DESIGN OF A CHIP ON BOARD (COB) LED BASED INDUSTRIAL LUMINAIRE WITH THERMAL SIMULATIONS

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ABSTRACT

As the technology advances, the efficiencies of Chip on Board (COB) LEDs are increasing. In this study, the utilization of COB LEDs in an industrial high-bay luminaire, which can be considered as a relatively high power application, has been investigated starting from the initial design process. For an industrial hall, single-chip LED based reference luminaires, which can provide the required lighting quality criteria have been identified. COB LED selection and photometric measurements are done, and the number of COB LEDs to be used has been calculated by targeting the luminous flux value of reference luminaires. The COB LED based luminaire prototype with a plate finned heat sink was modelled by using a CAD software and the computer aided thermal simulations were performed. Then the prototype was manufactured and experimentally analysed. The highest difference between the experimental analysis and the thermal simulation was found to be less than 7 %, which demonstrates the consistency of design and analyses. This study is an example of the steps to be followed in the manufacturing stage of a COB LED based luminaire. Additionally, it is aimed to provide a perspective to the use of COB LEDs in high power applications.

Keywords: COB LED, thermal simulation, experimental analysis

1. INTRODUCTION

Nowadays, Light Emitting Diodes (LEDs) are competing with conventional light sources in many areas through their advantages such as high luminous efficacy, long life-time expectations, and variety of white colour. On the other hand, high power LED light sources convert some percent of input electrical power to optical power, while the residual part is dissipated as heat [1–4]. If this heat energy is not removed steadily, the temperature of the structure increases. LED properties such as luminous flux, luminous efficacy, and efficiency are adversely affected from the increasing temperature [5]. The lifetime of an LED is also dependent on the temperature [6]. There are many studies about active and passive cooling systems in order to reduce the adverse effects of heat on the LEDs [7–11]. Passive cooling systems are more preferred in the market due to their advantages such as the ease of manufacturing, no maintenance need, no moving parts, no power requirement, the low cost, and the simple structure. Different type of metal fins are the most popular passive cooling solutions used by luminaire manufacturers.

With an appropriate cooling system, high power LEDs promise energy savings especially in power-intensive applications. One of these applications is industrial high-bay luminaires. In industrial high-bay luminaires, mostly single chip high power LEDs are used by combining large number of them together. COB LEDs, with their day-by-day increasing luminous efficacies, are also started to be used in industrial luminaires. Additionally, the number of light sources that has to be used for reaching a specified luminous flux value is less than single chip LED based luminaires. This situation can highlight COB LED based luminaires in terms of the mechanical design simplicity and the cost advan-

Table 1. Analyses Results of Single Chip LED Based Industrial High-bay Luminaires

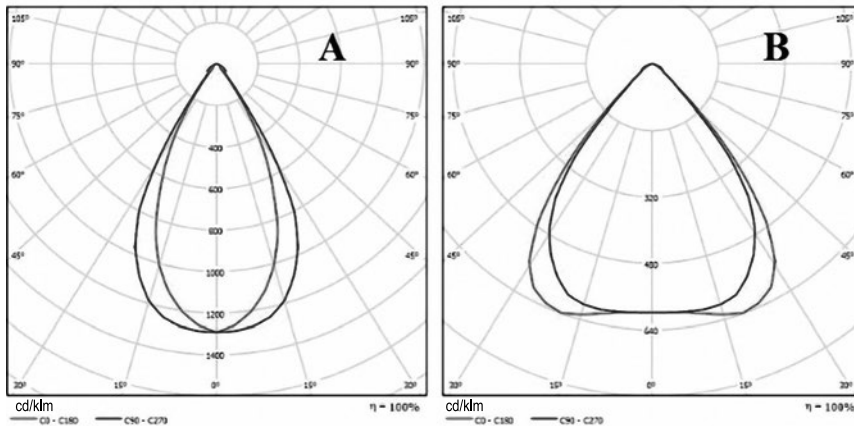| Luminaire	Average illuminance [lx]	Uniformity	Luminous flux of luminaire [lm]	Electrical power [W]	Luminous efficacy [lm/W]	Number of luminaires	Energy consumption [W/m²/100 lx]
A	315	0.722	25000	182	137.4	36	0.83
B	303	0.600	25000	200	125	36	0.95

