Dr. Michael Müller

Thermal Management for LED applications

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Dr. Dietrich Müller GmbH

- 1967 founded with the production of insulation parts for the electrical motor industry
- 1996 first certification according to DIN EN ISO 9002, constant certification due to required quality standards
- 15 registered trademarks (Thermigrease®, Thermipad®, Flexiso®, Rigidiso® etc.)
- Processing of different materials (electrical insulation materials, technical films, gaskets and thermally conductive products)
- Manufacturing techniques like die-cutting, plotter cutting, laser-cutting, water-jet cutting, cutting, laminating etc.

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Product range Dr. Dietrich Müller GmbH

- Flexible electrical insulating materials ➡ Flexiso®
- Mica products ➡ Rigidiso®, Flexiso®
- Prepregs ➡ Flexpreg®
- Technical films ➡ Tecfilm®
- Pressboard materials ➡ Rigidiso®, Pertinax®
- Gaskets ➡ Flexseal®
- Thermally conductive products ➡ Thermiflex®, Thermigrease®, Thermipad®, Thermiglue®

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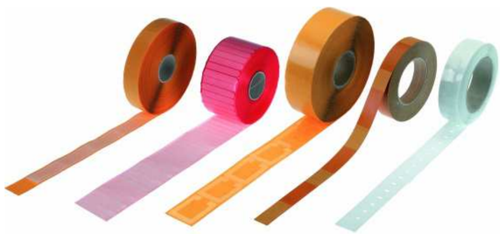

Production facilities

- Cutting
  - *Water-jet*
  - *Plotter*
  - *Laser*
- Finishing
  - *Laminating*
  - *Painting*
  - *Imprinting*
  - *Coating*
- Forming
  - *Heat forming*
  - *Cold forming*
  - *Die-cutting*
  - *Deep drawing*
  - *Pressing*

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Production facilities

- Machining
  - *Turning*
  - *Milling*
  - *Sawing*
- Further facilities
  - *Wire cutting*
  - *Injection molding*
  - *Assembling*
  - *Adhesion*
  - *Ultrasonic welding*

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LED technology

- One of the most efficient technologies, first completed LED was developed in 1962
- Usage in many innovative lightning solutions, longest service life
- Basis of LEDs is PCB technology
- Wide product variation, since there are currents of up to 3A
- Up to 80% of electrical energy is converted into heat which shortens service life of LEDs and effects light output and destroys the PCB

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LED technology

- Higher requirements for high-performance LEDs have to be considered
- PCB temperature quickly rises up to +100°C or more
- Desired properties of LED (brightness, service life etc.) are met when kept under defined target temperature
- Heat must be discharged from chip to LED body and then to ambient air, so cooling agents have to be kept in mind

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LED technology

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- PCB and conversion light emitter lose some of their physical properties over time, so LED degrades
- Lx/By value - IEC 6217 ed. 1 specifies the decrease in luminous flux & states the nominal service life e.g. 50,000 h (luminous flux must not be more than a specific percentage)
- The index states the percentage of installed LED which can fall short of this limit value (total failure is not considered)
- Tests have shown that after 50,000h 90% of LEDs still work, 10% have to be replaced (did not meet certain lightning level)

LED technology

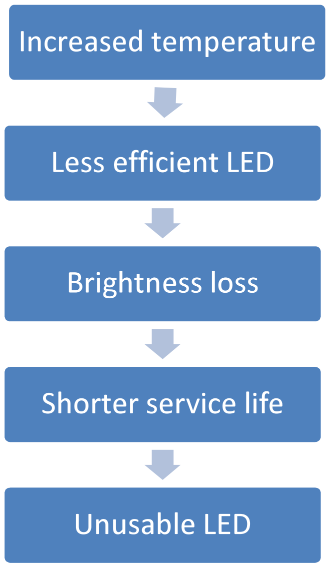
Content:

- Ageing process depends on p-n junction* temperature and is not proportional since it speeds up over time
- Service life and brightness data are only valid for certain p-n junction temperature and are based on statistical values
- Often LED manufacturers state data on the basis of a temperature of 25°C which is unrealistic , normal temperature is around 85°C – 15% decrease in temperature than that given in the data sheet
- To state a realistic service life, the p-n junction temperature has to be determined, which is difficult under realistic conditions

