

## THERMAL CIRCUIT CALCULATION AND REAL-TIME ANALYSIS OF LED LIGHT SOURCE LUMINAIRES

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*In semiconductor luminaires, thermal circuit design is important since operating temperature directly affects performance and life of luminaires. In this study; In order to keep operating temperature of LED light source luminaires normal, thermal circuit is emphasized. In this context, necessary information about LED and thermal resistance calculation are given in this study. As a real-time application, 10 different power luminaires have been determined on market, thermal resistance calculations have been made depending on heat that needs to be removed and required area calculations have been made for heatsink that needs to be used. Comparative analysis of thermal circuit area calculation results were made with existing heatsink areas of luminaires. Accordingly, it was concluded that thermal circuit designed luminaires which has insufficient heat sink area have a shorter life of approximately 22.7% compared to others.*


*Key words: LED; Thermal resistance; Junction Temperature; heatsink area*


### 1. Introduction

Artificial lighting, which constitutes about 19% of the world's electricity consumption, started with the discovery of electromagnetism and electric current. As a result, cheap and simple structured lighting sources were tried to be designed. First, incandescent bulbs were found. Electric current was passed through a filament lamp wire and light was obtained [1]. Incandescent bulbs have disadvantages such as short life and low light efficiency. For this reason, halogen lamps, high intensity discharge lamps, fluorescent lamps, which are more efficient light sources than incandescent bulbs, was preferred in lighting. These sources have also led solid state lighting studies, which are more efficient and environmentally friendly due to their low lumen depreciation and mercury content [2-4].

LEDs, which are solid state lighting sources, were first obtained in 1962 in red color with a efficiency of 0.1 lm / W [5]. At first, it was used in calculators, signage, brake lights, digital clocks and test equipment [6]. Thanks to the recently developed LED and LED technology, it is widely used in lighting. Considering the amount of electricity consumption, it has higher illumination than other lighting sources [7]. It provide long life, reliability and energy savings compared to traditional lighting [8].

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Operation principle of LEDs is based on an event called electroluminescence [9]. In its simplest sense, an LED is a combination of p and n type two semiconductor materials. Under forward bias condition electrons in n-type region move from junction region to p-type region. During transition, electron hole produces photons in infrared or visible light spectrum. Energy occurs when electron hole pair emits photon. Approximately 20% to 25% of energy output is light and the rest is heat. Wavelength and color of light are determined by differences in energy levels of electrons and holes [5,10,11].

As most of energy output is converted to heat, LED performance will be affected and its reliability will be shaken. Reliability problem which affect lighting quality and life of LED system is an important factor. LED systems contain two main components: optics and drivers. The driver is the weakest component in LED lamp [12]. Increasing temperature of LED driver will decrease its lifetime. For this reason, the operating temperature of an LED driver should be maximum 75°C-85°C [13].

Increase in temperature has also a significant impact on performance and cost. The efficiency of LED (lm/W) decreases when junction region temperature increases. When efficiency decreases, illumination intensity also decreases. Therefore, LED number and power in luminaire should be increased This causes cost to increase. The temperature may cause a decrease in CRI (color rendering index) of luminaire, an increase in dominant wavelength of luminaire and color temperature of light output. Dominant wavelength means reduced probability of reproducing true colors [14].

In this study, two different thermal resistance calculation methods were emphasized to investigate effect of LED operating temperature on its lifetime. For real-time luminaires with different powers, resistance and cooling area were calculated. Technical data was taken into consideration. In second of this study, semiconductor thermal circuit of LED is mentioned, and thermal resistance calculation methods are mentioned in third part. In fourth part, thermal resistances and cooler areas were calculated for different powers of real-time luminaire, and a comparative analysis of luminaires is made according to results of calculations.

## 2. Thermal Resistance for Semiconductors

Thermal resistance is defined as rate of temperature increase for given power and it is also known as ability to dissipate heat [15].

A typical LED package consists of an LED chip, epoxy resins, a heat slug, and a heat sink. The heat generated in the LED chip is distributed in three ways: transmission, convection and radiation [16]. Transmission is dissipation process that occurs as dominant on an LED chip or packet. Convection is the transfer of generated heat in LED from heat sink to ambient air in LED system. Radiation occurs when it leaves surface through electromagnetic waves and moves until another surface is encountered. Radiation heat transfer can be neglected when very low values are obtained compared to convection and conduction [15]. Figure 1 shows thermal resistance circuit of LED and flow direction of heat.