Fig. 1. Light distribution curves of reference single chip LED based industrial high-bay luminaires

tage. On the other hand, COB LEDs have a dense thermal power output from a small area, which indicates the importance of designing the cooling system to be used in the luminaire through thermal simulations and experimental analyses.

In this study, the procedure of designing a COB LED based luminaire is examined in detail. Selection of reference luminaires for benchmark, COB LED selection and measurements defining the number of COB LEDs, computer aided thermal simulations, experimental analyses and validation steps are followed, respectively. In addition, the thermal power value was determined by measurements rather than using a specific percentage of the electrical power, and then thermal simulations were performed according to these real measurement data.

2. LUMINAIRE BENCHMARK, SELECTION AND MEASUREMENTS OF COB LED

An industrial hall with the dimensions 50×50 m and 12 m ceiling height was used for analyses. The work plane height, boundary zone (distance between the walls and the calculation grid), the distance between the work plane, and the light emitting surface of the luminaires were 1 m, 1.5 m, and 9 m, respectively. The reflections of the ceiling, walls, and the floor were assumed as 70 %, 50 %,

and 20 %. The maintenance factor was also taken as 0.80.

It was aimed to illuminate the selected industry hall according to the value of 300 lx average illuminance and 0.60 uniformity, which is given in the standard EN12464–1:2011 "Light and Lighting – Lighting of Work Places – Part 1: Indoor Work Places" for general machine works with the reference number 5.8.3 [12]. Maximum 5 % tolerance was allowed at the average illuminance for the determination of reference single LED chip based luminaires. DIALux, which is a lighting design software, was used in the analyses [13]. A large number of single chip-LED based industrial high-bay luminaires on the market were analysed, and two of them, which provided the aforementioned criteria,

Fig. 2. Temperature controlled Ulbricht Sphere and equipment

Table 2. Properties Obtained from the Measurements and Calculations

Driving Current, mA	Property	Cold Plate Temperature, °C					
		25	35	45	55	65	75
350	Solder temperature [°C]	29.3	38.7	48	57.5	66.7	76.3
	Voltage [V]	33.14	32.98	32.82	32.67	32.53	32.38
	Current [A]	0.35	0.35	0.35	0.35	0.35	0.35
	Luminous flux [lm]	1963	1940	1916	1891	1865	1837
	Optical power [W]	5.81	5.75	5.69	5.62	5.55	5.48
	CCT [K]	3859	3868	3881	3893	3908	3924
	CRI	83.6	83.6	83.5	83.5	83.5	83.4
	Electrical power [W]	11.60	11.54	11.49	11.43	11.38	11.33
	Thermal power [W]	5.79	5.80	5.80	5.81	5.83	5.86
	Efficiency [%]	0.50	0.50	0.50	0.49	0.49	0.48
	Luminous efficacy [lm/W]	169.2	168.1	166.8	165.4	163.8	162.1
700	Solder temperature [°C]	35.9	45.2	54.5	64	73.3	82.7
	Voltage [V]	34.39	34.22	34.05	33.89	33.73	33.59
	Current [A]	0.7	0.7	0.7	0.7	0.7	0.7
	Luminous flux [lm]	3695	3648	3598	3547	3492	3436
	Optical power [W]	10.95	10.82	10.69	10.55	10.4	10.25
	CCT [K]	3884	3895	3908	3922	3937	3957
	CRI	83.2	83.1	83.1	83.1	83.0	82.9
	Electrical power [W]	24.08	23.95	23.83	23.72	23.61	23.51
	Thermal power [W]	13.13	13.13	13.14	13.17	13.21	13.26
	Efficiency [%]	0.45	0.45	0.45	0.44	0.44	0.44
	Luminous efficacy [lm/W]	153.5	152.3	151.0	149.5	147.9	146.1
1050	Solder temperature [°C]	43.4	52.8	62.1	71.3	80.7	89.8
	Voltage [V]	35.40	35.22	35.05	34.88	34.73	34.58
	Current [A]	1.05	1.05	1.05	1.05	1.05	1.05
	Luminous flux [lm]	5236	5161	5082	5002	4918	4825
	Optical power [W]	15.57	15.35	15.15	14.91	14.68	14.42
	CCT [K]	3916	3925	3939	3956	3973	3998
	CRI	82.8	82.8	82.7	82.7	82.7	82.6
	Electrical power [W]	37.16	36.98	36.80	36.63	36.47	36.31
	Thermal power [W]	21.59	21.63	21.65	21.72	21.79	21.89
	Efficiency [%]	0.42	0.42	0.41	0.41	0.40	0.40
	Luminous efficacy [lm/W]	140.9	139.6	138.1	136.6	134.9	132.9