**p-n junction is the interface between semiconductor material (positive & negative)*

LED modules

- High L value* (L90 or L70) and long service life are important for general lightning applications
- Effect lightning and auxiliary lightning can accept about L50
- The cooler the LED remains,
  the better and longer it will perform



** The L value represents the rated life at the point in which the lumen output falls to the declared level*

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Product characteristics

- p-n junction of the LED can suffer damage if tp* value is permitted to attain or exceed tc value

- Defining desired service life helps to determine requisite tp temperature and form a basis for thermal design

- To improve all parameters, the tp temperature must be kept as low as possible

**tc/tp = temperature performance*

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Thermal design

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- Thermal design must ensure that any generated heat is discharged from p-n junction to LED and temperature at tc/tp-point has to be under max. value

- Heat can only be discharged from warmer to cooler material, there are three different processes:

  Heat conduction

  Heat transfer via media with direct physical contact with one another, but without a flowing medium

  Convection

  Combination of heat conduction and heat transfer via moving medium that transports heated parts to cooler regions

  Heat radiation

  Heat is transported via electromagnetic radiation without needing medium. Radiation also functions in and through vacuum. Heat sink or LED casing radiates heat in form of infrared radiation

Thermal design

- Effective thermal design does not increase the casing temperature of an LED but lowers p-n junction temperature

  If LED casing is cold enough to touch, thermal design is inefficient

- For effective thermal design it is important to ensure heat conductive connection between module and LED casing (otherwise LEDs overheat)

- Thermal design can be improved by having a continuous thermal connection from LED module to metal LED body

  e.g. using additional aluminum base and adhere the LED to it with a thermally conductive self-adhesive pad

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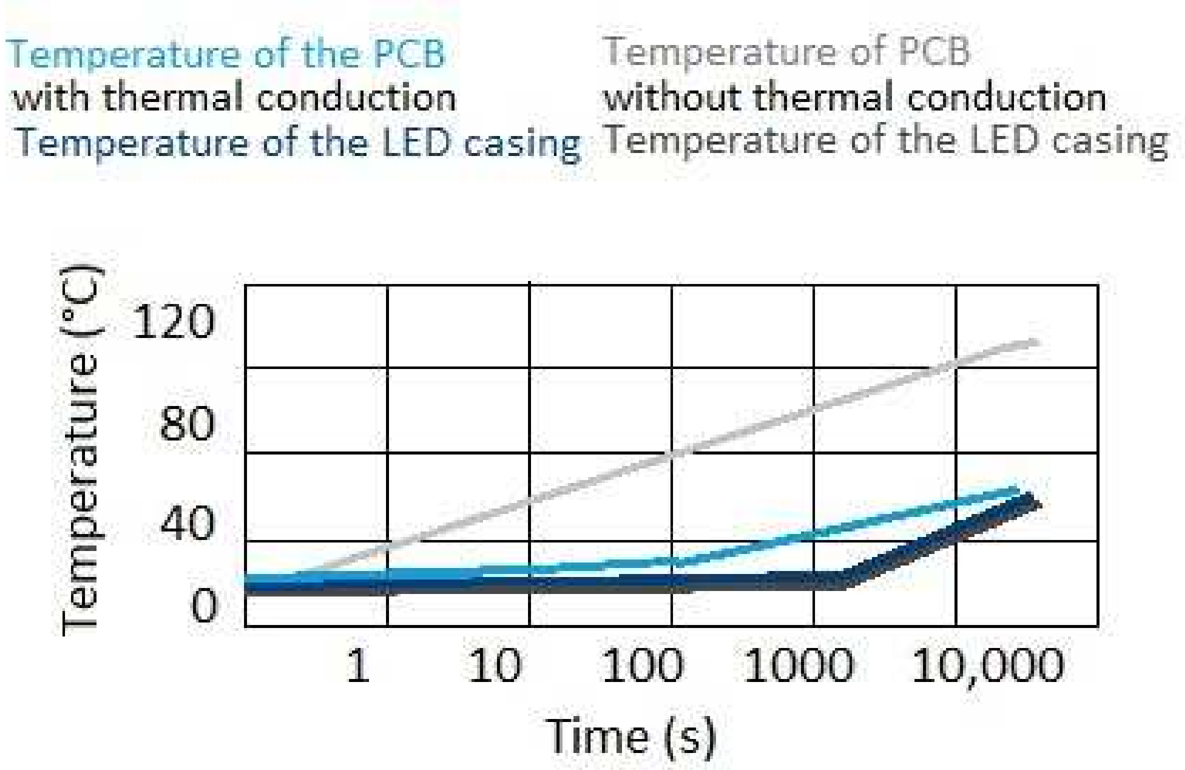
Thermal design

