ACTIVE COOLING METHOD FOR CHIP-ON-BOARD LEDS

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LEDs are the most efficient way to generate light, but much of the power consumed turns into heat. Active cooling solutions have been sought that are at the same time effective and allow to design luminaires of reasonable size and shape. The paper presents four such active cooling methods. The parameters that were analyzed and compared are: temperature, forward LED voltage, added power consumption. Each active cooling solution was compared to the passive one.

Keywords: fan, heat pipe, synthetic air jet, chip-on-board, active cooling, light-emitting diode

1. Introduction

The use of COB (chip-on-board) LEDs in general lighting is increasing due to the favorable emitted light ratio to source size. COB LED's are compact, modular and provide a generally homogenous light. The useful lifespan of an LED is different from its lifetime. By lifetime we define how long the LED emits light. By useful lifespan we limit this to the period until the values of some of its characteristic parameters fall below a given value enforced through standards (for example when the luminous flux reaches 70% of the initial value).

If the temperature on a LED is too high, parameters such as color, emitted light, direct voltage, etc. will be affected. Due to the high-power density on a small surface it is difficult to find passive cooling solutions which are small enough but also flexible enough and which allow an attractive design for the light fitting. Often, active methods such as synthetic air jets, fans, Peltier modules, etc. are used to cool LEDs. Ideally, the cooling solution will be customized depending on the application from the design stage, but sometimes this is impossible for economic reasons. When choosing a cooling solution for a light fitting, we will have to answer at least the following questions[1]: what dissipated power it will

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have to manage? what will be the dimensions of the light fitting (length, width, height, weight)? what noise it will introduce? how much additional power will the cooling module use? how complex is the manufacturing process? what effect it will have on the environment? what operating position will be used? how flexible is it in terms of design of the light fitting? what will be the final price? what will be the maintenance costs? what will be the life span of the parts?

2. Experimental set-up

Depending on the value of the current through the LED we will calculate the value of the thermal resistance of the heat sink.

If the LED power is: P_e=0.470A*33.9V=15.94W, and assuming that the LED had a 20% efficiency it follows that 80 % of the electric power will be converted into heat.

The dissipated power will be: P_d=15.94*0.8=12.75W.

If we assume that the ambient temperature T_a is 50°C and the case temperature T_c should not exceed 85°C, then the temperature difference is:

$dT=T_c-T_a$=85°C-50°C=35°C.

The thermal resistance shall be: $R_{th}=dT/P_d$=2.74°C/W.

If we infer that the resistance of the interface material is 0.2°C/W it follows that we will need a cooler for the LED with:

$R_{th\ LED\ cooler}$=2.74°C/W-0.2°C/W=2.54°C/W if we use a passive heat sink.

Solidworks models were created for two of the heat sinks used and thermal simulations were conducted. The material properties of the LED as well as the dimensions of the heat sink have been modified to see what the dimensions of the fitting would be if we were using only passive cooling solutions.

Four lighting fittings have been prepared. The same LED was used as a light source. The thermal interface material was the same (heat-conducting paste based on carbon micro particles, electrically non-conductive and with a thermal conductivity of 8.5W/mK). All temperature measurements were performed with a thermal imaging camera located at a distance of 0.4m from the light source. To determine the parameters of the thermal imaging camera (e.g. emissivity) and to check the accuracy of the values obtained with it, initial measurements were conducted both with the thermal imaging camera and with a thermocouple [5]. The LED for which different cooling solutions will be tested is COB (chip on board) type with a metallic substrate working at 470mA. The ambient temperature was 30°C. The fitting does not have an external lens, only the primary lens of the LED. Each active cooling solution was compared to the passive solution, achieved by not powering the active device or by removing it because different shapes, sizes and materials for heat sinks were used. The parameters that were compared were the temperature on the fitting (maximum value on the LED, maximum value on the heat sink), forward LED voltage, additional power consumption of the active device. The four fittings are presented below: with fan (Fig.1), with fan and heat pipe (Fig.2), with Peltier module and heat pipe (Fig.3) and with synthetic air jet generator (Fig.4).