were selected as reference luminaires. The light distribution curves of selected reference luminaires and analyses results are shown in Fig. 1 and Table 1, respectively.

As it is seen from the Table 1, the luminous flux values of both reference luminaires are 25 000 lm. This value was determined as the target for the design of COB LED based industrial high-bay luminaire. A COB LED light source, which is well documented and has a high luminous flux value, was selected and purchased from the market. The properties of COB LED for different currents and cold plate temperatures were measured using a 1-meter-diameter temperature controlled Ulbrich Sphere, which exists at the ITU, Energy Institute, Photometry and Radiometry Laboratory [14]. The temperature controlled Ulbrich Sphere and its equipment are shown in Fig. 2. Voltage, current, luminous flux, optical power, correlated colour temperature (CCT), and colour rendering index (CRI) were measured.

End of Table 2

Driving Current, mA	Property	Cold Plate Temperature, °C					
		25	35	45	55	65	75
1400	Solder temperature [°C]	51.9	60.9	70.3	79.4	88.7	98
	Voltage [V]	36.27	36.09	35.93	35.77	35.62	35.47
	Current [A]	1.4	1.4	1.4	1.4	1.4	1.4
	Luminous flux [lm]	6588	6486	6379	6260	6143	6017
	Optical power [W]	19.62	19.32	19.03	18.68	18.34	17.98
	CCT [K]	3948	3962	3979	3996	4018	4043
	CRI	82.5	82.5	82.4	82.4	82.3	82.3
	Electrical power [W]	50.78	50.53	50.30	50.08	49.86	49.65
	Thermal power [W]	31.16	31.21	31.27	31.40	31.52	31.67
	Efficiency [%]	0.39	0.38	0.38	0.37	0.37	0.36
	Luminous efficacy [lm/W]	129.7	128.4	126.8	125.0	123.2	121.2

Solder temperatures, which are the key parameters for the calculation of junction temperature, were also measured by the K type thermocouple. Electrical power, thermal power, efficiency, and luminous efficacy values were calculated from the Equations (1)–(4), respectively. Properties obtained from the measurements and calculations are given in Table 2.

$$\text{Electrical power } [W] =$$
$$= \text{Voltage } [V] \times \text{Current } [A]. \quad (1)$$

$$\text{Thermal Power } [W] =$$
$$= \text{Electrical Power } [W] -$$
$$- \text{Optical Power } [W]. \quad (2)$$

$$\text{Efficiency } [\%] =$$
$$= \frac{\text{Optical Power} [W]}{\text{Electrical Power} [W]} \times 100\%. \quad (3)$$

$$\text{Luminous Efficasy } [lm/W] =$$
$$= \frac{\text{Luminous Flux} [lm]}{\text{Electrical Power} [W]}. \quad (4)$$