The purpose of LED thermal circuit is obtain low thermal resistance. After LED chip comes PCB part and it consists of upper part which is circuit layer, middle part which is dielectric layer, thin copper layer or third part which is thick metal layer. Metal core PCB (MPCB) or FR-4 PCB are most commonly used PCB materials according to heat dissipation requirement FR-4 is used in low power LED applications and MPCB is used in medium power applications [17].

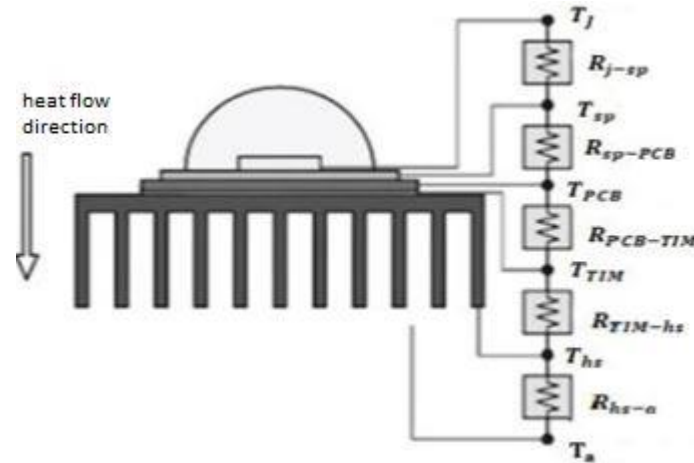


Figure 1. Thermal Resistance circuit of a LED [15]

Main thermal objective in packaging of LED is transfer heat efficiently from LED chip to environment. Contact surfaces between package and heatsink are somewhat incompatible and rough. Heat transfer between package and heat sink occurs via micro contacts of surfaces and air-filled micro gaps. This causes significant thermal resistance.

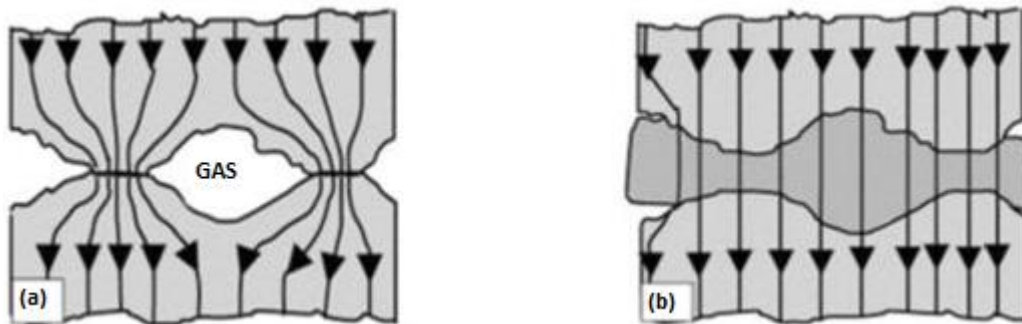


Figure 2. (a) Heat flow in directly contact (b) heat flow separated by a thermal interface material [18]

As shown in Figure 2, thermal interface materials (TIM) with a high thermal conductivity are generally used to reduce thermal contact resistance between package and heat sink. Interface materials used should not be thicker than 0,3 mm. If it is thicker it causes an increase in resistance [18].

### 3. Thermal Resistance Calculation Methods

When a voltage is applied to LED, current passes over semiconductor material and heat is created on LED under effect of this current. General formula of thermal resistance that will occur as a result of current passing is shown in Eq (1).

$$R_{a-b} = \frac{T_a - T_b}{P_{th}} \quad (1)$$

#### 3.1. Resistance Calculation with Conventional Method

Thermal surface calculation formulas are calculated with the help of Equation 2-5 when heat sink channels are designed horizontally on ground:

$$P_d = P_{th} * (efficiency) \quad (2)$$

$$T_{sp} = T_j - (R_{j-sp} * P_d) \quad (3)$$

$$T_{hs} = T_{sp} - (R_{sp-hs} * P_d) \quad (4)$$

$$R_{hs-a} = \frac{T_{hs} - T_a}{P_{th}} \quad (5)$$

$P_d$  is amount of heat that must be cooled as a result of power consumed by LED. If an insulating material is used between LED and heat sink, value of  $R_{sp-hs}$  should be chosen between 0,2 and 0,5.