- Material and process should be chosen wisely

  e.g. a difference of temperature at tc/tp point of 105°C to 46°C increases service life to more than 60,000 hours and brightness by 17%



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Basics thermal management

- Optimum ratio of applied electrical power to cooling solution has to be met to ensure stable operational performance over numerous hours

- Depending on available space and material selection, brightness can be achieved at higher operating current and fewer LEDs or lower operating current and more LEDs

  Service life will certainly be shorter in case 1

- Depending on the end-usage of an LED and operating conditions, priorities have to be set

  Electrical power

  Reducing the need for cooling measures

  Increasing light output

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Basics thermal management

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- As soon as LED is connected, heat is given off to ambient air

  Amount of heat is influenced by surface area provided by LED or heat sink

- Improving degree of cooling can be realized by increasing speed of air flow (fans)

  Never operate LEDs without appropriate degree of cooling

- Surface area can be increased by adding lamellae which optimizes heat discharge

  Guideline: surface area of 25cm² is required to discharge 1 Watt

- Efficiency of design should be checked by measuring temperature

  Measure in a steady thermal state (in accordance to EN 60598-1), a thermocouple or sensor must be used to take tc/tp temperature of LED module – max. ambient temperature also has to be simulated

Internal thermal management

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- Heat transfer from p-n junction to LED or heat sink
- Heat conduction is the most efficient heat transportation mechanism
- Degree of heat conduction depends on materials used and on the geometry of LED, most important factors:

  Materials with low specific thermal resistance such as copper or aluminum should be used

  Thickness of materials with a poor heat conduction should be as thin as possible

  Air is an extremely poor conductor, so air gaps should be avoided, e.g. by using thermally conductive pastes or pads

External thermal management

- Discharge of heat from LED body or heat sink to ambient air

- Main processes are convection and heat radiation

- Degree of convection depends on speed of ambient air flow and the surface area at which the air can circulate

  Large surface area and free air circulation are critical

- Heat radiation depends on temperature and surface area of LED

  The hotter and larger, the more heat can be given off in form of IR radiation (normally noticeable at temperatures from 50°C)

  Highly polished metal surface radiate only little heat while varnished surfaces enable very good heat radiation