As it is seen from Table 2, luminous flux, luminous efficacy, optical power, and efficiency values were adversely affected from the increasing temperature. Luminous efficacy and efficiency values were also decreased with increasing current steps. Correlated colour temperature (CCT) and colour rendering index values (CRI) were also changed with the temperature and the current. Considering the adverse effects of high currents on LED proper-

ties, 1050 mA current was selected to reach high luminous efficacy values and also to obtain a cost effective solution in terms of COB LED number. When the optical losses and driver efficiency are considered, the luminous efficacy value will also be lower than the measured values of COB LED.

The solder point temperature has been targeted as 60 °C for avoiding negative effects of high temperatures on COB LED properties and at the same time not to cause very large heat sink dimensions. The luminous flux at 1050 mA current and 60 °C solder point temperature was calculated as 5100 lm by interpolating the luminous flux measurement values at 52.8 °C and 62.1 °C. The number of LEDs used in the COB LED based luminaire was calculated with the Equation (5) (luminous fluxes of reference luminaires were 25000 lumens, the approximate efficiency value of the reflectors on the market was 85 %, the measured luminous flux value of COB LED at 1050 mA current and 60 °C solder point temperature was 5100 lumens). From the Equation (5), the number of COB LEDs was calculated as 5.8 and the number of 6 was selected as an upper integer.

$$\text{Number of COB LEDs} = \frac{25000 \, lm}{5100 \, lm \times 0.85} = 5.8 \quad (5)$$

3. THERMAL SIMULATIONS AND EXPERIMENTAL ANALYSES

In this section, the computer aided thermal simulations and experimental analyses will be explained in detail.
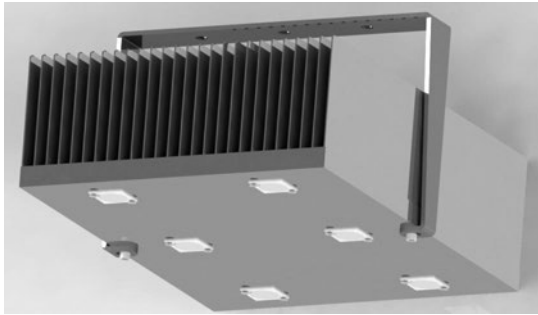
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Fig. 3. 3D luminaire model with plate finned heat sink

3.1. Thermal Simulations

In this study, a commercial computational fluid dynamics program was used for thermal simulations. A plate finned heat sink with a pendant, which is expected to provide the targeted 60 °C solder point temperature, is designed with preliminary thermal simulations taking into account production possibilities. Selected dimensions of the base plate of the heat sink were 290×221×14 mm, the fin height was 76 mm, the fin thickness was 1 mm, and the number of fins was 26. In Fig. 3, the 3D model of the heat sink and mounted COB LEDs can be seen.

In detailed thermal simulations, material properties of the parts and thermal resistances were tried to define accurately in the software for the exact results. Materials of the parts and their thermal conductivities are listed in Table 3. For the simplicity of thermal simulations, the Printed Circuit Board (PCB) was assumed as one aluminium layer and the COB LED was assumed as two layers consisted of an LED chip and its coating. The thermal conductivity of LED top coating [15], pendant-stainless steel 304 [16] and heat sink-aluminium 1050 [17] were defined as 0.2 W/mK, 16.2 W/mK, and 222 W/mK, respectively.