According to result obtained from eq. 5, required surface area for horizontal heat sink channels is calculated based on graphic in figure 3.

If heat sink channels are designed vertical to ground, horizontal surface wideness is calculated as follows ( $S_y$ ):

$$S_y = \sqrt{P_d * 10} \quad (6)$$

In order to calculate required heat sink area per total watt of luminaire, surface areas calculated for both horizontal and vertical design must be collected.

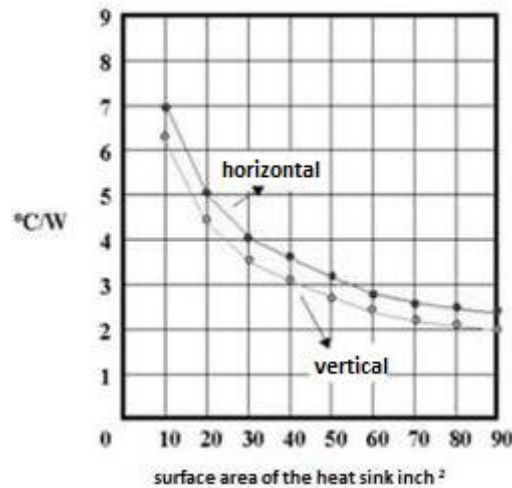


Figure 3. Heat Sink Area- Thermal Conduction [20]

Material used as heat sink was chosen as aluminum because it is cheap and easy to process [19]. Figure 3 is heat sink area-thermal conduction graph of aluminum [20].

### 3.2. Resistance Calculation with Convection Method

Another resistance calculation method is resistance calculation method obtained from convection heat dissipation. It is calculated with the help of Equations 7-11.

$$R_{th} = \frac{1}{hA} \quad (7)$$

$$h = \frac{Nu\lambda}{l} \quad (8)$$

$$Nu = 0,59 \sqrt[4]{Gr * Pr} \quad (9)$$

$$Gr = \frac{g\beta(T_{hs} - T_a)l^3}{\nu^2} \quad (10)$$

$$\beta = \frac{1}{\frac{T_{hs} + T_a}{2}} \quad (11)$$

Calculation with convection resistance method is more common than these two resistance calculation methods.

#### 4. Applications of Real Time Luminaires

Thermal resistance and heat sink area calculation were made by using two thermal resistance calculation methods for ten luminaires with different powers. Electrical and thermal properties of luminaires used for calculation were obtained from the manufacturer. Table 1 shows real time data of luminaires.

**Table 1. Real time data of luminaires**

Luminaire Name	Operating Voltage (V)	Operating Current (A)	Power (W)	Luminous flux (lm)	Power Factor	Thermal circuit resistance (°C/W)	Heat sink thickness (mm)	Heat sink area (cm <sup>2</sup> )
Luminaire 1	24	500	14	300	0,7	5,164	44	207,165
Luminaire 2	24	650	15	500	0,7	4,75	54	233,779
Luminaire 3	24	720	18	750	0,7	3,873	56	285,307
Luminaire 4	24	800	20	1500	0,8	2,902	61	374,782
Luminaire 5	25	850	24	2000	0,8	2,354	28,5	381,723
Luminaire 6	25	920	25	2200	0,8	2,252	45	420,924
Luminaire 7	32	980	27	2500	0,9	1,793	24	454,541
Luminaire 8	32	1000	29	3000	0,9	1,638	27	505,324
Luminaire 9	50	1050	45	4000	0,9	0,978	3,8	518,948
Luminaire10	50	1200	48	4500	0,9	0,904	3,7	550,709

##### 4.1. Resistance Calculations with Conventional Method

Solder point temperature ( $T_{sp}$ ) value was taken as 85 °C and ambient temperature ( $T_a$ ) value as 40 °C in calculations conventional method calculations. Thickness value ( $R_{sp-hs}$ ) between solder point and the heat sink was taken 0,2 and the results were obtained. An example calculation with conventional method for luminaire 1 is shown below. Analysis results for other luminaires are given in Table 2.

