ANALYSES OF THERMAL REGIME OF LEDs LUMINAIRES DURING THEIR DESIGN

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Abstract: *The junction temperature of LEDs determines their life and has influence on their luminous flux. That's why the thermal regime of the assembly determines the reliability and the efficiency of LED luminaires. The ability to calculate precisely the temperature distribution of the luminaire at different stages of its design is extremely precious for the designer team. Theoretically the problem for analysis of thermal field is considered completely solved but there are many issues that constrict the practical application of theoretical formulations. Those issues are connected with the complexity of the model and the need of "tune up" in other to achieve trustworthy results. The available engineering approaches for the analysis of the thermal regime of LED luminaires at design time are discussed in the paper. The special attention is paid to their precision and the parameters that influence it. Some considerations about the tuning of the numerical thermal models, based on the authors experience are presented and supported with experimental results. The reliability of the results is estimated especially when real measurements are not possible that is the typical situation during the design.*

LEDs are considered to become the light source with the highest efficiency. The best currently available LEDs are wit efficiency of 160 lm/W and even higher numbers are expected in the near future. That figure translates LEDs from the category "Light source to the future" to the category "Light source of the present". There are three main areas concentrating the efforts of the LED luminaire designers – the thermal management, the design of the optical system and the control of the luminous flux over time.

Temperature dependent LED parameters

The temperature regime of LEDs is determined by the temperature of their p-n junction, often called temperature of the crystal. It affects the luminous flux and the life of LEDs as well as the reliability of entire luminaire.

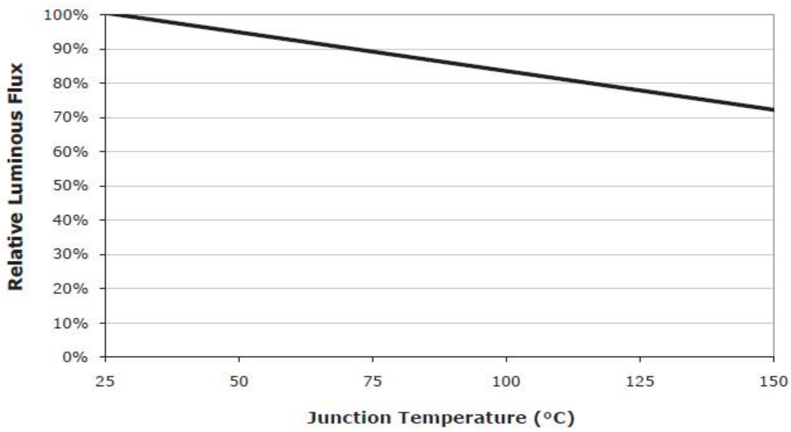

Fig. 1. Decrease in luminous flux of LEDs depending on the transition temperature

The impact of the junction temperature on the luminous flux of LEDs [4, 5] is shown in Fig. 1. With increasing temperature, light output decreases. LED manufacturers usually present figures like that but do not give details for the setting in which they are obtained. LED temperature regime determines the reliability and the life of the entire luminaire.

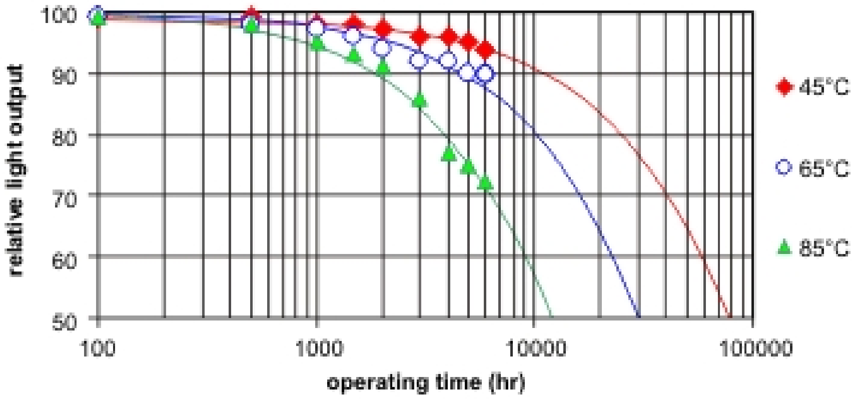

Fig. 2. LEDs life as a function of working temperature.

LEDs and LED luminaires are expensive, particularly more expensive than similar items with conventional lighting sources. The initial cost should be compensated with higher energy efficiency, long life and lowered maintenance expenses of LED lighting compared with conventional lighting. The data shown in Figure 2 make clear that long life can be achieved only if an adequate thermal regime of LEDs is provided. Exactly the influence of the temperature on the operating characteristics of the LEDs determines one of the main challenges in the design of new LED luminaires. The luminaire designer should be able to estimate the junction temperature of the LEDs right at the state of design before any experiments can be ever made.