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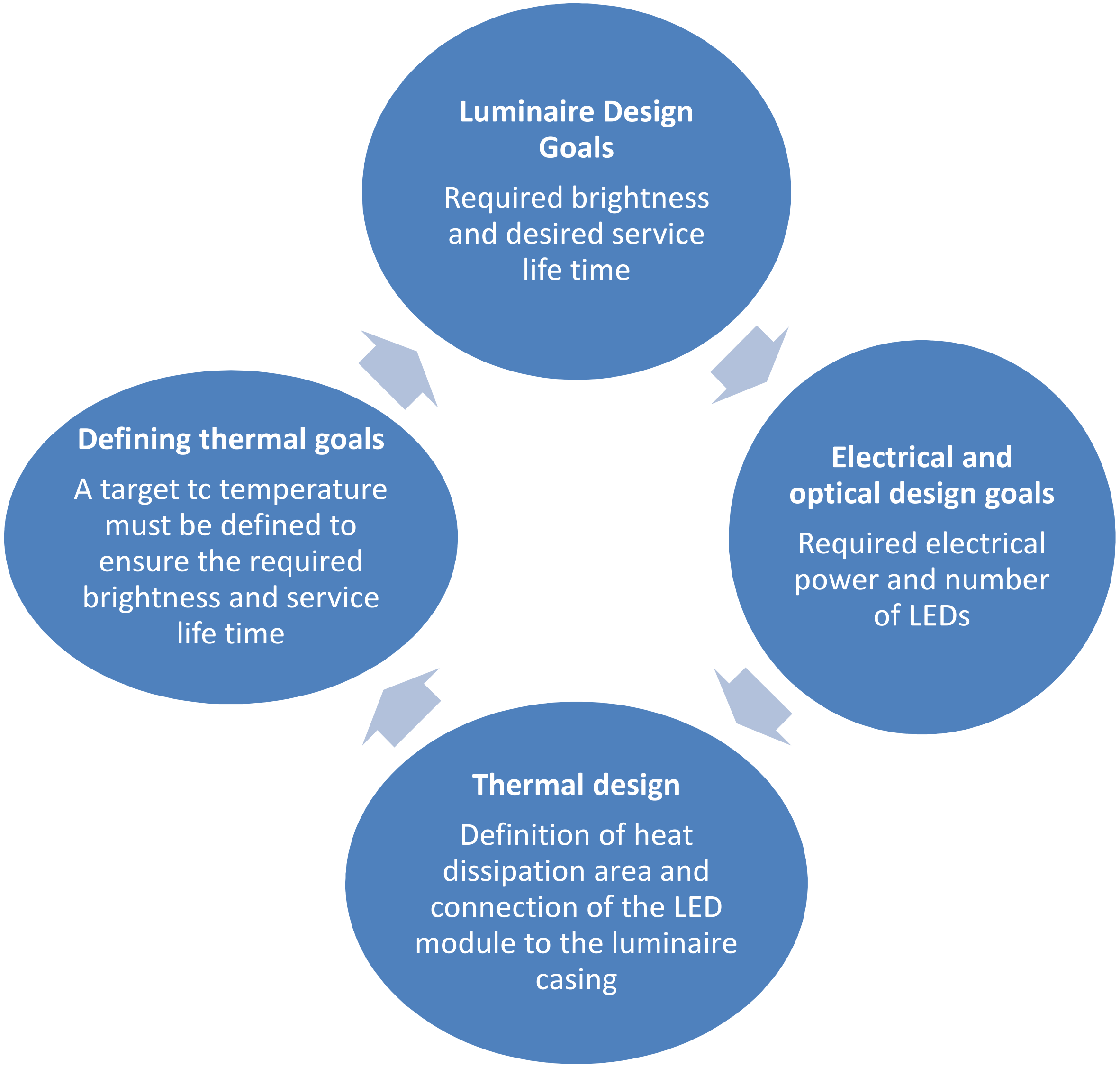
Summary thermal management



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Formula and calculation example

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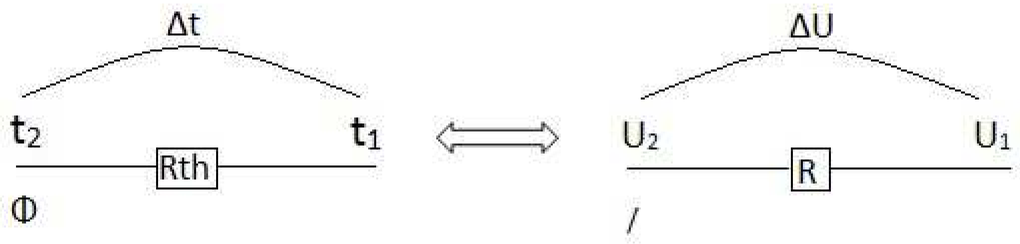
Analogy of a basic electrical circuit to a thermal network

Same principles as for connection of thermal resistors in parallel or series as to electrical circuits

Thermal quantity	Electrical quantity
Absolute thermal resistance Rth [$\frac{K}{W}$]	Electrical resistance R [Ω]
Temperature difference Δt [K]	Electric voltage U [V]
Heat flow Φ [W]	Electric current I [A]
Thermal conductivity λ [$\frac{W}{mK}$]	Electrical conductivity σ [$\frac{S}{m}$]