The thermal resistance of the grease used between the PCB and the heat sink was defined approximately as 0.17 Kcm^2/W from the manufacturer catalogue at the supplied lowest pressure value (5 N/cm^2) [18]. The thermal resistance between the pendant and the heat sink was defined as 3.3 Kcm^2/W. The thermal resistance between the LED chip and the PCB was defined as 0.9 Kcm^2/W by considering the thermal resistance value, which is given in the datasheet of selected COB LED between the junction and solder points. In thermal simulations, the air temperature was defined as 24 °C. The thermal power of a COB LED was calculat-
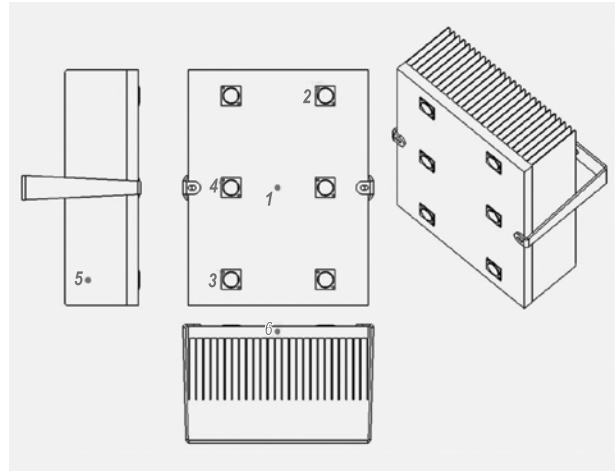

Fig. 4. Temperature measurement points

ed from Table 2 at 1050 mA current and 60 °C solder point temperature and found as 129.84 W for 6 COB LEDs.

Mesh sensitivity analysis was performed for different mesh configurations, which are shown in Table 4. The maximum temperature was controlled according to the increasing number of mesh elements. The results of Mesh 4 were used in this study because after mesh 4 the maximum temperature did not change considerably.

Six temperature measurement points were specified on the thermal model (Fig. 4). From the temperature measurement points number 2, 3, and 4, which were the solder points of different COB LEDs, 59.7 °C, 59.7 °C, and 60.4 °C temperature values were obtained by the thermal simulation, respectively. The obtained thermal simulation results are consistent with the accepted 60 °C soldering point temperature used for determination of the luminous flux and the thermal power in the design beginning. The results of the thermal simulation will be compared and evaluated in the results and discussion section. The temperature distribution of the
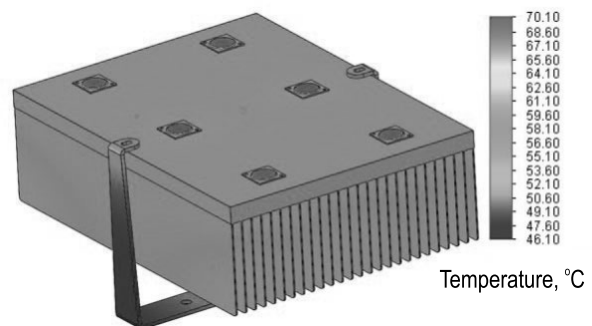

Fig. 5. Temperature distribution of the designed model

Table 3. Thermal Conductivity of the Parts Materials

Material	Thermal conductivity [W/mK]
Heat Sink – Al 1050	222
PCB – Al 5052	140 (at 273 K)
LED Chip – SiC	Between 150–126.6 (293 K – 473 K)
LED Top Coating	0.2
Pendant – 304 Stainless Steel	16.2

Table 4. Mesh Sensitivity Analysis

Mesh	The number of solid mesh elements	The number of total mesh elements	Maximum temperature of the system [˚C]
1	273 705	753 648	68.9
2	403 717	1 188 612	69.4
3	520 764	1 492 682	70.0
4	663 822	1 864 318	70.1
5	1 170 087	3 271 968	70.1
6	1 683 470	4 615 745	70.1
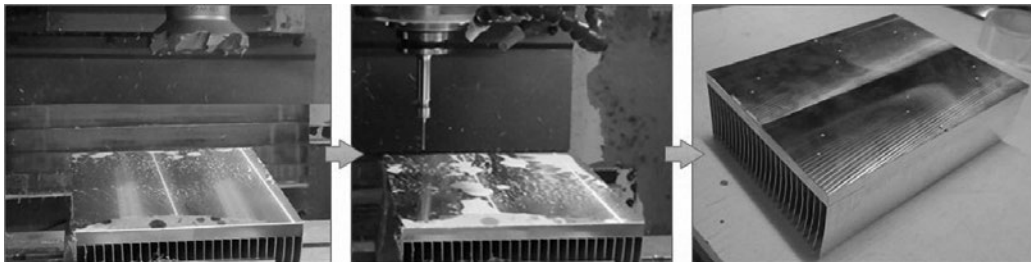
Fig. 6. Manufactured heat sink

