Light Emitting Diode (LED) manufacturers sort their products into 'bins' based on forward voltage, with the purpose of delivering the most consistent light possible. Despite the tight grouping of forward voltages in these bins, manufacturing tolerances continue to lead to significant variations in both current draw and temperatures inside the LEDs, resulting in a inhomogeneous light distribution, even within the same batch. These discrepancies also undermine the most noteworthy selling point of the LED : its long operational life. Zumtobel, a leading supplier of integral lighting solutions for professional lighting applications, has addressed this problem by investigating the highly interconnected process between the thermal and electrical characteristics of LEDs using coupled simulations with STAR-CCM+ and NGSPICE.

COUPLED THERMAL–ELECTRICAL SIMULATIONS SHED LIGHT ON LED PERFORMANCE

PIER ANGELO FAVAROLO & LUKAS OSL
Zumtobel Group

SABINE GOODWIN & RUBEN BONS
CD-adapco

THE LED EXPLAINED

Figure 1 shows the forward current vs. forward voltage (I-V) characteristics of a typical diode. When placing a forward voltage across an LED, as is the case with any diode, the current initially does not flow until the forward voltage is increased to a level sufficiently high to pass a certain threshold, after which it flows freely in the normal conducting direction. For LEDs, the I-V characteristics at which point this occurs affects the color and intensity of the light emitted; in other words, although the principal behavior is the same for all LEDs, the light produced highly depends on each individual current voltage characteristics.

THE LED THERMO-ELECTRICAL CHALLENGE

Although the working principle of a diode is rather simple, in reality, designing luminaires that produce consistent light (both intensity and color) can be particularly challenging due to a number of unique operational characteristics of LEDs. Inherent manufacturing variations (both in materials and processes) often cause unexpected variations in the electrical response of an LED. As discussed above, its optical output (both total amount and spectrum) is highly dependent on the electrical energy (voltage and current) driving it and thus these manufacturing variations can lead to a deterioration of light quality. A typical disparity of the I-V characteristics due to manufacturing variations is shown in figure 1. Binning LEDs after assembly to group them in batches that have similar responses narrows these variations, but it does not eliminate them.

The choice of driver circuit topology – whether the LEDs are electrically in series or parallel – also makes a significant difference in its sensitivity to variations (Figure 2). To make sure that failure of one LED does not cause an entire circuit to break down, they are often placed in parallel on the circuit driver. This means

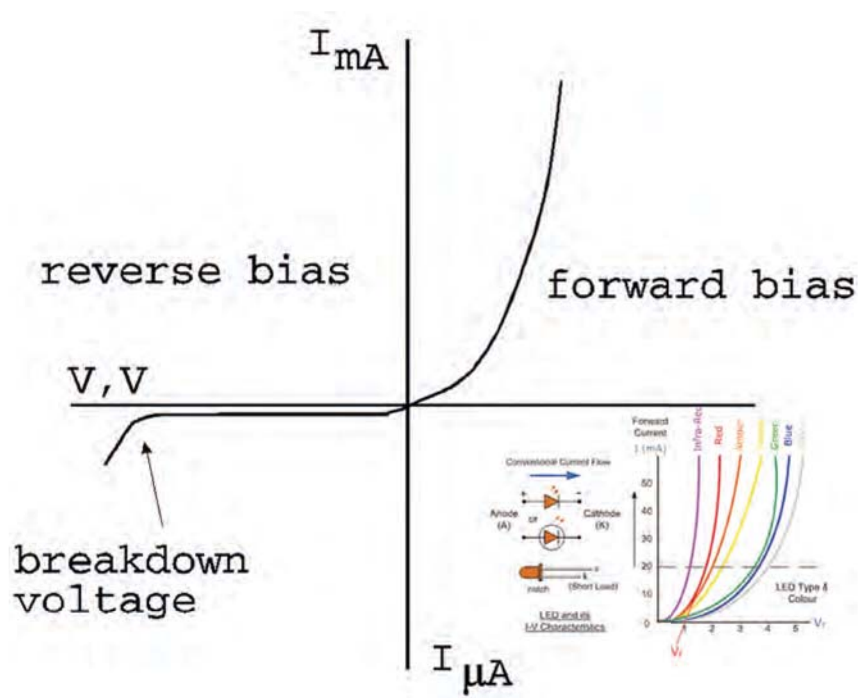

FIGURE 1: Typical forward and reverse voltage characteristics of a diode/LED

that each light in the circuit operates at the same voltage (as opposed to when they are placed in series where they see the same current). Thus, they are typically run on the steep part of their characteristic curve, resulting in a higher sensitivity in response to variations in manufacturing within even a single bin.