Thermal equivalent circuit

Electrical equivalent cicuit

Formula and calculation example

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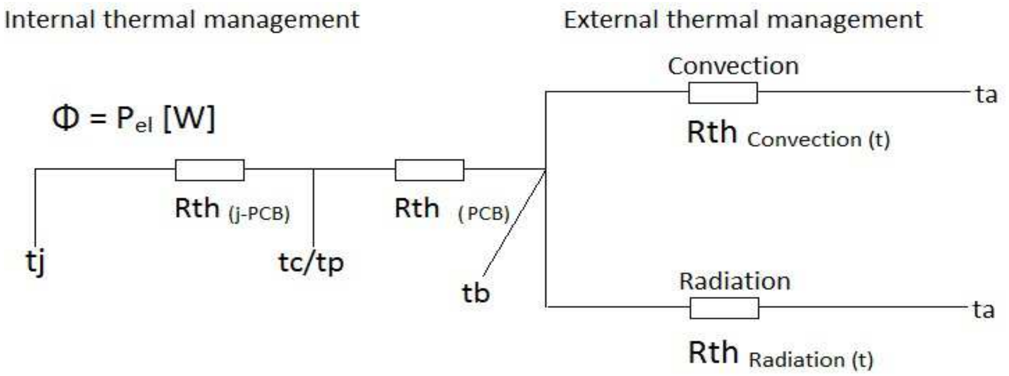
Equivalent thermal circuit diagram of an LED



- Φ = Pel = thermal flow
- To simplify matters, this is assumed to equal the consumed electrical power
- t_j = p-n junction temperature of the LED (Junction Temperature)
- t_p = PCB temperature (Performance Temperature)
- t_a = Ambient temperature
- Rth (j-PCB) = thermal resistance of the p-n junction to the PCB
- $Rth_{Convection}$ (t) = temperature-independent thermal resistance in the convection path

Formula and calculation example

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Thermal transport and thermal resistance

- $\Phi = \lambda \frac{A}{l}(t2 - t1) = \frac{\Delta t}{Rth}$ and thus $Rth = \frac{l}{\lambda A}$
- $\lambda\ [\frac{W}{mK}]$ = specific thermal conductivity of the material
- t_1 = lower temperature; t_2 = higher temperature
- $Rth\ [\frac{K}{W}]$ = thermal resistance

Material	Specific thermal conductivity $\lambda\ [\frac{W}{mK}]$
Copper	398
Aluminum	234
Silicium	148
Tin	67
Silver	429
Air	0.0261

Formula and calculation example

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Heat radiation

- $\Phi = \sigma \varepsilon A \, (t_2^4 - t_1^4)$
- Due to 4th power of temperature, it is not possible to simplify $\Phi = \frac{\Delta I}{Rth_{Radiation}}$
- At higher temperatures thermal resistance decreases in radiation path and more heat is given off (radiation)
- σ = Stefan-Boltzmann constant = $5{,}670 \times 10^{-8} \frac{W}{m^2K^4}$
- ε = emission coefficient = factor between 0 and 1, depending on the surface finish of the heat sink
- A = surface area; t_2 = temperature of the heat source; t_1 = ambient temperature

Formula and calculation example

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Example for emission coefficient ε	
Aluminum, polished	0.038
Aluminum, untreated	0.09
Aluminum, anodized	0.8
Cast iron, polished	0.21
Mild Steel / Stainless Steel	0.2
Copper, polished	0.04
Ceramic, grey	0.9
Ceramic, matte black coated surface	0.97

Formula and calculation example

Convection

- $\Phi = hA\,(t_2 - t_1) = \frac{\Delta I}{Rth_{Convection}}$ and thus $Rth_{Convection} = [\frac{1}{hA}]$
- h $[\frac{W}{m^2K}]$ = thermal transfer coefficient, temperature-independent; typical values for the thermal transfer coefficient for heat transfer from heat sink to ambient air range between 3.5 and 35 $[\frac{W}{m^2K}]$
- A [m²] = surface area
- t_1 = lower temperature; t_2 = higher temperature