Power of luminaire 1 is 14W and its efficiency is 0,7

$$P_d = 14 * 0,7 = 9,8W$$

$$T_{hs} = 85 - (0,2 * 9,8) = 83,04°C$$

$$R_{hs-a} = \frac{83,04 - 40}{9,8} = 4,39^{\circ}\text{C/W}$$

Horizontal Heat Sink Channel Surface Area:

$$249,037 \text{ cm}^2$$

Vertical Heat Sink Channel Surface Area:

$$\sqrt{9,8 * 10} = 9,89 \text{ cm}^2$$

Total heat sink area of luminaire 1:

$$249,037 + 9,89 = 258,927 \text{ cm}^2$$

**Table 2. Thermal analysis results with conventional method**

Luminaire Name	( $P_d$ ) (W)	Heat sink temperature ( $T_{hs}$ ) ( $^{\circ}\text{C}$ )	Thermal Resistance ( $R_{hs-a}$ ) ( $^{\circ}\text{C}/\text{W}$ )	Horizontal Heat Sink Channel Surface Area ( $\text{cm}^2$ )	Vertical Heat Sink Surface Area ( $\text{cm}^2$ )	Total Heat Sink Area of luminaire ( $\text{cm}^2$ )
Luminaire 1	9,8	83,04	4,39	249,037	9,89	258,957
Luminaire 2	10,5	82,9	4,085	267,958	10,24	278,198
Luminaire 3	12,6	82,48	3,37	325,413	11,22	336,663
Luminaire 4	16	81,8	2,612	390,957	12,64	431,197
Luminaire 5	19,2	81,16	2,143	425,126	13,856	438,982
Luminaire 6	20	81	2,05	465,712	14,142	479,854
Luminaire 7	24,3	80,14	1,65	502,589	15,588	518,177
Luminaire 8	26,1	79,78	1,524	539,702	16,155	555,857
Luminaire 9	40,5	76,9	0,91	550,727	20,12	570,843
Luminaire 10	43,2	76,36	0,841	585,170	20,78	605,78

#### 4.2. Resistance Calculations with Convection Method

Solder point temperature ( $T_{sp}$ ) value was taken as  $85^{\circ}\text{C}$  and ambient temperature ( $T_a$ ) value as  $40^{\circ}\text{C}$  in calculations convection method calculations. Thermal conductivity ( $\lambda$ ) of air at  $40^{\circ}\text{C}$  is  $0,2662 \text{ W/mK}$ , kinematic viscosity value of air ( $\nu$ )  $1,702 \cdot 10^{-5}$ , Prandtl number for air was taken as  $0,7255$ , heat sink thickness was selected for characteristic length value of  $l$ . An example calculation with convection method for luminaire 1 is shown below. Analysis results for other luminaires are given in Table 3.

Power of luminaire 1 is  $14\text{W}$  and its thickness is  $2,7\text{mm}$

$$\beta = \frac{2}{85+40} = 0,016$$

$$Gr = \frac{9,81 * 0,016 * 45 * (0,0027)^3}{(1,702 * 10^{-5})^{10}} = 2531488,543$$

$$Nu = 0.59 \sqrt[4]{(2531488,543 * 0.7255)} = 21,719$$

$$h = \frac{21,719 * 0,2662}{0,0027} = 12,603$$

$$R_{th} = \frac{1}{12,603 * 191,82 * 10^{-4}} = 4,252$$

**Table 3. Thermal analysis results with convection method**

Luminaire Name	Heat Sink Thickness (mm)	$\beta$	Groshof number (Gr)	Nusselt number (Nu)	Heat transfer coefficient ( $W/m^2 K$ )	Thermal Resistance ( $R_{hs-a}$ ) ( $^{\circ}C/W$ )	Total Heat Sink Area of Luminaire ( $cm^2$ )
Luminaire 1	44	0,016	2077018,772	20,671	12,46	3,873	300,389
Luminaire 2	54	0,016	3839402,751	24,1	11,849	3,61	336,641
Luminaire 3	56	0,016	4281998,13	24,769	11,753	2,982	407,989
Luminaire 4	61	0,016	5534417,238	26,41	11,495	2,321	524,694
Luminaire 5	28,5	0,016	564438,946	14,925	14,925	1,883	530,594
Luminaire 6	45	0,016	2219611,682	21,017	12,412	1,914	580,875
Luminaire 7	24	0,016	337066,908	13,120	14,435	1,524	613,63
Luminaire 8	27	0,016	479925,343	4,331	14,054	1,408	667,027
Luminaire 9	3,8	0,016	1337,929	3,293	22,912	0,841	674,596
Luminaire10	3,7	0,016	1235,058	3,227	23,102	0,786	699,4

