SIMULATION AND EXPERIMENTAL ANALYSIS OF LED WEATHERPROOF LUMINAIRE THERMAL PERFORMANCE

Carlos Javierre^(a), Daniel Elduque^(b), Víctor Camañes^(c), David Franch^(d)

^(a,b,c)Department of Mechanical Engineering, University of Zaragoza, C/ María de Luna, 3, 50018 Zaragoza, Spain ^(d)Zalux, Centro Empresarial Miralbueno, 50012 Zaragoza, Spain

^(a)carlos.javierre@unizar.es, ^(b)daniel.elduque@gmail.com, ^(c)victor.camanes@gmail.com, ^(d) dfranch@zalux.com

ABSTRACT

In this paper the experimental and simulation analysis of a LED weatherproof luminaire is carried out. A CFD model that properly correlates with the real measurements has been created. After this, it is used as a tool to assess different design structures and new thermal solutions, showing that some LED luminaires designs create new thermal problems due to the coupling between the LED's and driver's heat. This problem must be solved or at least decreased in order to obtain higher LED lifetimes and efficiencies. This problem of thermal management is forcing engineers to come up with new solutions for weatherproof luminaires. The use of CFD simulation helps designers to properly understand the thermal behaviour and improve new designs reducing significantly prototyping costs.

Keywords: LED weatherproof luminaire, simulation, measurement, design

1. INTRODUCTION

Reducing the environmental impact of new products is key factor as environmental awareness increases in society. New techniques such as Life Cycle Assessment have been developed to assess and improve the environmental performance of products and services by using new materials (Sarasa, et al. 2009) and reducing energy and raw materials consumption (Martinez, et al. 2009) (Martinez, et al. 2010) (Grignon-Massé, et al. 2011) (Fernández, et al. 2013) (Elduque, et al. 2014) (Jiménez, et al. 2014).

Energy efficiency has become a vital factor in most electrical and electronic products (Welz, et al. 2011). For several decades fluorescent lighting has been widely used in most industrial applications. The search for higher efficiency levels is a major concern for the lighting industry. In the last decade, significant improvements have been made, making LED (Light Emitting Diode) lighting a reality.

This technology offers higher output efficiency and lowers the environmental impact of the use phase but due to its characteristics it also creates new problems that must be addressed. LED lifetime and efficiency output is highly dependent on working temperatures, meaning that keeping the LED modules cool is a priority when developing a new luminaire.

Simulation approaches are currently used in multiples fields (Latorre, et al. 2009) (Martinez, et al. 2010) (Latorre-Biel, et al. 2012) (Latorre-Biel, et al. 2013), including LED lighting. Simulation software is also currently used to improve design results (Aisa, et al. 2006) (Javierre, et al. 2006) (Ruiz Argáiz, et al. 2008) (Jiménez, et al. 2009) (Javierre, et al. 2013) (Javierre, et al. 2014). Several authors have used simulation software to analyze .the thermal behaviour of LED and improve its efficiency. Some studies have analyzed the cooling of one LED lamp, improving its heat dissipation by means of optimized heat sinks (Costa and lopes 2014) The thermal modelling of individual LED and its boundary condition have also been assessed to improve led manufacturing and its performance

Other authors have studied LED arrays and how its placement affects the thermal management (Li, et al. 2011) (Yung, et al. 2014). Also the use of new LED substrates materials has been analyzed (Yin, et al. 2010). Finally, other researchers have focused on complete luminaires

In order to solve this problem, the Spanish leading manufacturer of weatherproof luminaires and industrial battens, Zalux, has worked with the Department of Mechanical Engineering of the University of Zaragoza to develop new design solutions to improve the thermal behaviour of its luminaires.

To carry out this project both simulation and experimental measurements have been performed with the aim of developing new LED luminaires made out of different materials such as aluminium, thermoplastics or thermally conductive thermoplastics.