Much like a computer chip, an LED is also very sensitive to temperature changes. The operating temperature not only affects its lifetime, it determines the optical light output (how the eye perceives it) and thermal characteristics (amount of dissipated heat) of the LED-powered luminaire. Problems such as color shift (change in color over time) and luminous flux depreciation (loss in light amount) resulting from temperature variations can quickly become daunting for a manufacturer. One of the main selling points of LEDs is that they can run for 8 hours a day for 15 to 30 years, but if the thermal design is not right, this full potential will never be reached.

Some of the variations described above can be mitigated with electrical control circuitry, however, the proper design of an LED-powered luminaire that produces both consistent light color and intensity calls for a coupled electrical and thermal approach that can address the interdependencies between the electrical circuit response, temperature, heat dissipation and cooling approach.

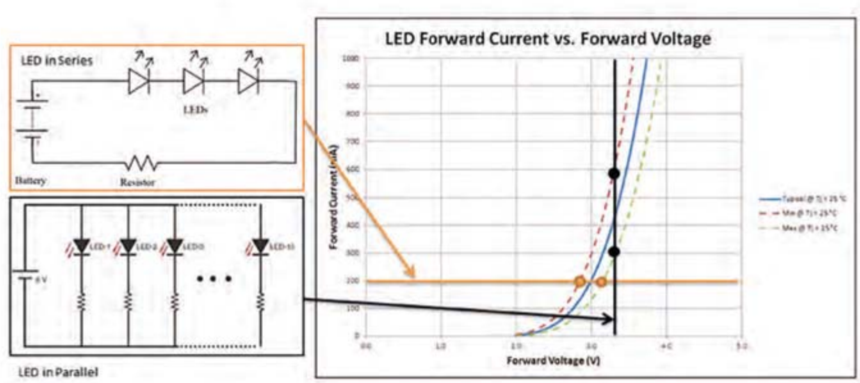

FIGURE 2: LEDs in parallel have a high sensitivity to variations within a single bin

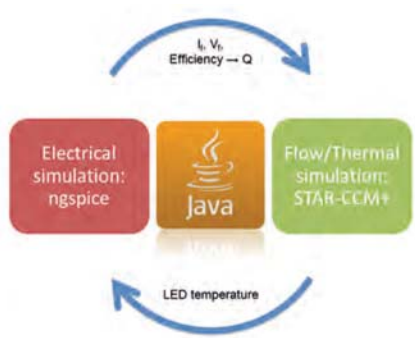

FIGURE 3: Electro-thermal simulation using STAR-CCM+ and NGSPICE

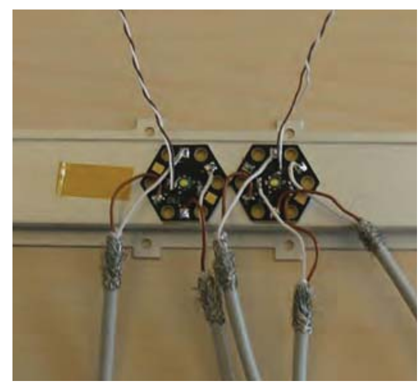

FIGURE 4: Test luminaire consisting of two LEDs connected in parallel

COUPLING THE THERMAL AND ELECTRICAL RESPONSES

Zumtobel has coupled STAR-CCM+ (a computational tool for simulating flow/ thermal behavior) to NGSPICE (an open-source circuit simulation software) to enable the accurate prediction of the interplaying effects between electrical and thermal behaviors of LEDs. Communication between the codes is established using an interactive JAVA macro.