designed model obtained from the thermal simulation is shown in Fig. 5.

3.2. Experimental Analyses

A prototype was manufactured and experimental analyses were carried out in order to determine the consistency of the method used in the design and thermal simulation of COB LED based industrial high-bay luminaire prototype. In the first stage of prototype manufacturing, a heat sink was produced from an aluminium block and the roughness of the surface, at which the LEDs will be mounted, was corrected. LED mounting holes were drilled. The manufactured heat sink is shown in Fig. 6.

Then the assembly steps were carried out in the following order (Fig. 7):

1. The surface was cleaned with isopropyl alcohol to remove residuals from production, which could adversely affect heat transfer;

2. The thermocouples were soldered to the solder point of the COB LEDs;

3. A thermal grease was applied between the PCB of COB LEDs and the heat sink to improve heat transfer;

4. COB LEDs were mounted on the heat sink;

5. The electrical and driver connections of the COB LEDs were made and the pendant of the prototype was mounted.

After manufacturing of the luminaire prototype, experimental analyses with laboratory measurements were done. The prototype was held in the air with the help of a pendant setup so that it was not touching anywhere as in computer-aided thermal simulations (Fig. 8). In the experimental analysis, the
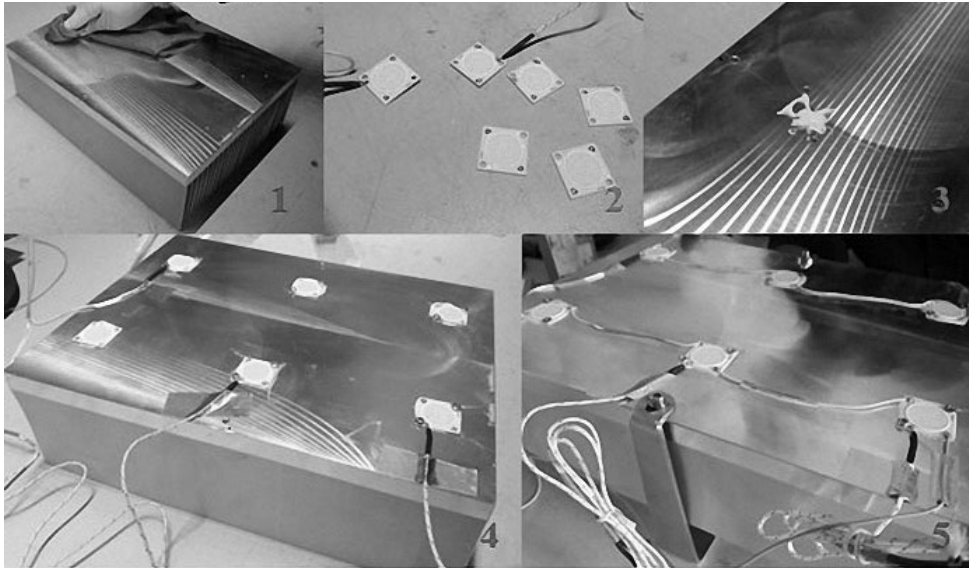
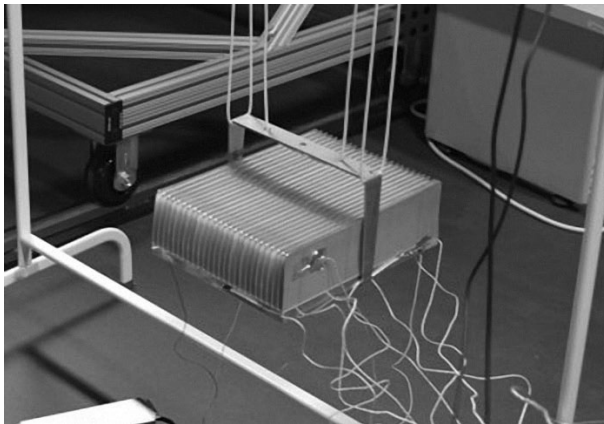Fig. 7. Assembly steps of COB LED based luminaire prototype