2. EXPERIMENTAL SETUP AND THERMAL MODELLING

2.1. Experimental Setup

LED temperatures are a key factor when developing new weatherproof luminaires. These light fittings enclose into a plastic housing all the lighting system: an ECG (Electronic Control Gear) and the LED modules, obstructing heat dissipation and thus reducing the efficiency. This makes necessary to find new designs that guarantee appropriate heat dissipation, improving the efficiency of the luminaire. This factor is especially critical for weatherproof luminaires, as the heat transfer via convection is lower due to the enclosed housing (Figure 1).



Figure 1: Weatherproof luminaire structure

A commercial LED weatherproof (Figure 2) sold by Zalux has been chosen to set the benchmark and allow a correlation between experimental data and simulation results. This luminaire has a new weatherproof design base on aluminium housing to improve LED cooling as it works as a heat sink, reducing LED temperatures. This is a fully functional design but expensive as the housing is produced by injecting aluminium into a mould.



Figure 2: Zalux Nextrema luminaire

The internal component distribution of the commercial luminaire is shown in Figure 3. The ECG is placed near end of the luminaire, where the mains cable is connected. The LED MCPCBs are placed at the centre of the luminaire.



Figure 3: Components used in Zalux Nextrema luminaire

First of all, the luminaire will be measured using a thermocouple logger and a thermo-graphic camera.

Thermal images allow us to understand how the housing cooling effect is working and which the temperatures in the external walls are (Figure 4).



Figure 4: Thermal image

These images allow us to see that the electronic driver is an important source of concentrated heat whereas the LEDs also generate heat but it is more distributed along the length of the luminaire. This means that near the driver there is a heat coupling effect that increases the temperature in this area.

Thermocouples are used to determine the temperature of internal components, like the LEDs (Figure 5) or the electronic driver.



Figure 5: Thermocouple used to measure LED temperature

2.2. Simulation model

After obtaining the real working temperatures values, a CFD model was developed with Solid Works Flow Simulation, obtaining a simulation model that can be used to improve new designs.

Solidworks is a well-known simulation software. Its developer has validated its ability to calculate essential features of flows and to solve conjugate heat transfer problems (flow problems with heat transfer in solids). This software is currently used to solve a wide range of fluid flow and heat transfer phenomena. It numerically solves the Navier-Stokes equations (mass, momentum and energy conservation for fluid flows). These equations are supplemented by definitions of thermophysical properties and state equation for the fluids. Also radiation heat transfer is considered (SolidWorks, 2012).

To solve all the equations, a numerical solution technique is employed by Flow Simulation. It uses a cell-centered finite volume method with a rectangular computational mesh in a Cartesian coordinate system. Values of the variables are calculated at the mesh cell centres and equations are discretized with first (time) or second order (space) accuracy. Mesh cells intersecting with a solid/fluid interface are split into smaller cells. To accurately solve this interface, additional boundary faces are used to consider boundary conditions and geometry. If needed, the mesh is refined during the calculation process to solve high-gradient regions.

Material properties (Table 1) were obtained from suppliers' data and introduced into the model. The upper wall is defined as an insulator and polycarbonate is used for the light diffuser.

| Part | Material | Conductivity (W/mK) |
|-----------|------------------------|------------------------|
| Wall | Isolator (WC scenario) | 0 |
| LED MCPCB | Aluminium | 136.7 |
| Diffuser | Polycarbonate | 0.22 |
| Tray | Steel | 52 |

Table 1: Material conductivity

Thermal resistances between LED and MCPCB (Metal Core Printed Circuit Board) were also taken into account. The Solid/Fluid Interface has been improved using small solid fluid refinement, curvature and tolerance refinement and optimization of the resolution for thin walls. An example of the fluid mesh is shown in the next figure.



Figure 6: Example of fluid mesh definition

Also cell refinement was used, especially for solid cells so as to achieve a better modelling of the geometry; also several local meshes were used to improve the LED temperature distribution. The CFD mesh with solid and partial cells is shown below (Figures 7 and 8).



Figure 8: Example of LED MCPCB mesh definition

Models between 4 and 8 million cells were used to obtain appropriate results with reduced computing times with a desktop PC (i7 quad-core, 32GB RAM memory).