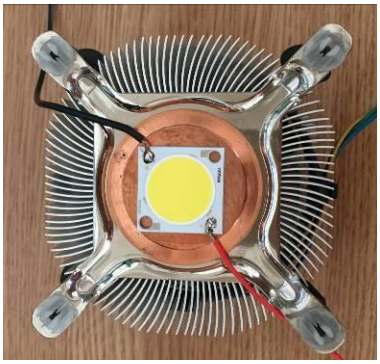
Fig.1. Light fixture with fan

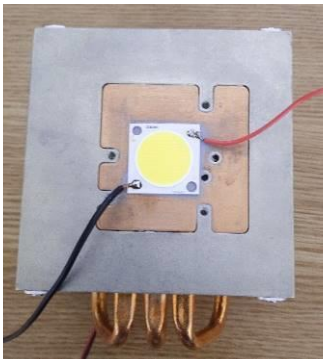
Fig.2.Light fixture with fan and heat pipe

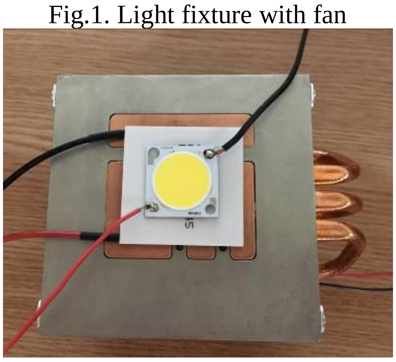
Fig.3. Light fixture with Peltier module

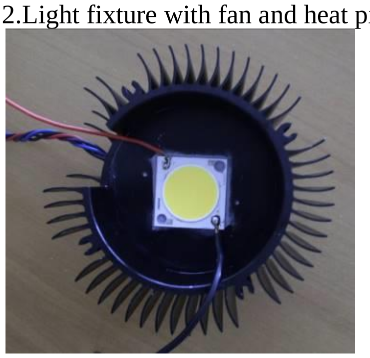
Fig.4.Light fixture with synthetic jet generator device

3. Measurements and results

3.1. Light fitting 1

The fitting was based on an aluminium heat sink with a copper heart, a power COB LED with an aluminium substrate and fan. The fan that was used is axial and it is used to move the air around the fins of the heat sink on which the LED is mounted. The LED current was I_{LED}=470mA. Measurements of temperature and forward voltage on the LED both with the fan turned on and off were conducted. The fan works at U_{fan}=12V and I_{fan}=80mA with a rotational speed of 2000rpm and its noise input is 18dB according to its datasheet. The results of the measurements are presented in Fig.5 and Fig.6.

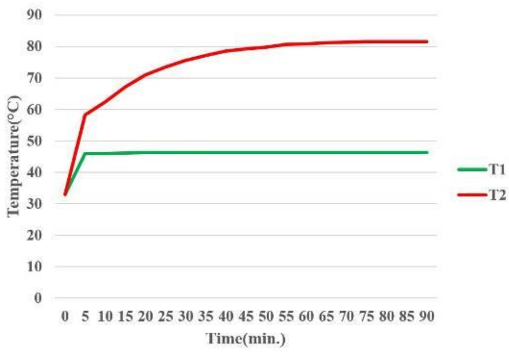

Fig.5. Temperature evolution on the LED

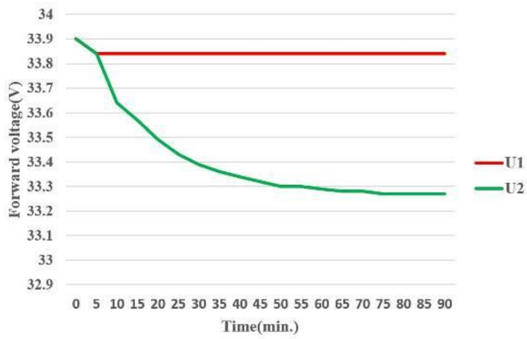

Fig.6. Forward voltage characteristic

We can observe that the temperature value stabilized at 46.2°C (Fig.7) for the active cooling method (T1) and at 81.6°C respectively (Fig.8) for the passive cooling method (T2). The temperature on the heat sink was 39°C in the first case and 56.8°C in the second.

It is known that with temperature rise on the LED, the forward voltage on it will decrease due to changes in the semiconductor material [3]. Fig. 6 shows forward voltage characteristic. We note that the forward voltage value stabilized at 33.84V for the active method (U1) and at 33.27V for the passive method (U2). The additional power consumption of the fan is 960mW.

