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Thermal simulation simplifies LED luminaire development

Executive summary

Every form of electric lighting produces an unwanted by-product: heat. In the case of incandescent and fluorescent lighting, generations of engineers have developed ways to minimize and/ or divert heat from luminaires and fixtures. But LED lighting, appearing today in growing quantity and variations, poses new and different challenges. The movement to LED lighting systems worldwide is accelerating as energy savings and the reduction in hazardous materials increase in importance.

Heat buildup can reduce an LED's light output and cause a color shift and at the same time, shorten the component's useful life. It has been said that thermal management is by far the most critical aspect of LED system design. From an engineer's perspective, this may mean learning to work with tools and procedures that go beyond the comfortable realms of mechanical and electronic design. Fortunately a host of thermal design solutions is ready to help simplify the engineer's journey through thermal validation and measurement challenges.

Dr. John Parry, CEng

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Validating the design concept

When developing a new luminaire “system,” the basic product concept must be validated, reconciling mechanical and aesthetic ideals with the realities of thermal behavior.

The key to successful LED system design is to transfer the active device’s heat efficiently from its own PN junction to the ambient. The path involves both the printed circuit board that mounts the LED and the enclosure. The designer must confirm that housings and shrouds participate efficiently in carrying heat away from the LED. Building and testing a series of physical prototypes to validate this premise is costly and time-consuming, so today’s designers generally use software-based methods in this early design phase.

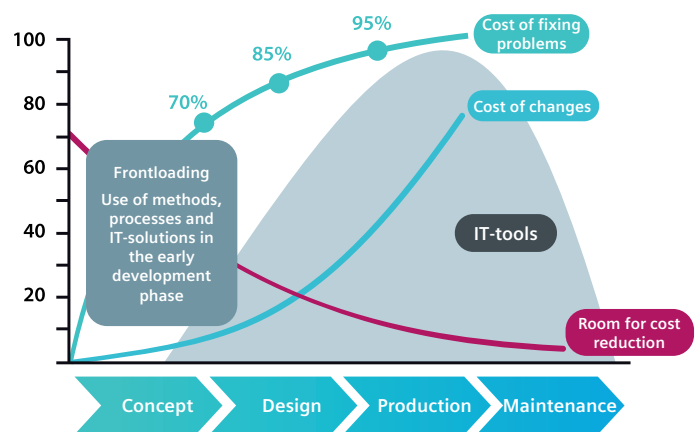
The preferred approach is to use computational fluid dynamics (CFD) analysis to simulate the proposed device in virtual form. This method is far more flexible than hardware prototyping for early design proposals, and just as effective. With a virtual model’s behavior well characterized, hardware prototyping can begin with a good grasp of what works and what doesn’t. Historically CFD simulations have been the province of analysts with specialized skills in advanced math and fluid dynamics, plus a command of the complex modeling tools required for CFD work.

Recent advancements have brought CFD technology to the mechanical engineer’s desktop, dramatically simplifying and accelerating analysis. The new process known as frontloading moves CFD simulation early into the design process, enabling design engineers to evaluate design options and optimize product performance as well as reliability. Frontloading simulation would require that the CFD tool be embedded in a standard MCAD environment such as PTC Creo, CATIA V5, Siemens NX™ and Solid Edge® software allows staff mechanical engineers to develop models and test the heat dispersion properties of an emerging luminaire design.

A full-featured frontloaded CFD application such as Simcenter FLOEFD™ software:

- Uses the dimensions and physical characteristics of the proposed design stored within the MCAD application by directly using the MCAD geometry

- Detects and grids the solids and flow spaces, creating an optimized computing mesh
- Aids the designer in setting boundary conditions
- Automatically provides solution-control settings to help ensure convergence when the solver runs



Source: Prof. Dr. Martin Eigner VPE TU Kaiserslautern

The baseline for design validation, whether the product is a new luminaire or a replacement for an existing design is of course a detailed understanding of the LED device’s thermal behavior. This is also important when developing an LED lamp intended to retrofit into an existing fixture, since it is essential to match the thermal and cooling characteristics of the original equipment.

Thermal information *should* be available from the LED vendor, though in the absence of industry standards for such information, printed specifications are sometimes less than complete. For example, thermal performance data is normally provided, but may not span the operating temperature range at which practical end-user systems actually work. Nevertheless, designers must proceed with their luminaire evaluation based on data or compact models provided by the LED maker, or in-house measurements, or experience with earlier luminaire designs.

The process starts with the mechanical design of the luminaire. Figure 1 illustrates the outcome of this initial design step. The depicted system includes an integral connector (shown in yellow) attached to a lamp housing whose fins act as a heatsink. The connector plugs into a socket which may itself be designed to further disperse heat, acting as part of the cooling system for the lamp. However in this particular system the socket is simply a means of supporting and connecting the lamp. The light source is a power LED mounted on a metal-core PCB. In figure 1 the lamp's lens is omitted to expose a more detailed perspective on the LED itself.

Using frontloading CFD tools, the preparation for thermal analysis proceeds efficiently. As the CFD application is embedded within the MCAD environment, the luminaire's dimensions and physical characteristics are already available to the CFD application. The application "sees" the image in figure 1.

Where appropriate, the CFD tool also automatically models any internal cavities as fluid regions, a requirement for analysis. While the need for this step is more obvious for a pipe carrying a liquid, it is also necessary to predict the air flow through and around the luminaire.