Heat losses for LEDs and the electronic gear were obtained from the manufacturer.

After creating the CFD model, an external analysis to achieve a steady state was performed, showing that experimental and simulation results were very similar (Figure 9)



Figure 9: Temperature results of Zalux Nextrema

CFD simulations also allow us to understand how the heat sink is working and the effect of the airflow in the cooling (Figure 10).



Figure 10: Airflow results of Zalux Nextrema

It also allows us to identify heat coupling and potential temperature hotspots.



Figure 11: LED temperatures of Zalux Nextrema

3. DESIGN IMPROVEMENTS

These results and the simulation model are used to develop new designs in order to improve the performance and reduce temperatures. These modelling approaches were also tested with other smaller weatherproof luminaires used for emergency lighting, obtaining adequate results (Figure 12).



Figure 12: Temperature results of Zalux Emergency Nextrema

Also the simulation and experimental analysis are applied to propose new design configurations, like the one shown below (Figure 13), using an aluminium heatsink for the LED surrounded by a polymer housing to ensure the weatherproofness. The aluminium heatsink can be extruded, also meaning lower production costs.



Figure 13: New design using an extruded heatsink

Instead of creating a prototype, which is expensive for plastic parts, a CFD model was carried out to assess if this solution achieves and adequate thermal behaviour (Figure 14) (Table 2).



Figure 14: Temperature results of the redesigned luminaire

| Table 2: LED I | emperature Denas |
|----------------|-----------------------|
| Design | LED temperature Delta |
| | |

| Design | LED temperature Delta (K) |
|---------------------|---------------------------|
| Nextrema Aluminium | 27.8 |
| housing | |
| Extruded heatsink + | 30.3 |
| Polymer housing | |

In order to determine whether or not the use of a thermally conductive polymer housing may have a significant cooling in a standard weatherproof luminaire, three different materials were tested: production PC, and two PolyOne Therma-Tech thermally conductive polymers (Table 3) (Figure 15)

| T 11 0 11 | r • | | 1 | |
|--------------|------------|-------------|----------|-----|
| Toble 3. H | Olicing t | motorial or | manativi | tx7 |
| | IOUSING I | | линилту | 1 V |
| 1 4010 01 11 | io abing i | | | •) |

| | U | | |
|-----------|--------------|--------------|-------------|
| Material | In-plane | Through- | Maximum |
| | conductivity | plane | temperature |
| | (W/mK) | conductivity | Delta (K) |
| | | (W/mK) | |
| Standard | 0.22 | 0.22 | 39.2 |
| PC | | | |
| Therma- | 0.9-1.3 | 0.9-1.3 | 35.8 |
| Tech | | | |
| White | | | |
| Therma- | 19-21 | 4.5-5.5 | 33.3 |
| Tech Grey | | | |



Figure 15: Temperature measurements of Therma-Tech Grey thermally conductive polymer housing

The temperature reached by the light source shows a noteworthy reduction (Table 3), showing that the use of thermally conductive polymers is an interesting approach to improve the efficiency of the luminaire by means of reducing its operating temperature, but as this design was based on a standard luminaire structure, temperatures are higher than in designs optimized for LEDs.

Another adaptation of traditional weatherproof design solutions to use LED were also tested in this project, finding that LED technology (Light sources and the Electronic Control Gear) produce several higher problems due to heat concentration, creating hotspots that would decrease LED performance (Figure 16)



Figure 16: Temperature results showing thermal coupling

To check if the CFD simulation was producing accurate results, a prototype of this luminaire was assembled, allowing us to compare temperatures between the CFD model and the prototype (Table 4).

| ruble 4. Comparison between er D and prototype | | | | |
|--|-----------|------------|------------|--|
| Temperatures | Prototype | CFD | Difference | |
| (°C) | values | Simulation | | |
| MCPCB1 | 52.8 | 51.7 | -1.1 | |
| MCPCB2 | 59.8 | 60.7 | +0.9 | |
| Driver | 65.5 | 62.6 | -2.9 | |
| Tray | 60.0 | 62.1 | +2.1 | |

Table 4. Comparison between CFD and prototype

Differences lower than 3°C were found, meaning that the CFD was producing good results for the working conditions

The use of thermally conductive polymers was also tested for LED-specific design solution, using an anisotropic material model in the CFD simulation. Thanks to the way fins are filled in the injection process, they have a conductivity of around 20 W/mK in the proper direction to help even more with heat dissipation. A reduction of 3.8 K was obtained for the

LEDs maximum temperature when comparing with isotropic modelling.