Fig. 7 shows the thermal map after 90 minutes if the fan is switched on and in Fig. 8 the thermal map is presented for the case in which the fan is off.

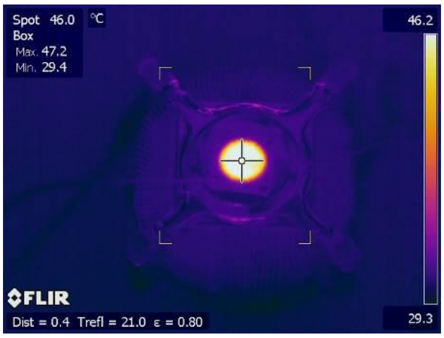

Fig.7. Measurement results after 90 minutes for the lighting fitting with the fan turned on

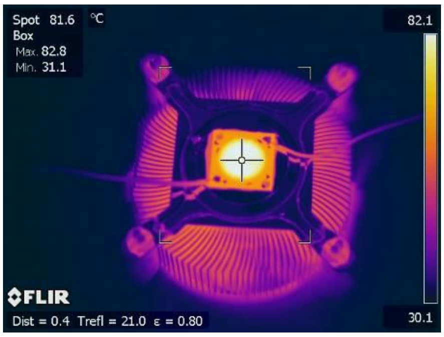

Fig.8. Measurement results after 90 minutes for the lighting fitting with the fan turned off

A virtual model of the LED (Fig.9) was developed based on the real model. For this simulation it was considered that the materials used are homogeneous and isotropic and their thermal conductivity is not affected by temperature. One of the parameters considered in the simulation was the natural convection coefficient that was set at $7 W/m^2K$. It was simulated at an ambient temperature of 27°C. The results are shown in Fig.10.

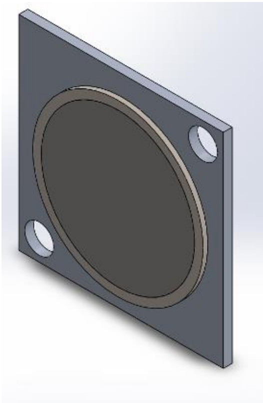

Fig.9. LED model

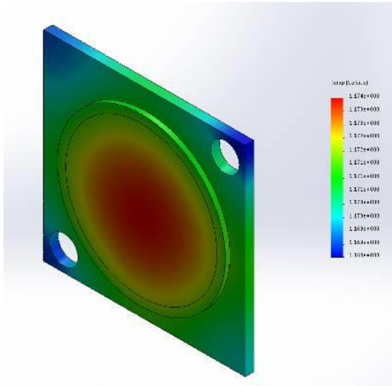

Fig.10. Temperature distribution on the LED

We notice that the values obtained are very high (1174°C) so we will have to use a heat sink.

The virtual model of the fitting on which we conducted the previous measurements (Fig.11) was also developed. The simulation was conducted with the following initial conditions: ambient temperature (T_a) - 30°C, dissipated power (P_D) - 12.8W and natural convection coefficient (K) - 7W/m^{2}K. The results are shown in Fig. 12.

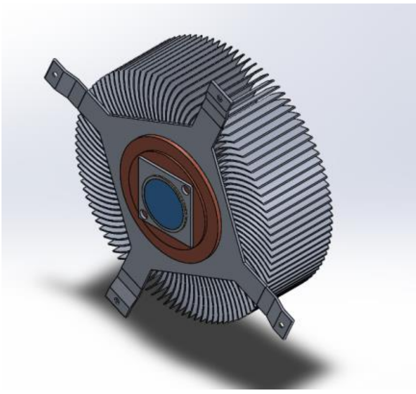

Fig.11. Light fixture model

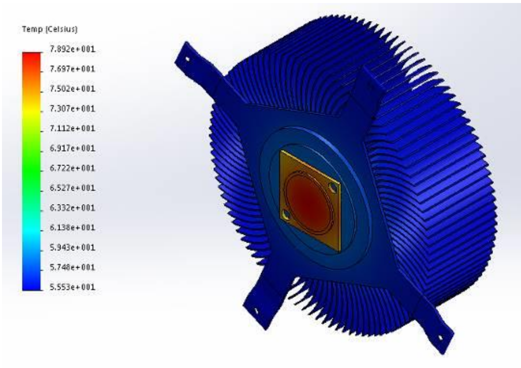

Fig.12. Simulation results for P_D=12.8W, the natural convective coefficient K=7W/m^{2}K

We observe a slight difference of almost 3°C between the measured and the simulated results, these are due to the approximations used in the simulation. To see how much the temperature value on the LED is affected by the material from which the substrate is made, a new simulation was conducted in which the substrate material has been changed from aluminium to alumina. The simulation results are presented in Fig. 13. We notice that the temperature increased with almost 6°C.