There are publications [2] where the temperature regime is regarded to be optimal when the junction temperature Tj does not exceed 55 ºC. Such a value can not be considered absolute and it will vary with the type of LEDs and the particular application but this value as well as the data from Figure 2 show that the junction temperature should be estimated quite precisely.

Heat sources

In the LEDs the main quantity of heat is generated in the p-n junction. Only a part of the carrier’s energy leaves the LED as a light the remaining is converted into heat. A second source of heat is phosphor, which converts the blue light emitted by the crystals to white one. As "warmer" is the emitted light (lower color temperature), as greater are the losses in the phosphor (Fig. 3). The Joule heat due to the Ohm resistance along the path of the current is additional heat source.

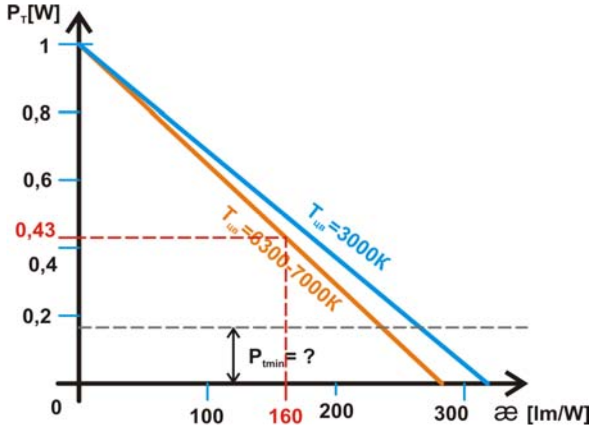

Fig. 3. Thermal losses (PT) in white LED vs light efficiency for different color temperatures.

Analysis of thermal processes

The thermal problem is considered to be completely solved on a theoretical level - the laws governing the thermal processes are known and methods for their analysis are developed.

In the real task, the main amount of heat is dissipated into the ambient by air convection. This is a mass exchange processes and its mathematical modeling requires computational fluid dynamics (CFD) methods featuring highly complexity. The precision of the approach is considered to be very high but only if the model is well tuned to the real application. Usually the “tuning” requires experimental data which are unavailable at design time. The work with such heavy mathematical apparatus can be avoided and the complexity of the task reduced if the process is modeled up to the border between the luminaire and the ambient air and appropriate Neumann boundary conditions along that border are applied. In later case finite element method (FEM) can be used. Its precision is directly dependent by the provided boundary conditions.

FEM method can very accurately determine the temperature distribution in the volume of a luminaire while at the same time it is much easier to use and more accessible as software than CFD.

Many engineers prefer the thermal circuits’ method which exploits the analogy between the linear electrical circuits and thermal processes. It uses thermal resistance which is defined as a ratio of temperature difference between two points of interest and the thermal power passing though them. This method is often referred by the LED manufacturers in thermal guides published by them. The method is easy and convenient for so called direct task – when all thermal resistances and heat dissipation are known and junction temperature of LEDs must be found. When a new luminaire is under design the thermal resistance of the main element of the cooling system – the heatsink is unknown which makes this method hardly applicable.

Thermal resistances concentrated in the junctions between LEDs, PCB and heatsink are not subject to calculation, and their values are determined experimentally or based on experience.

Thermal resistance between the LED housing and PCB depends on the size of the thermal pad and the quality of installation, but in general its value is much smaller than the thermal resistance R_{jc} from the crystal to the body of LEDs [1].

The thermal resistance of the contact between PCB and heat sink depends on the strength of pressure, contact area, contact paste and the type of surface. Typical values are below 10 ${}^{O}C\ cm^2/W$ [1,3].

The last two components are difficult to model and their values are set as heat resistance, even when high-precision numerical methods for thermal analysis are used.

FEM analysis of thermal processes in LED luminaires

The accuracy of the FEM is determined by the accuracy of boundary conditions. The normal component of thermal flow dissipated by the luminaire to the ambient actually defines Neumann boundary conditions. The value of film coefficient h, $\left[W/m^2K \right]$ should be set at all dissipating surfaces.