In order to optimize the design's thermal behaviour via convection, also several simulations were performed to obtain the optimal pitch between cooling fins (Figure 17). More fins create a bigger cooling and irradiative area, but if the gap between fins is too small, the air does not flow properly due to natural convection, increasing the temperature.



Figure 17: Temperature results for 5 mm and 30 mm fin distance

The CFD results allow us to better understand how the air flow works between the fins, as shown in Figure 18 below.



Figure 18: Air flow between fins

The optimum pitch between fins was 10mm as shown in Figure 19.



Figure 19: Maximum LED temperature depending on fin pitch

After studying the air flow, a new design was proposed, creating two banks of fins and placing the driver at the centre of the luminaire. This creates a symmetrical flow, increasing the cooling created by the fins and reducing average temperature (Figure 20). Although, due to the thermal coupling caused by the LED and the driver the maximum temperature of the LED is increased, meaning that the lifetime and efficiency would be lower.



Figure 20: Temperature results showing thermal coupling

Also, in order to find other ways of improving thermal performance, the effect of the surface emissivity was studied. In natural convection flows, radiation has an important effect. Even though temperatures of a luminaire housing are not high, any way of improving the performance is useful. To do that, the effect of the material surface was studied. A comparison between a raw housing (without any surface treatment), an enamel paint (emissivity around 0.9) and black matt paint (emissivity around 0.98).



Figure 21: Black matt paint (Left) and Enamel paint (Right) inside the oven

To determine if there was any significant difference, two housing were heated at the same time in an oven (Figure 21), and the cooling time to achieve different temperatures was measured. Optimum results were obtained with the black matt pain after applying 5 layers of paint.

4. CONCLUSION

In this paper the process measuring a luminaires to create a CFD model that properly correlates with the real measurements is shown. After this model is obtained, it is used as a tool to assess different design and thermal solutions, showing that LED luminaire create new thermal problems that must be solved in order to obtain higher LED lifetime and efficiency. The problem of thermal coupling between the LED and the ECG is forcing engineers to come up with new solution for weatherproof luminaires.

The use of CFD simulation helps designers to properly understand the thermal behaviour and helps in reducing prototyping costs.

ACKNOWLEDGMENTS

The authors would like to thank the help provided by Zalux's development team.

REFERENCES

- Aisa, J., Javierre, C. & De la Serna, J., 2006. An example of simulation tools use for large injection moulds design: The CONTENUR[™] 2400 1 solid waste container. *Journal of Materials Processing Technology*, 175(1-3), 15-19.
- Costa, V., & Lopes, A. (2014). Improved radial heat sink for led lamp cooling. *Applied Thermal Engineering*, 70, 131-138.
- Elduque, D. et al. 2014. Life cycle assessment of a domestic induction hob: electronic boards. *Journal of Cleaner Production*, 76, 74-84
- Fernández, A., Javierre, C., González, J. & Elduque, D., 2013. Development of thermoplastic material food packaging considering technical, economic and environmental criteria. *Journal of Biobased Materials and Bioenergy*, 7(2), 176-183.
- Grignon-Massé, L., Rivière, P. & Adnot, J., 2011. Strategies for reducing the environmental impacts of room air conditioners in Europe. *Energy Policy*, 39(4), 2152-2164.
- Javierre, C., Abad-Blasco, J., Camañes & V., F. D., 2013. Redesign of metalic parts with thermoplastic materials: Application example | Rediseño de componentes metálicos En materiales termoplásticos: Ejemplo de aplicación. DYNA, 88(2), 197-205.
- Javierre, C., Fernández, A., Aísa, J. & Clavería, I., 2006. Criteria on feeding system design: Conventional and sequential injection moulding. *Journal of Materials Processing Technology*, 171(3), 373-384.
- Javierre, C., Fernández, Á., Clavería, I. & Elduque, D., 2014. Textile injection process characterisation by means of a spiral mould. *Measurement: Journal of* the International Measurement Confederation, 47(1), 100-109.
- Jiménez, E., Ruiz, I., Blanco, J., & Pérez, M. (2009). Design and simulation of production of injection pieces in automobile industry. International *Journal of Simulation: Systems, Science and Technology*, 10(3), 23-30.
- Jiménez, E. et al. 2014. Methodological approach towards sustainability by integration of environmental impact in production system models through life cycle analysis: Application to the Rioja wine sector. *SIMULATION*, 90(2), pp. 143-161.
- Latorre, J. I., Jiménez, E., Pérez, M., & Martínez, E. (2009). The design of a manufacturing facility. An