## 5. Conclusions

In study, resistance and cooling calculate were made by conventional and conventional methods for 10 different luminaires. For heat sink area of first luminaire, calculation results obtained by conventional method and convection method were found 258,957  $cm^2$  and 300,389  $cm^2$ , respectively. The results show that heat sink area obtained by conventional method is 20% larger than heat sink area of first luminaire, and heat sink area obtained by convention method is 45% larger. For heat sink area of second luminaire, calculation results obtained by conventional method and convection method were found 278,198  $cm^2$  and 336,641  $cm^2$ , respectively. The results show that heat sink area obtained by conventional method is 19% larger than heat sink area of second luminaire, and heat sink area obtained by convention method is 44% larger. For heat sink area of third luminaire, calculation results obtained by conventional method and convection method were found 336,663  $cm^2$  and 407,989  $cm^2$ , respectively. The results show that heat sink area obtained by conventional method is 18% larger than heat sink area of third luminaire, and heat sink area obtained by convention method is 43% larger. For heat sink area of fourth luminaire, calculation results obtained by conventional method and convection

method were found 431,197 cm<sup>2</sup> and 524,694 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 15% larger than heat sink area of fourth luminaire, and heat sink area obtained by convention method is 40% larger. For heat sink area of fifth luminaire, calculation results obtained by conventional method and convection method were found 438,982 cm<sup>2</sup> and 530,594 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 15% larger than heat sink area of fifth luminaire, and heat sink area obtained by convention method is 39 % larger. For heat sink area of sixth luminaire, calculation results obtained by conventional method and convection method were found 479,854 cm<sup>2</sup> and 580,875 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 14% larger than heat sink area of sixth luminaire, and heat sink area obtained by convention method is 38% larger. For heat sink area of seventh luminaire, calculation results obtained by conventional method and convection method were found 518,177 cm<sup>2</sup> and 613,63 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 14% larger than heat sink area of seventh luminaire, and heat sink area obtained by convention method is 35% larger. For heat sink area of eighth luminaire, calculation results obtained by conventional method and convection method were found 555,857 cm<sup>2</sup> and 667,027 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 10% larger than heat sink area of eighth luminaire, and heat sink area obtained by convention method is 32% larger. For heat sink area of ninth luminaire, calculation results obtained by conventional method and convection method were found 570,843 cm<sup>2</sup> and 674,596 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 10% larger than heat sink area of ninth luminaire, and heat sink area obtained by convention method is 30% larger. For heat sink area of tenth luminaire, calculation results obtained by conventional method and convection method were found 605,78 cm<sup>2</sup> and 699,4 cm<sup>2</sup>, respectively. The results show that heat sink area obtained by conventional method is 10% larger than heat sink area of tenth luminaire, and heat sink area obtained by convention method is 27% larger. Results of comparison are given graphically in Figure 4.

Minimizing of heat sink area will negatively affect deterioration constant (e) (approximately 22.7) according to T21 method, which is one of LED life tests performed for 1000 hours, LED chip life will be shortened negatively at similar rates. Within scope of reducing cost of heat sink circuit of the companies, it is observed that there are differences in the ratio of heat sink areas of products produced with actual heat sink area depending on method. Similarly, there are differences in calculation of thermal circuit resistance. As a dependent on calculated resistance, it will change in area that needs to be cooled. Therefore, resistance calculation must be done correctly. When calculations are investigated, resistance value of first luminaire obtained as a result of resistance calculation by conventional method is 4,39°C/W and resistance value obtained by convection method is 3,873°C/W. When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 15% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 25% smaller.