The exact value of this coefficient is difficult to calculate and is not constant, although it is often considered as such. It depends on the shape of the interface between air and the heatsink, the orientation and the size of the heatsink, the temperature difference between dissipating surface and ambient air. Usually, the dependence of the film coefficient h of these factors is expressed in the form of non-dimensional equation:

$$\left| \begin{aligned} & \frac{h \cdot L}{k} = Nu \\ & Nu = c\left(Gr \cdot Pr\right)^n \end{aligned} \right. \qquad (1)$$

where:

h - Film coefficient

L - The major size of the radiator, (taken as a flat surface)
k - Thermal conductivity of air
Nu - number of Nusselt,
Gr - Number of Grashof,
Pr - Including Prandtl,
c, n - constants defined by the geometric relations.

There are expressions, derived in thermodynamics, which can be used for calculation of Grashof and Prandtl numbers. The values obtained that way as well as the equation (1) are accurate only for a simple planar geometry. Furthermore, the constants c and n from equation (1) depend from the orientation of the heatsink. Therefore further simplification can be made:

$$h = c\left(\frac{T_s - T_a}{L}\right)^n, \qquad (2)$$

where
T_s - average surface temperature of the heatsink
T_a - ambient temperature,
the other parameters are as above.

Fig. 4 shows the film coefficient vs average temperature of the heatsink, calculated according to (2), for different cases.

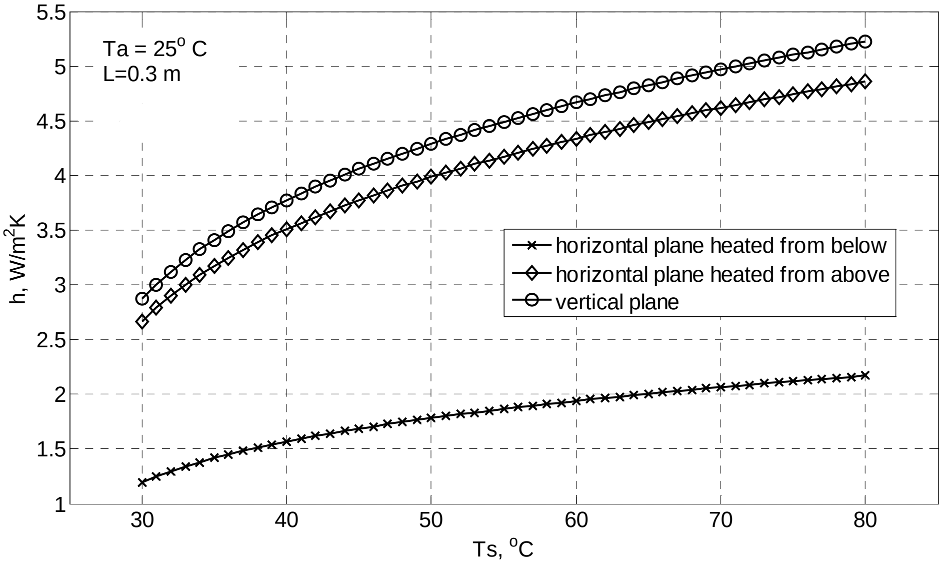

Fig. 4. The film coefficient vs. average surface temperature for a heatsink with simple flat shape.

As it is seen from Fig. 4 the film coefficient, which determines the precision of the FEM results, depends significantly on the position of the heatsink and temperature difference between heatsink and ambient. When a new luminaire is designed the values of the important parameters of the thermal model of the luminaire are unknown and they have to be set based on researcher's experience which constraints the precision of the results – typically above 10%.

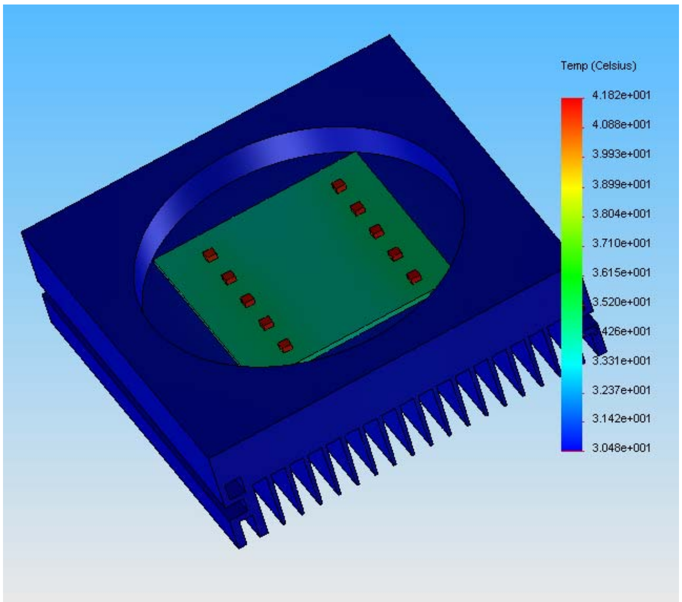

Fig. 5. Temperature distribution in the LED street lamp.