Figure 3 illustrates the approach taken to solve this closely coupled electro-thermal problem. When NGSPICE is executed from the macro, the circuit is solved including the forward voltage and forward current of the LEDs. From this, using a proprietary method developed by Zumtobel, the electrical power is determined, and using the temperature supplied by STAR-CCM+, the optical power (how much of the energy goes out as visible light) is computed. The heat rate (representing the portion of the power that is dissipated as heat) can subsequently be calculated by subtracting the radiant power from the electrical power. This heat rate is then fed to STAR-CCM+ which in turn computes all the system temperatures to be passed back to NGSPICE for the next step in the simulation. As discussed above, the temperatures have a significant impact on the electrical characteristics of the LED, thus this cycle is repeated until the simulation converges to an equilibrium state.

This process was demonstrated and validated on a test luminaire consisting of two LEDs connected electrically in parallel, mounted on an aluminum channel and placed on a wood table (Figure 4). This model has been extensively validated in the laboratory as it is one of Zumtobel's standard experimental test configurations. A four terminal sensing method was used to measure current and voltage of each LED. The temperature was obtained through thermocouples (type T) on specific points of the copper pad, Printed Circuit Boards (PCB) and heat-sinks and these locations were used as reference points for the thermal simulations. In addition, a parametric study was performed during testing to better understand the impact of manufacturing tolerances (e.g. thickness of the traces, thermal conductivity) on the thermal

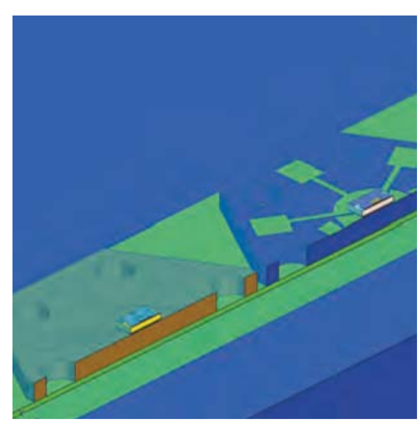

FIGURE 5: The STAR-CCM+ luminaire model includes the PCB, LED pad and semi-conductor die

behavior of the system. One significant detail of the set-up that must also be noted is that there is a current meter connected in series with one of the LEDs which increases the resistance in that branch of the circuit. As a result, each of the lights in the circuit is expected to have a unique electrical response and operating temperature.

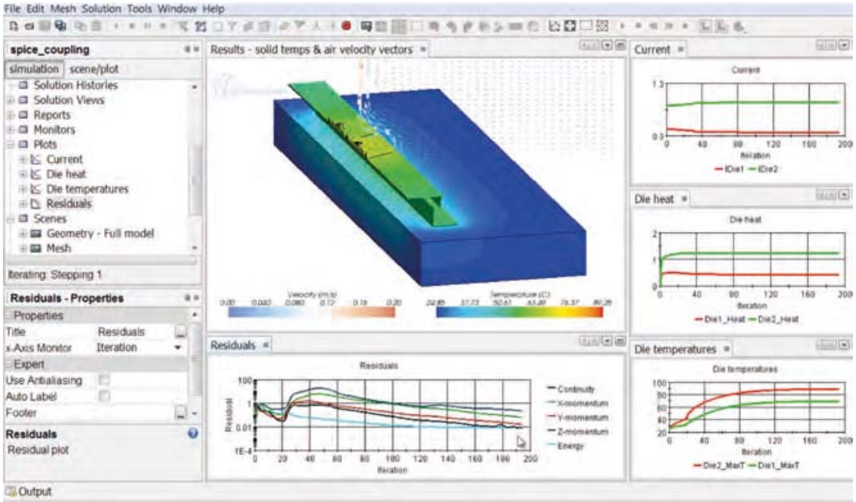

FIGURE 7 : Interface of NGSPICE and STAR-CCM+ after 20 updates (200 STAR-CCM+ iterations)