Fig. 8. Prototype pendant setup

The thermocouples were mounted on the points of the prototype, which are shown in Fig. 4 in order to compare the temperature values obtained from the experimental analysis and the thermal simulation. The temperature data were recorded with respect to time by using a digital multimeter. The sensors and the entire measurement system are shown in Fig. 9.

The temperature-time graph obtained as a result of the measurements is shown in Fig. 10. As it can be seen from the figure, the temperature increased with time and reached to thermal equilibrium. In the experimental analysis, the highest temperature values obtained from each thermocouple and the values obtained from the thermal simulation for the exact same points will be compared in the results and discussion section.

The luminous flux, optical power, CCT, and CRI properties were measured using a 2-meter-diame-

speed and the temperature of air were controlled by measurement devices. Two air temperature sensors and one hot bulb speed sensor were used. The air temperature was between 24–24.5 °C and the air speed was below 0.04 m/s during measurements.

Table 5. The Results of Measurements and Calculations

Property	Value
Total electrical power supplied to drivers, W	246
Total electrical power supplied to LEDs, W	218.5
Driver efficiency, %	88.8
Optical power, W	94.8
Luminous flux, lm	31200
CCT, K	3923
CRI	82.42
Efficiency of LEDs,%	43.4
Luminous efficacy of LEDs, lm/W	142.8
Thermal power, W	123.7

Table 6. Comparison of the Temperatures Obtained from Experimental Analysis and Thermal Simulation for the Measurement Points

Number of thermocouple	Experimental analysis [°C]	Thermal simulation [°C]	Difference [%]
1	55.16	58.47	−6.0
2	56.20	59.67	−6.2
3	55.83	59.66	−6.9
4	57.05	60.37	−5.8
5	51.78	54.63	−5.5
6	54.25	57.52	−6.0

Table 7. Comparison of Properties for Prototype Measurement and COB LED Measurement Results

Property	Prototype measurement	Calculations from COB measurement	Difference [%]
Optical power [W]	94.8	91.2	3.8
Electrical power [W]	218.5	221	−1.1
Thermal power [W]	123.7	129.84	−5.0
Luminous flux [lm]	31200	30600	1.9
Efficiency of LEDs [%]	43.4	41.2	5.1
Luminous efficacy of LEDs [lm/W]	142.8	138.4	3.1
CCT [K]	3923	3936	−0.3
CRI	82.42	82.73	−0.4

ter Ulbricht Sphere after the prototype reached the thermal equilibrium (Fig. 11). For the prototype, electricity was supplied with two separate 1050 mA constant current drivers. The voltages applied to the LEDs were also measured for these two circuits, and the total electrical power supplied to the LEDs from the drivers was found by multiplying the current and measured voltages. Driver efficiency was found by dividing the electrical power given to the LEDs to the electrical power delivered to the drivers. Additionally, the efficiency, luminous efficacy, and thermal power of the LEDs were found using the Equations (3), (4), and (2), respectively. The results obtained by measurements and calculations are shown in Table 5. Results from experimental analyses and single COB LED measurements will be compared in the results and discussion section.