Fig. 5 shows the FEM model of a street luminaire. The ambient temperature is set to $21^{O}\ C$, thermal power (heat loss) of each LED is P = 2 W, thermal resistance between the PCB and heatsink 0,34 K / W, film coefficient of 2,7W/m^2K.

The temperature of luminaire, which model is shown on Fig. 5, is measured with thermocouple on the surface of the heatsink and on PCB. The measurement is done under the following conditions:

Ten LEDs are used – Cree XP-G, 110 lm/W;

Electric power LEDs $P_E = 28.6\ W$,

Ambient temperature $T_a = 21^{O}\ C$,

Color temperature of the LEDs used 6000K.

In this situation, according to Fig. 3, heat losses in the LED can be assumed to be 70% of electrical power. Thus, computational heat power is taken - $P_T = 20\ W$. Comparison between measured and calculated temperatures are shown in following table.

	measured	calculated by FEM
average temperature of the radiator, $^{O}\ C$	30	30,05
average temperature of the board, $^{O}\ C$	33	34,1

The value of the film coefficient in the above example is close to the case ov vertical plane (Fig.4). This can be explained by the significant surface of fins.

The quality of the finite element mesh and its influence on the results is well known issue. In real world applications the limited abilities of the mesh generator should be taken into account. When a new luminaire is under construction it would be very useful if the engineering team is able to evaluate the thermal regime of the new system on different stages of its development. The construction documentation for that lumionaire is already created in a CAD software and it is a big temptation if that very documentation could be used directly for thermal simulation. There are even commercial CAD packages that point that feature in their advertisement. Unfortunately in most cases this is impossible. The huge number of details – small dimensions, complex surfaces, chamfers est. usually exceeds the “strengths” of mesh generators and consistent mesh can not be obtained.

Actually a new model has to be build that includes only the features important for the thermal regime. Aside from elimination of small dimensions and complex surfaces that must be made additional simplifications are possible without serious loss of accuracy. The air layer between the LEDs and protective glass can be disregarded (for low temperature). The LEDs can be also omitted and their thermal power can be concentrated in the volume of PCB.

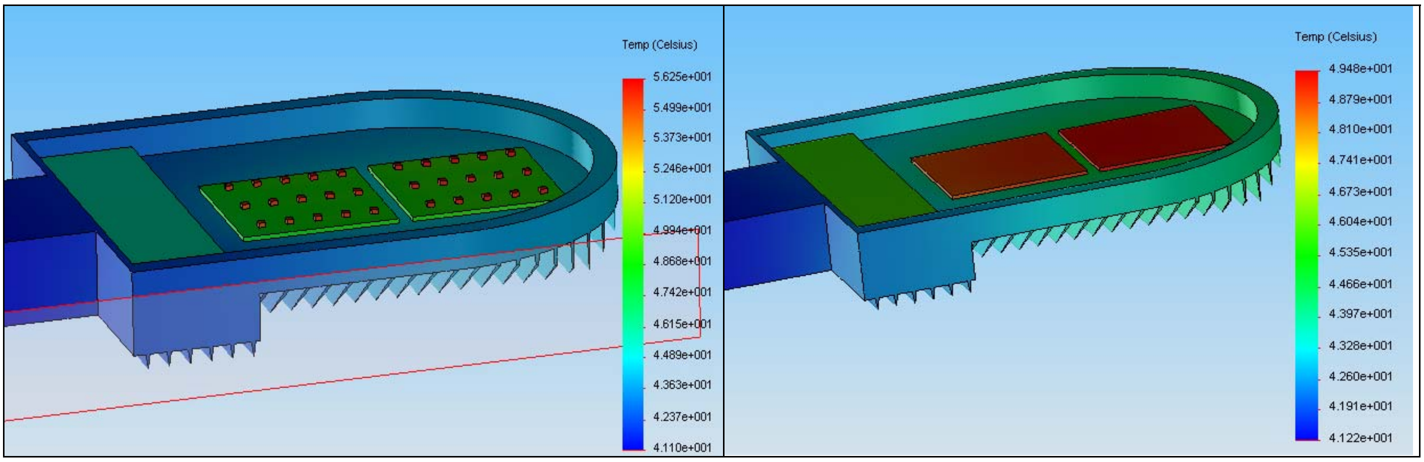

Fig. 6. Thermal analysis for identical geometry and heat power of luminairesn but different degree of simplification.

