) that are suitable for use with Bridgelux LED Arrays. These products can be procured quickly directly from the company or their distributor for expediting concept and prototype testing processes.

Thermal Modeling Service Companies can be used by companies in need of thermal and mechanical engineering assistance during their design, prototype or manufacturing processes. These companies offer services ranging from mechanical design to thermal simulation.

Thermal Simulation allows for cost and time reductions during the design and prototyping phases.
Thermal transfer is increased directly under the thermal source. Therefore, conduction vertically through the heat sink is critical in order to fully utilize any heat sink fin design.

Note there is little heat transfer along the top surface.

Thermal transfer density:
As a rule of thumb, heat travels downward at 45° to the surface. Thus, increasing the surface area with a large heat spreader will not significantly improve the thermal design.
10. Thermal Design Process: Build Prototype
11. Thermal Design Process: Test Prototype

Key Tests

• Ambient temperature
• Case temperature
• Light output
• Color

**TIP:** To measure Case Temperature a thermocouple can be mounted under the head of a mounting screw. This is usually within 2 degrees of the case temp.
And don’t forget manufacturing

- Once you’ve designed a good thermal system solution, don’t forget to be sure it is implemented in production
  - TIM application
  - Mounting to heat sink
    - Correct screw torque
Thermal Interface Material – Greases/Epoxies

- Excessive amounts of thermal paste
- Thermal paste fillet too high and could cause electrical short

Bond-line too thick
Insufficient coverage

Insufficient thermal grease coverage

Excessive amounts thermal grease will result in a thick bond-line and possibly an excessive fillet height
Thermal Interface Material – Greases/Epoxies

Proper Application Concepts

Ensure entire bottom of device is covered

Squeeze part on sides onto heat sink (Do not press down on yellow resin area)

Minimize bond-line thickness
Recap

• Most problems with LED applications are related to system level thermal considerations
• Good thermal design is critical
  – Simulate
  – Prototype
  – Test
• Accounting for thermal effects to light output, color and electrical properties are critical
Thank You!