RESULTS AND DISCUSSION

In this study, the design of a COB LED based high-bay industrial luminaire was described step by step. The results obtained by the thermal simulation and experimental analysis from the temperature measurement points determined on the luminaire prototype are as shown in Table 6. The greatest difference between the thermal simulation and experimental analysis is −6.9 %, and these differences can be considered within acceptable limits. This situation demonstrates the consistency of the assumptions made and the thermal model.

The values obtained from the measurements made for one COB LED at the beginning of the design were used for six LEDs. The differences between the calculations from COB measurement and prototype measurements are given in Table 7. In this case, the differences between the thermal simulation and the experimental analysis, which are given in Table 6, can be explained by the difference between the single COB LED measured in the beginning of the initial design and the six COB LEDs used in the prototype. Already in the manufacturer catalogues, the properties of the LED products are given within certain tolerances (±7 % for the selected COB LEDs luminous flux).

The obtained results indicate the necessity of determining properties of the COB LED light source to be used in the beginning of the design process.
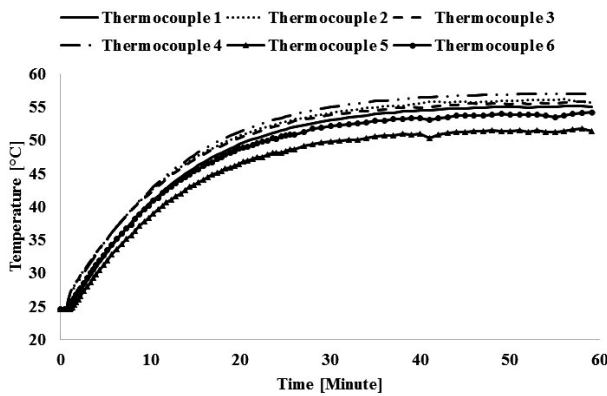
Fig. 9. Sensors and the entire measurement system

Fig. 10. Time dependent temperatures of the measurement points
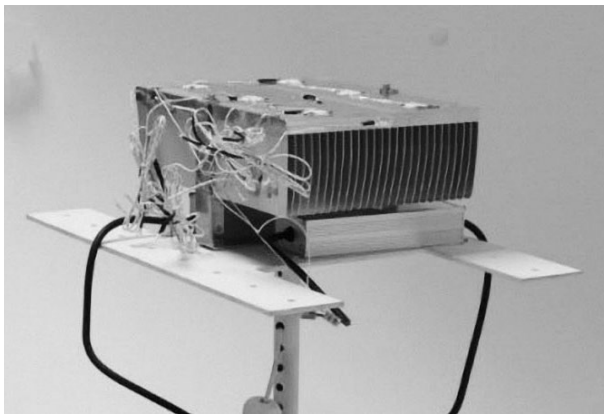

Fig. 11. Measurement of luminaire prototype using 2-meter-diameter Ulbricht Sphere

The thermal simulation should then be performed to ensure that the cooling system can provide the desired temperature values. Finally, the consistency of thermal simulation results should be checked with measurements on a prototype to be manufactured before mass production is started.

Another result of this study is, with a suitable thermal management system, COB LEDs can be used in high-power luminaires as an alternative to the single-chip LEDs, which are commonly used in the market. Thus, the number of LEDs used in luminaires as well as the mechanical design difficulty can be reduced. On the other hand, assuming an optical loss about 15 %, the COB LED based prototype, which was designed and experimentally analysed in this study, has a luminous efficacy of 108 lm/W. This value is lower than the luminous efficacy values of the single-chip LED based luminaires, which were selected for benchmarking in this study. But the main motivation of this study was to validate the thermal simulation results and experimental prototype measurement results of a COB LED based industrial high-bay luminaire starting from the single COB LED measurements. The validity of the method used in this study was verified with the analyses. It is also possible to apply this method starting from the first step for different design targets such as higher luminous efficacy etc.

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