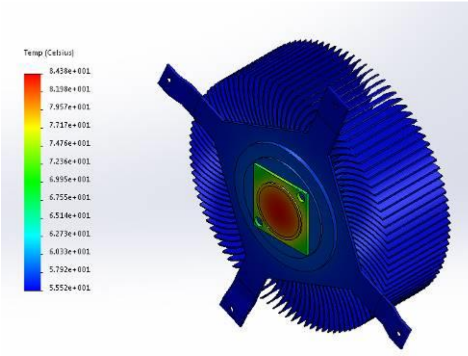

Fig.13. Simulation results for P_D=12.8W, the natural convective coefficient K=7W/m^{2}K and alumina substrate

3.2. Light fitting 2

The same measurements were made on the fitting in Fig.2. It consists of LED, fan, heat sink with heat pipe. The LED contact of the heat sink was made out of copper and the rest is made of aluminium. Measurements were performed with the fan turned on, respectively with the fan turned off. The LED was powered at 470 mA. The fan works at U_{fan}=12V and an I_{fan}=28mA with a rotational speed of 2200rpm; the noise input by the fan is 18dB according to its datasheet. The results of the measurements are shown in Fig.14 and Fig.15.

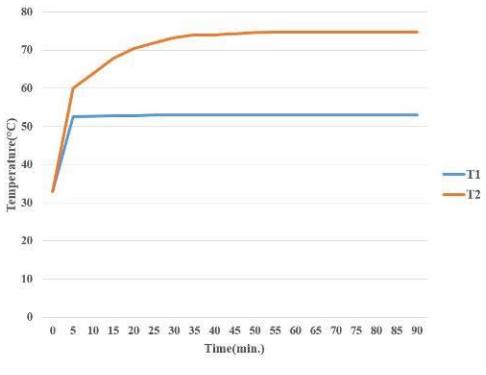

Fig.14. Temperature evolution on the LED

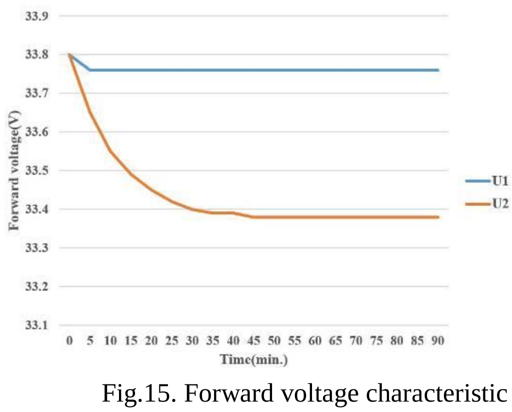

Fig.15. Forward voltage characteristic

We note that the temperature value stabilized at 53°C (Fig.16) for the active method (T1) and at 74.8°C (Fig.17) for the passive method (T2). The temperature on the heat sink was 36.2°C in the first case and 75.8°C in the second.

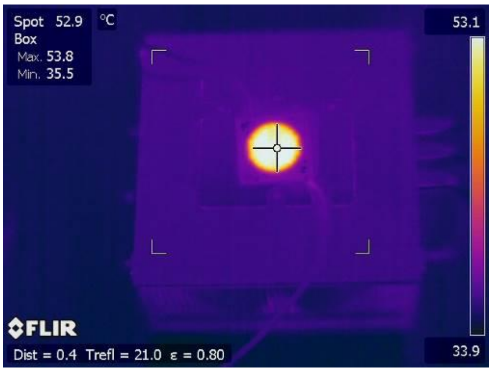

Fig.16. Measurement results after 90 minutes for the lighting fitting with the fan turned on

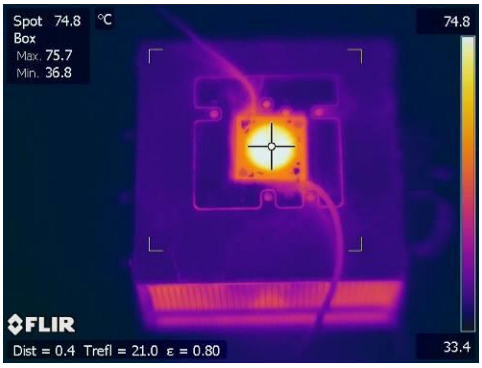

Fig.17. Measurement results after 90 minutes for the lighting fitting with the fan turned off

We observe that the forward voltage value stabilized at 33.74V for the active method (U1) and at 33.39V for the passive method (U2) respectively. Additional fan consumption is 340mW.