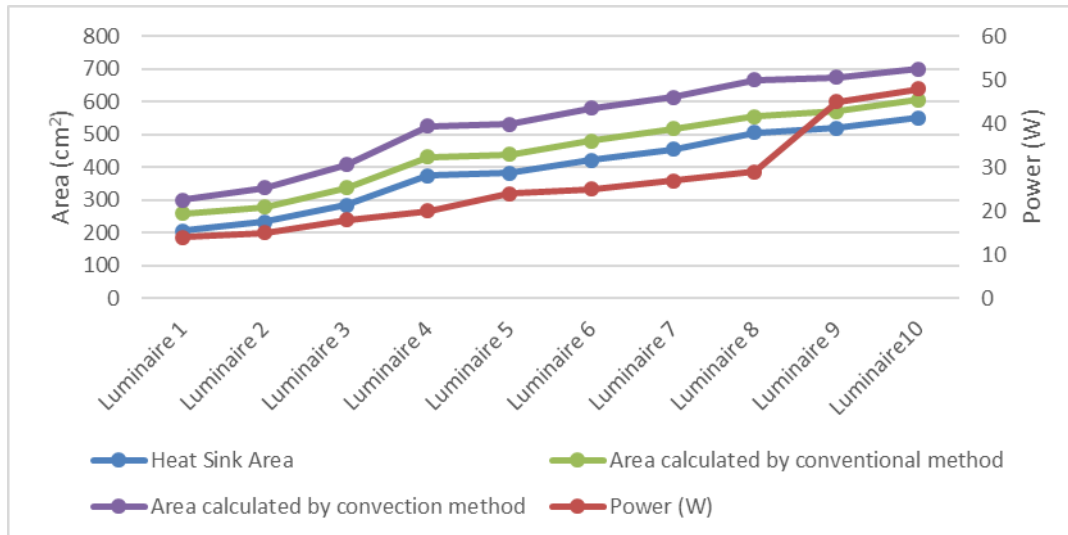
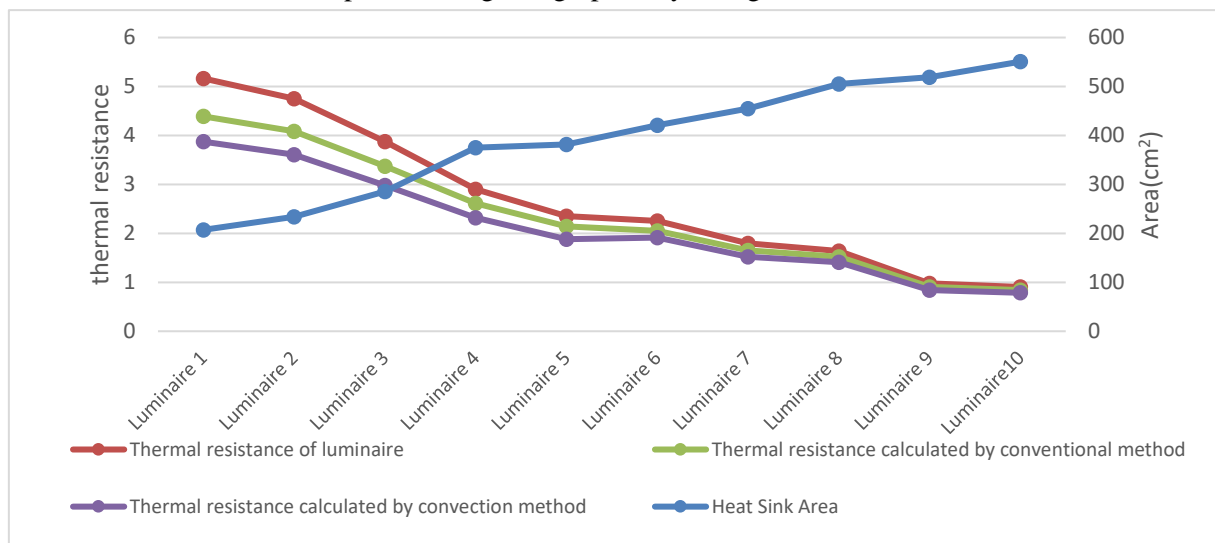


Figure 4. Comparison graph of power and heat sink surface areas of different luminaires