efficient approach based on Alternatives Aggregation Petri nets. *Paper presented at the 21st European Modeling and Simulation Symposium, EMSS 2009.*

- Latorre-Biel, J. I., Jiménez-Macías, E., Blanco-Fernández, J., & Sáenz-Díez, J. C. (2012). Decision making in the Rioja wine production sector. Paper presented at the 24th European Modeling and Simulation Symposium, EMSS 2012.
- Latorre-Biel, J. I., Jiménez-Macías, E., Blanco-Fernández, J., & Sáenz-Díez, J. C. (2013b). Optimal design, based on simulation, of an olive oil mill. Paper presented at the 25th European Modeling and Simulation Symposium, EMSS 2013.
- Li, J., Yang, Q., Niu, P., Jin, L., Meng, B., Li, Y., Zhang, X. (2011). Analysis of Thermal Field on Integrated LED Light Source Based on COMSOL Multi-physics Finite Element Simulation. *Physics Procedia*, 22, 150-156.
- Martínez, E. et al. 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy*, 34(3), 667-673.
- Martínez, E., Jiménez, E., Blanco, J., & Sanz, F. (2010). LCA sensitivity analysis of a multi-megawatt wind turbine. *Applied Energy*, 87(7), 2293-2303.
- Martínez, E., Jiménez, E., Sanz, F., Pérez, M., Blanco, J., & Santamaría, J. (2010). Virtual representation of terrain through the web with VRML-Web3D and graphic libraries. *International Journal on Interactive Design and Manufacturing*, 4(2), 125-136
- Ruiz Argáiz, I., Jiménez Macías, E., Blanco Fernández, J., & Pérez de la Parte, M. (2008). Design and simulation of production of injection pieces in automobile industry. Paper presented at the Proceedings - EMS 2008, European Modelling Symposium, 2nd UKSim European Symposium on Computer Modelling and Simulation
- Sarasa, J., Gracia, J. & Javierre, C., 2009. Study of the biodisintegration of a bioplastic material waste. *Bioresource Technology*, 100(15), 3764-3768.
- SolidWorks, 2012. SolidWorks Flow Simulation Technical Reference, SolidWorks.
- Wang, J. (2014). Thermal module design and analysis of a 230 W LED illumination lamp under three incline angles. *Microelectronics Journal*, 45, 416-423.
- Welz, T., Hischier, R. & Hilty, L. M., 2011. Environmental impacts of lighting technologies — Life cycle assessment and sensitivity analysis. Environmental Impact Assessment Review, 31(3), 334-343.
- Yin, L., Yang, L., Yang, W., Guo, Y., Ma, K., Li, S., & Zhang, J. (2010). Thermal design and analysis of multi-chip LED module with ceramic substrate. *Solid-State Electronics*, 54, 1520-1524.
- Yung, K., Liem, H., Choy, H., & Cai, Z. (2014). Thermal investigation of a high brightness LED array package. *Applied Thermal Engineering*, 63, 105-118.