3.3. Light fitting 3

The same measurements were made on the fitting in Fig. 3. It consists of the LED, the same heat sink with heat pipe from the previous case and a Peltier module. The parts of this fitting are shown in Fig.18.

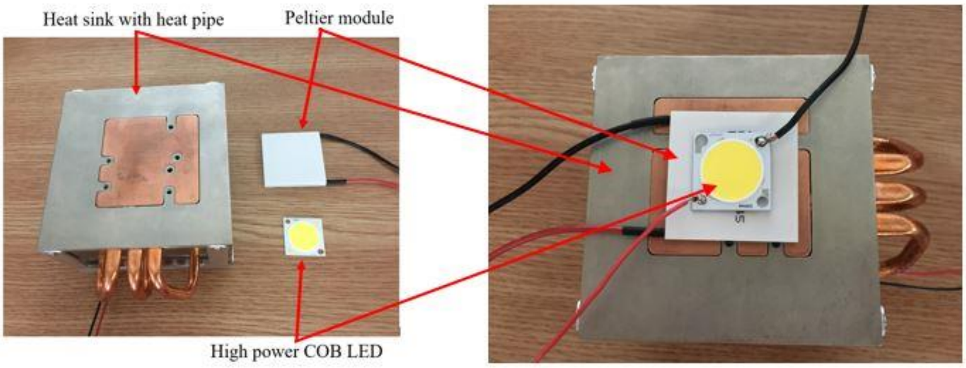

Fig.18. The main elements of the lighting fixture using the Peltier module for LED cooling

The operating principle of the Peltier module is based on the Peltier effect entailing thermal energy transfer in response to applied voltage. The heat flows between the two sides (cold and warm) of the module. The Peltier module absorbs heat from the LED that is mounted on the cold side and releases heat to the heat sink that is mounted on the hot side of the Peltier module [4].

The Peltier module works at I_{PM} = 1.5A and U_{PM} = 7.3V. The LED contact of the heat sink was made out of copper and the rest of heat sink is made of aluminium. The measurements were made with the Peltier module mounted and with the fitting without the Peltier module. The results of the measurements are shown in Fig.19 and Fig.20.

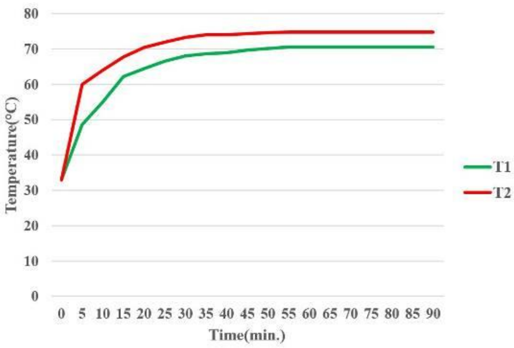

Fig.19. Temperature evolution on the LED

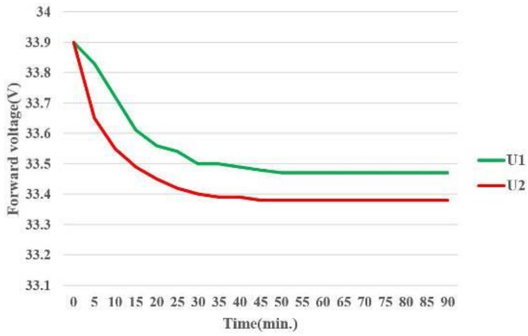

Fig.20. Forward voltage characteristic

We note that the temperature value stabilized at 70.6°C (Fig. 21) for the active method (T1) and at 74.8°C (Fig. 22) respectively for the passive method (T2). The temperature on the radiator was 79.6°C in the first case and 75.8°C in the second.