Resistance value of second luminaire obtained as a result of resistance calculation by conventional method is  $4,085^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $3,61^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 14% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 24% smaller. Resistance value of third luminaire obtained as a result of resistance calculation by conventional method is  $3,37^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $2,982^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 13% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 23% smaller. Resistance value of fourth luminaire obtained as a result of resistance calculation by conventional method is  $2,612^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $2,321^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 10% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 20% smaller. Resistance value of fifth luminaire obtained as a result of resistance calculation by conventional method is  $2,143^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $1,883^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 9% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 20% smaller. Resistance value of sixth luminaire obtained as a result of resistance calculation by conventional method is  $2,05^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $1,914^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 9% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 15% smaller. Resistance value of seventh luminaire obtained as a result of resistance calculation by conventional method is  $1,65^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $1,524^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately

8% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 15% smaller. Resistance value of eighth luminaire obtained as a result of resistance calculation by conventional method is  $1,524^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $1,408^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 7% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 14% smaller. Resistance value of ninth luminaire obtained as a result of resistance calculation by conventional method is  $0,91^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $0,841^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 7% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 14% smaller. Resistance value of tenth luminaire obtained as a result of resistance calculation by conventional method is  $0,841^{\circ}\text{C}/\text{W}$  and resistance value obtained by convection method is  $0,786^{\circ}\text{C}/\text{W}$ . When the resistance value obtained from the technical data is compared with the resistance value obtained by the conventional method, the resistance value calculated is approximately 7% smaller, and compared to the resistance value obtained by the convection method, the resistance value is approximately 13% smaller. As a result of analysis methods, it is observed that conventional method is not sufficient for a detailed calculation, but convection method contains detailed calculations. Results of comparison are given graphically in Figure 5.



**Figure 5. Comparison graph of thermal circuit resistance and heat surface areas of different luminaire**

As a result, it is observed that thermal resistance decreases due to increase in power, but area required for heatsink increases. It was concluded that luminaire group with powers of 14W, 15W, 18W was bad, luminaire group with powers of 20W, 24W, 25W was medium, luminaire group with powers of 27W, 29W, 45W and 48W was good thermal analysis values. As a result of analysis methods, it is observed that conventional method is not sufficient for a detailed calculation, but convection method contains detailed calculations. While only temperature and power are used in conventional method calculations, many factors such as viscosity of air, which changes depending on temperature that will affect resistance, gravity acceleration and heat transmission coefficient are used in calculations of convection method. Temperature is very important for LED. If temperature in LED cannot be removed correctly,

heat generated will affect performance of LED. As a result, consumers will lose confidence in the product. Therefore, thermal management should be given importance in LED designs, thermal resistance value should be calculated correctly and heat sink design must be done well. Using the convection method for thermal calculations of LED will provide more reliable results.

Abbreviation List	Explanations	Abbreviation List	Explanations
$R_{a-b}$	the thermal resistance from point "a" to point "b" ( $^{\circ}\text{C}/\text{W}$ )	$\nu$	Kinematic viscosity of air
$P_{th}$	the thermal power (W)	$R_{j-sp}$	Junction to solder point thermal resistance
$T_a$	the temperature at point "a" ( $^{\circ}\text{C}$ )	$R_{sp-PCB}$	Solder point to printed circuit board resistance
$T_b$	the temperature at point "b" ( $^{\circ}\text{C}$ )	$R_{PCB-TIM}$	Printed circuit board to thermal interface material resistance
$A$	Heatsink area ( $\text{m}^2$ )	$R_{TIM-hs}$	Thermal interface material to heat sink resistance
$h$	Heat transfer coefficient of the surface ( $\text{W}/\text{m}^2 \text{K}$ )	$R_{hs-a}$	Heat sink to ambient resistance
$Nu$	Nusselt number	$T_j$	Junction temperature ( $^{\circ}\text{C}$ )
$\lambda$	Thermal conductivity of air	$T_{sp}$	Solder point temperature ( $^{\circ}\text{C}$ )
$l$	Characteristic length	$T_{PCB}$	Printed circuit board temperature
$Gr$	Grashof number	$T_{TIM}$	Thermal interface material temperature
$Pr$	Prandtl number	$T_{hs}$	Heat sink temperature
$g$	Acceleration of gravity	$T_a$	Ambient temperature

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