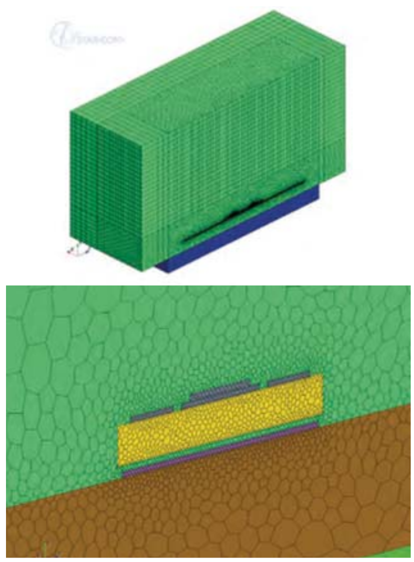

FIGURE 6: Conformal mesh showing the details of the model in STAR-CCM+

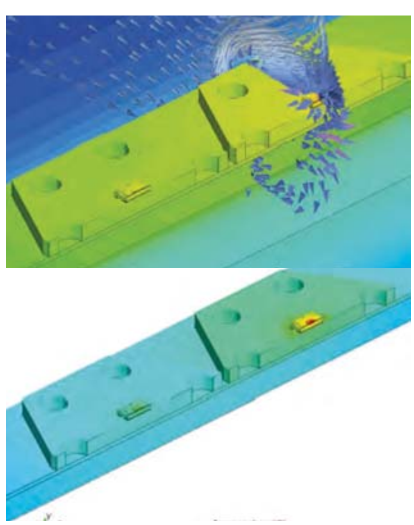

FIGURE 8: Final solution showing solid temperatures and circulation around each of the LEDs

For the simulation, geometrical and material properties of the LEDs were provided by the manufacturer and half symmetry was used to keep the simulation time to a minimum. To include the effects of the current meter from the experiment in the simulation, a current-limiting resistor was modeled in series with one of the LEDs on the circuit. As shown in figure 5, significant attention was paid to modeling the important details of the system, including the Metal-Core Printed Circuit Board (MCPCB) with copper traces, the LED pad (with electrical connections) all the way down to the semiconductor die. For the simulation in STAR-CCM+, accurate capturing of the physics, including natural convection cooling and limiting temperature of the semiconductor die, was key. Furthermore, unique meshing capabilities available in STAR-CCM+ were applied to ensure accuracy of the simulations. As shown in figure 6, an all-conformal polyhedral mesh was generated and extrusions were used to allow for efficiently meshing the surrounding air while at the same time capturing the small physical features in the core area of the LEDs themselves. The flow and thermal behavior of the system were obtained by performing steady-state simulations using the segregated flow and energy solvers.

Figure 7 shows a screenshot of the coupled interface which facilitates real-time tracking of the various system parameters, including the forward current through each LED and the die temperatures as the solution unfolds. At start-up, an initialization (first guess) of current, temperature and optical power was made and during the simulation, for every one step of NGSPICE, ten steps of STAR-CCM+ were performed. After approximately 200 iterations of STAR-CCM+ (which required only about 20 minutes of simulation time on a laptop), the forward current started to converge and the die temperatures settled. A fully converged solution was obtained after approximately 50 updates between NGSPICE and STAR-CCM+.

Figure 8 depicts the surface temperatures of the solids of the system. As discussed above, the simulation shows exactly what is expected: the increased resistance due to the presence of a current meter (modeled with a current-limiting resistor) in the experiment results in a significant difference in the final temperatures of each of the LEDs. A cut through one of the LEDs also shows the velocity field at convergence, displaying the expected natural convective air flow that cools the system.

CONCLUSION

LEDs have gained a tremendous amount of popularity in recent years due to their small size, efficiency and long life. In order to meet these expectations, the interdependencies between the electrical circuit response, temperature, heat dissipation and cooling must be taken into account during the design phase of LEDs. For companies like Zumtobel, delivering consistent light with the right intensity and color is crucial to the success of their product portfolio, and performing electro-thermal simulations early in the development process facilitates the prediction of the luminaire performance in lieu of physical prototyping and testing.

ABOUT ZUMTOBEL

Zumtobel, a company of the Zumtobel Group, is an internationally leading supplier of integral lighting solutions for professional indoor and outdoor building lighting applications. For more than 50 years, Zumtobel has been developing innovative, custom lighting solutions that meet extremely exacting requirements in terms of ergonomics, economic efficiency and environmental compatibility as well as delivering aesthetic added value. Besides the very latest technology advances and research developments, the company's many years of experience in project business with leading international architects, lighting designers and artists provides valuable impetus that stimulates the ongoing development of the company's already comprehensive product portfolio.