We note that the forward voltage value stabilized at 33.47V for the active method (U1) and at 33.39V for the passive method (U2).

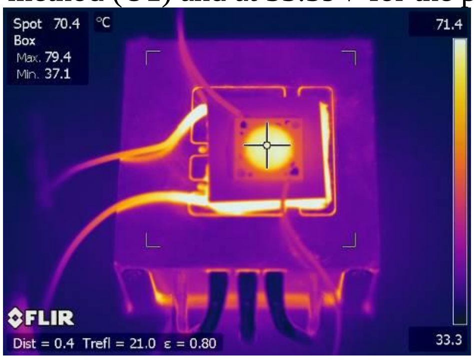

Fig.21. Measurement results for the fitting with the Peltier module

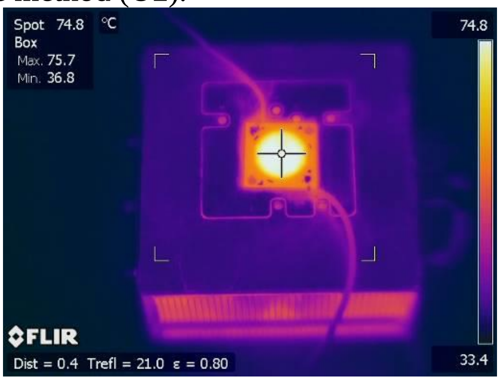

Fig.22. Measurement results for the fitting without the Peltier module

The additional power consumption introduced by the Peltier module is 10.95W.

3.4. Light fitting 4

The same measurements were also made on the fitting in Fig.4. Its parts are shown in Fig. 23. The measurement stand is shown in Fig.24.

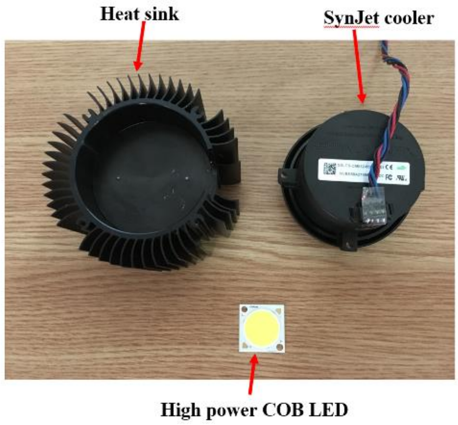

Fig.23. The main elements of the lighting fixture using the synthetic jet for LED cooling

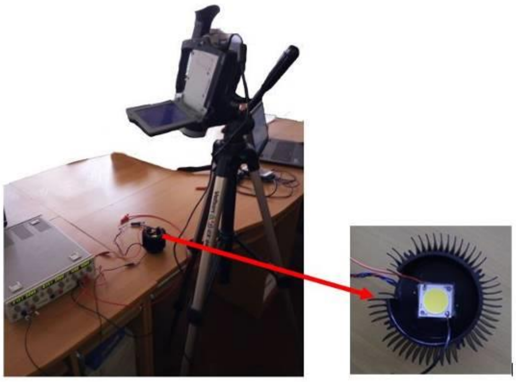

Fig.24. The workbench

It consists of LED, passive heat sink and a device for generating synthetic jets. It works at I_{SynJet} = 70mA and U_{SynJet} = 12V.

The synthetic jets are obtained by absorbing and discharging a fluid through a cavity opening by periodically moving a diaphragm in the cavity. The vibration of the diaphragm can be obtained by several methods: piezoelectric, electromagnetic or electrostatic [2]. The device used in this paper for generating synthetic jets uses the air as the fluid and uses the electromagnetic method for vibrating the diaphragm. These air jets are oriented toward the channels of the heat sink on which the LED is located. The temperature and voltage evolution are shown in Fig.25 and Fig.26 respectively.