The results shown in Fig. 6 were obtained with the built-in FEM package in SolidWorks. A luminaire with 30 LEDs (Cree XP-G) is studied. The model parameters are:

- film coefficient h = 2.7 K / W,
- thermal power of each LED $P_T = 1 \quad W$ (this means an electric power consumed by each LED $P_E = 1.65 \quad W$),
- thermal resistance between the PCB and heatsink $R_{bh} = 0.3 \quad K/W$,
- thermal resistance between each LED and PCB $R_{cb} = 6 \quad K/W$ that way the internal thermal resistance of the package is taken into account,
- thermal power (heat loss) of the driver - 6 W,
- material of the heatsink and PCBs - aluminum alloy Al 1066.

In the model to the right (Fig. 6), the thermal power is concentrated in the PCB. The temperature of LEDs if they are presented in the model (Fig6 – left) will be with 6 ^{o}C higher than the temperature of the board for each watt of thermal power. It is seen that the temperature distribution is practically identical in both cases.

The temperature distribution in the volume of luminaire body can be easily analyzed with numerical methods.

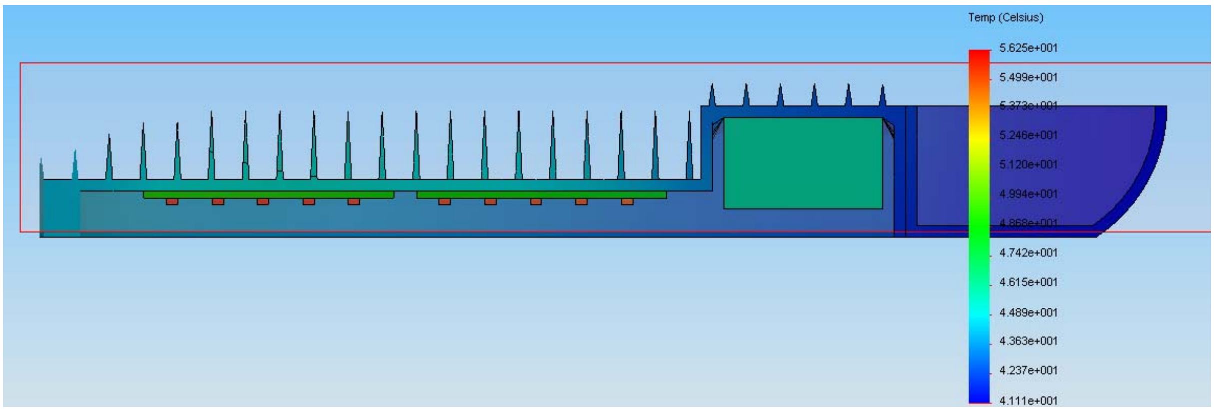

Fig. 7. Cross section of hull-cooler, with temperature distribution in steady-state. It is seen that the ribs are used effectively, but not at the right (caudal) part of the luminaire.

This is demonstrated in Fig. 7, where a cross-section of luminaire is shown (luminaire body, PCBs, LEDs, and driver). The body of luminaire is made by aluminium and all of its parts should be used as a heatsink. From the temperature distribution in the cross-section it is obvious that the “tail” of luminaire is much cooler than its central area (about 4 ^{o}C) so its heatsinking capacity is not used completely. This can be improved by increasing the cross-section along to the thermal flow toward the “tail”.

Conclusion

The methods of thermal circuits and FEM are two major engineering methods used for analysis of thermal regimes in the design of LED luminaires.

Thermal circuits are very convenient if verification or approximate calculations are necessary but it is inapplicable in evaluating the thermal regime for newly developed LED luminaires because the main thermal resistance in the system – that between the heatsink and the ambient is unknown.

The accuracy of the FEM depends on the film coefficient. In the case of new design the exact value of that coefficient can not be measured and it should be estimated based on experience. In the presence of experimental data for a given type of geometry very accurate results can be obtained. That way the thermal regime of different luminaire concepts can be verified by software means with acceptable accuracy.

References

[1]. Valenzuela J A., Advanced Thermal Management of Power Electronics, Mikros Thermal Systems.

[2]. Thomas Kuhn, Christoph Schiler, Tran Quoc Khanh, Eine Analyse aktueller LED-Strassenleuchten aus lichttechnischer Sicht, LICHT, 1-2/2009

[3]. TheoTreurniet and Li Zhang, On The Challenges of Thermal Characterization of High-Power, High-Brightness LED Packages, May 1st,2008

[4]. Cree, Inc, SSL Design Process/Considerations

[5]. Cree, Inc, XLamp XP-G LEDs, Data Sheet

[6]. Biber C., Effect of thermal environment of LED light emission and life time, Led professional, 2009