Formula and calculation example

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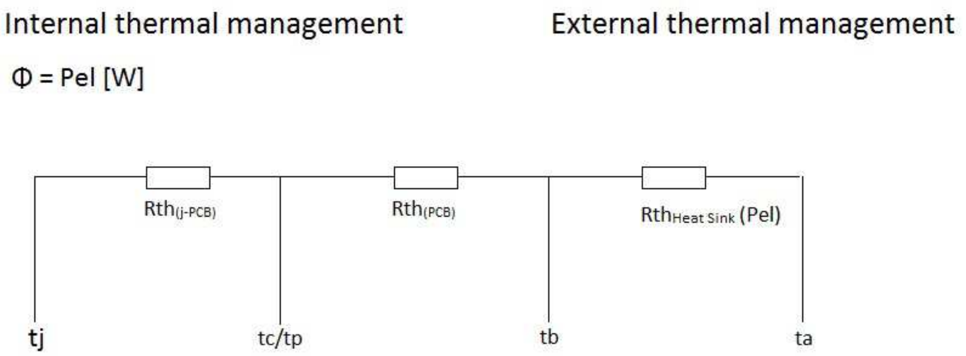
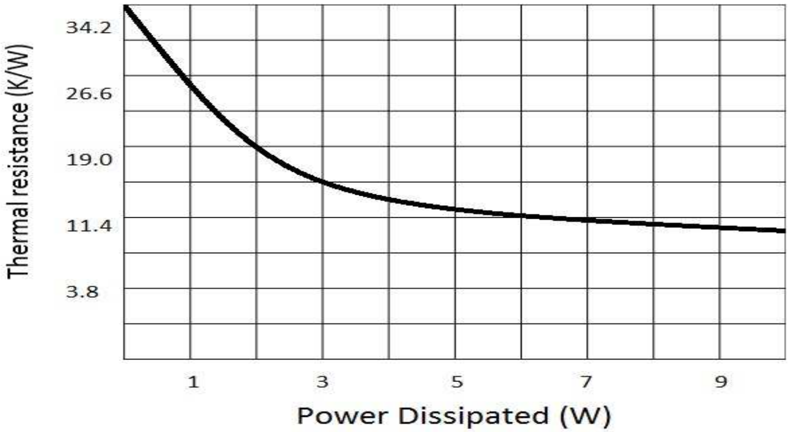
Thermal resistance of heat sinks



- Manufacturers of heat sinks sum up Rth to a value which is dependent on the amount of thermal energy that will be discharged, that simplifies to dimension cooling measures



- The lower the Rth value of the heat sink, the more efficiently it conducts heat

Formula and calculation example

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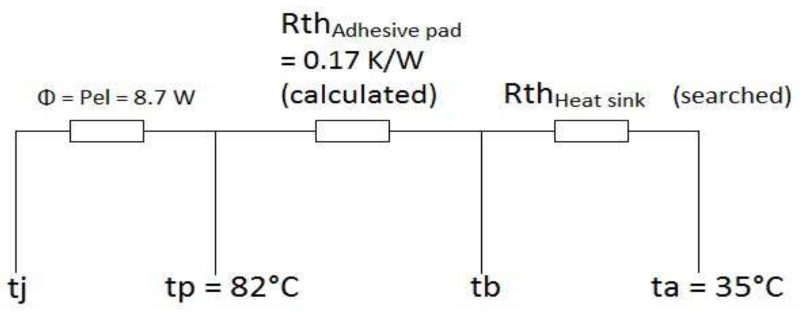
Example:

- Matching heat sink is determined for operating at 700 mA, target service life of at least 40,000 hours by several tests
- LED is adhered to heat sink using an adhesive pad and is operated while unhindered air convection is ta max. 35°C, no casing

Φ = Pel max. at 700 mA = 8.7 W (data sheet details)

Target tp temperature for the desired 40,000 hours: tp = 82°C

Ambient temperature ta max. = 35°C



Formula and calculation example

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Calculation:

- $\Phi = \frac{\Delta t}{Rth}$ and thus $Rth = \frac{\Delta t}{\Phi}$
- The temperature difference Δt results from $t_p - t_a$
- The quality of heat Φ to be discharged is known
- Two thermal resistors $Rth = Rth_{adhesive\ pad} + Rth_{heat\ sink}$ are connected in series between t_a and t_p

Thermal resistance of adhesive pad can be calculated using geometry of article: $\lambda = 0.8\ \frac{W}{mK}$, diameter Ø 43 mm, thickness 0.20 mm and thus

$$Rth_{adhesive\ pad} = \frac{I}{\lambda A} = \frac{4I}{\lambda A} = \frac{4 \text{ x } 0.0002 \text{ m}}{0.8 \frac{W}{mK} \text{ x } \pi\ x\ (0.043\ mm)^2} = 0.17\ \frac{K}{W} = 5.40\ \frac{K}{W} - 0.17\ \frac{K}{W}$$

$$= 5.23\ \frac{K}{W}$$

- tp temperature is max. 82°C at an ambient temperature of 35°C and must not exceed, so a heat sink with thermal resistance value = 5.23 K/W at power consumption of 8.7 W is needed

Thank you for your attention, if you have any questions, please do not hesitate to ask!

Thermal Management for LED applications