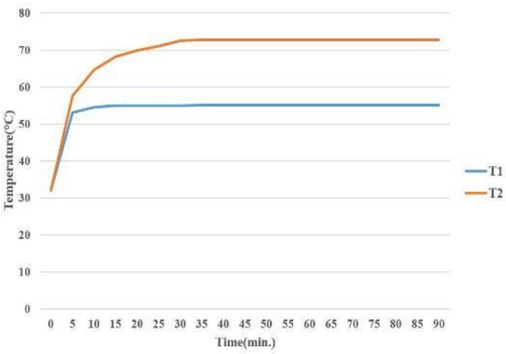

Fig.25. Temperature evolution on the LED

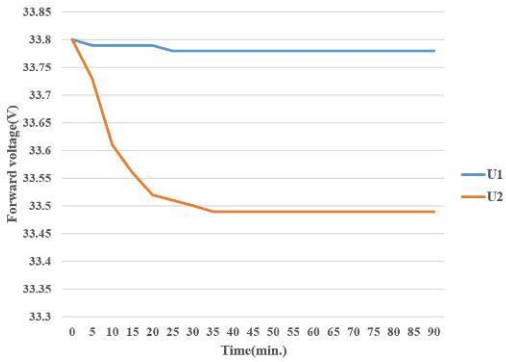

Fig.26. Forward voltage characteristic

The temperature value stabilized at 55.1°C (Fig.27) for the active method (U1) and at 72.8°C (Fig.28) for the passive method (U2). The forward voltage value stabilized at 33.78V for the active method (U1) and 33.47V for the passive method (U2) respectively. The additional power consumption introduced by the synthetic jet generator is 840mW.

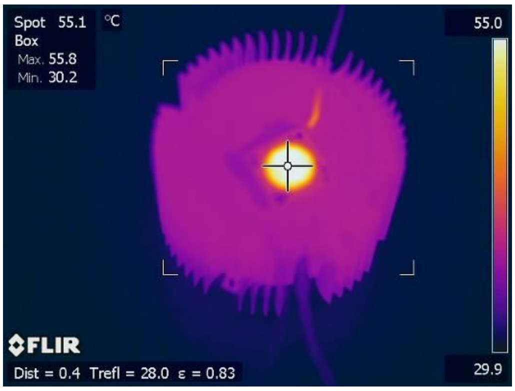

Fig.27. Measurement results after 90 minutes for the fitting with the synthetic air jet generator

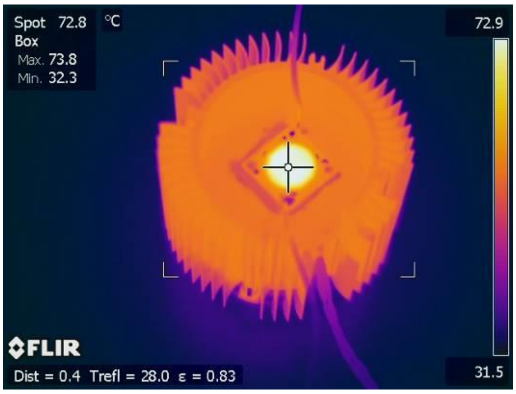

Fig.28. Measurement results after 90 minutes for the fitting when using only the passive heat sink

The temperature on the heat sink was 38.5°C (Fig.29) in the first case and 56.1°C (Fig.30) in the second.

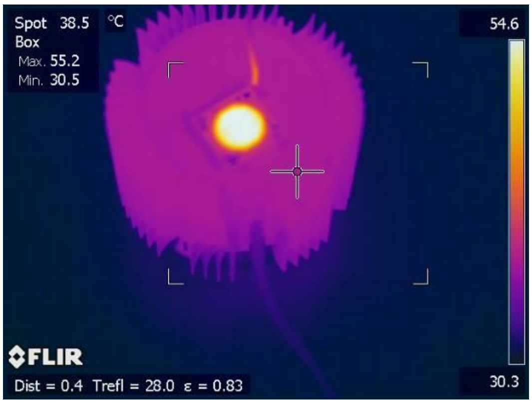

Fig.29. Temperature on the heat sink after 60 minutes for the fitting with the synthetic air jet generator

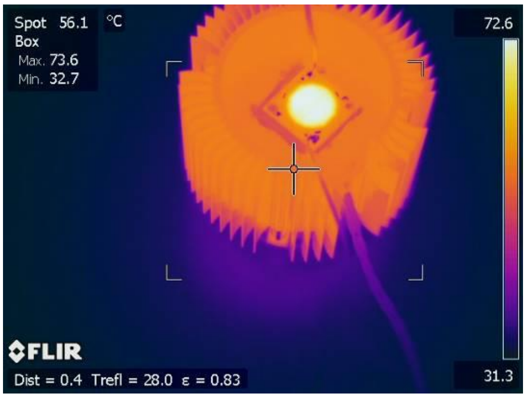

Fig.30. Temperature on the heat sink after 60 minutes for the fitting using only the passive heat sink

We built a virtual model of the fitting using the synthetic air jet generator on which we conducted the previous measurements (Fig.31). The simulation was conducted under the following initial conditions: ambient temperature (T_a) - 31 °C, dissipated power (P_D) - 12.8W and the natural convective coefficient (K) - 7W/m^{2}K. The results are shown in Fig.32.

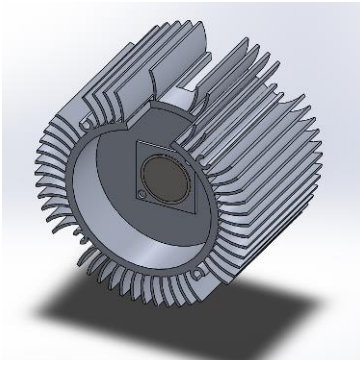

Fig.31. Model of the fitting with heat sink

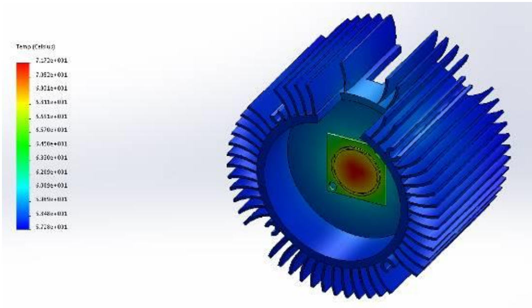

Fig.32. Simulation results for P_D=12.8W, the natural convective coefficient K=7W/m^{2}K

We observe that the temperature obtained after the simulation is 71.7°C, one degree lower than the temperature obtained from the measurements.

To see what the heat sink dimensions would have to be to obtain the same temperature as when using the active method, the heat sink was resized. To reach this value we doubled the length of the heat sink. The simulation results after doubling the length are shown in Fig.33.

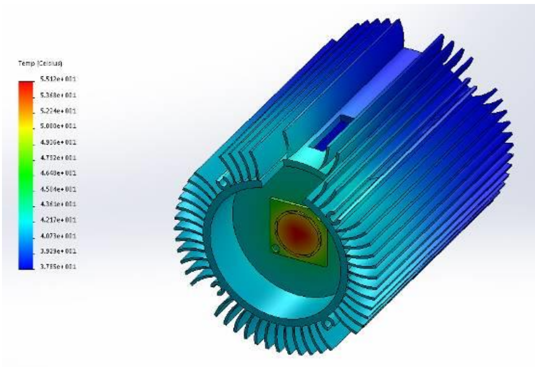

Fig.33. Simulation results for P_D=12.8W, the natural convective coefficient K=7W/m^{2}K with the length of the heat sink doubled

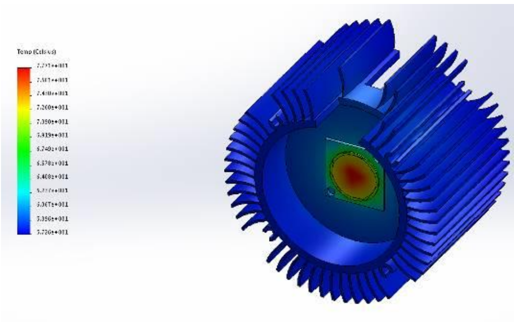

Fig.34. Simulation results for P_D=12.8W, the natural convective coefficient K=7W/m^{2}K with LED substrate changed to alumina

We observe that the value obtained after the simulation is 55.1°C.

The LED substrate material was modified from aluminium to alumina and the simulation was resumed under the same conditions. The results of the simulation are shown in Fig.34. We note that the temperature has increased by about 6°C as a result of this change.

4. Conclusions

Four lighting fittings have been made. All four used the same LED as the light source and the same thermal interface material. Each active cooling solution was compared to the passive one obtained by not powering the active device or by removing it because various heat sink shapes, sizes and materials were used. The parameters that were compared were the temperature on the fitting (maximum value on the LED, maximum value on the heat sink), the forward voltage on the LED, the additional power consumption of the active device. It has been found that one of the quietest and most efficient methods from thermal and electrical points of view is the one useing devices for generating synthetic air jets. Models have also been created to allow for the thermal simulation of the fitting to help choose the applications in which they can be used.

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