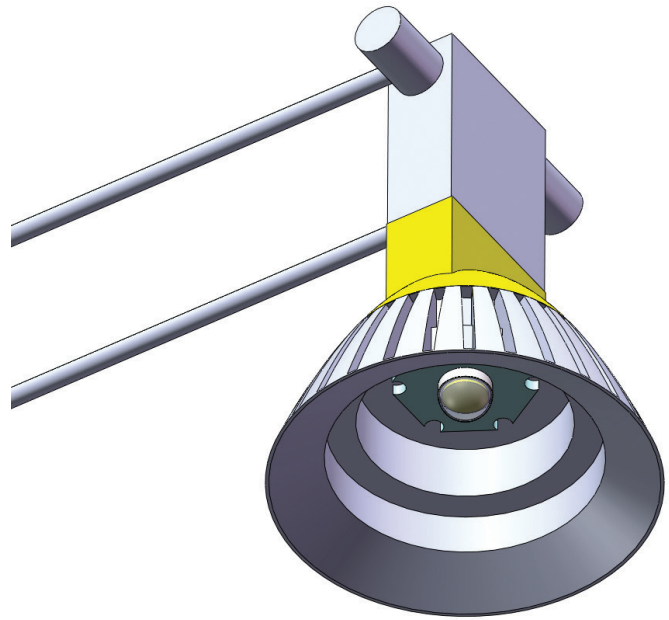


Figure 1: The MCAD representation of the LED luminaire.

Building a computational grid

Internal temperatures and distribution are of great interest in this thermal analysis, and the front-loaded CFD application (again using MCAD data) can show a thermal profile on any two-dimensional slice, providing a cross-section view that reveals the interior of the luminaire. But first it is necessary to build a computational grid known as a “mesh,” shown here in figure 2. The frontloaded CFD tool performs this step automatically.

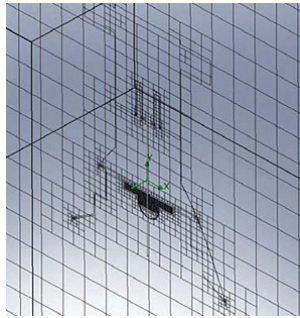


Figure 2: Computational mesh shown on a central slice through a lamp assembly.

The mesh is simple in concept, yet it is the heart of complex CFD calculations. The surface of the device is mapped into tiny rectangular cells, each of which is split into solid and fluid volumes which are analyzed discretely. The process then develops a composite result that incorporates all of the cells.

Note that the cells in figure 2 are not uniform in size. Those clustered around the LED are much smaller than those on the periphery of the housing. This feature found in advanced frontloaded CFD applications provides higher resolution where it is most needed. This technology is referred to as SmartCells™ - to learn more about SmartCells and how they enable accurate analysis please read *SmartCells – Enabling Fast and Accurate CFD*.

Next the engineer must define boundary conditions, that is the operating parameters and limits that will be used in the calculations. Values for the external air temperature and the LED device heating power must be specified, and can be incremented over multiple iterations of the CFD analysis.

Figure 3 displays the outcome of the CFD operation on the cross-sectional slice. It shows not only the heat distribution across the physical elements of the lamp, but also the vectors for air flow due to convection over the exterior of the lamp. In this example the 3D perspective has been restored for visual reference but the flow vectors pertain to the slice. In this view, the color spectrum goes from red (hottest) to blue (coolest), with gradations of orange and green between the two extremes.

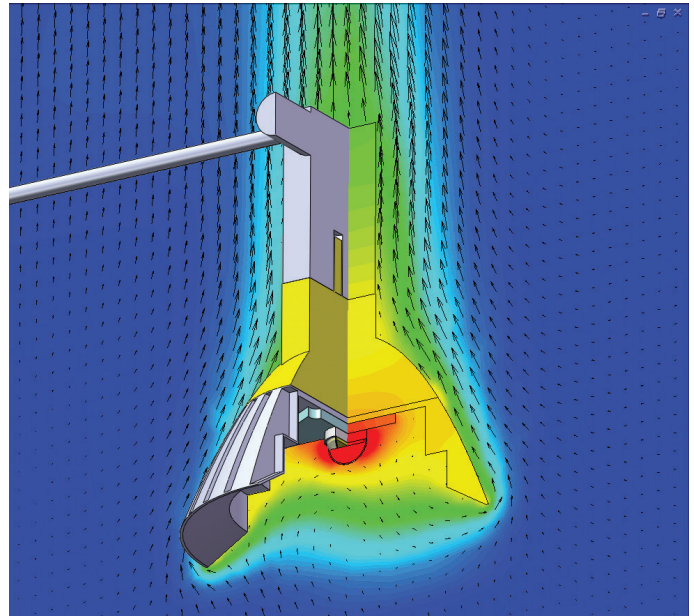


Figure 3: Temperatures on a 2-D slice through the center of the lamp with vectors showing flow caused by natural convection over the outside of the lamp. The vectors in this and subsequent images were calculated with Simcenter FLOEFD, an award-winning frontloading CFD tool by Siemens PLM Software. It works with device geometries taken directly from the MCAD environment.

Transporting heat

Of course, the object of this exercise is to ensure that a proposed physical design will transport heat away from the LED source and conduct it safely toward the ambient environment. Figure 4, another frontloading CFD view, provides an answer to this important question. In this view, weightless particles trace the air flow path, almost like infinitesimal dust motes. Here again the color spectrum reveals the heat distribution and in this image a color legend quantifies the values. Note the flow pattern: blue (cool) air comes up from below and is warmed to blue-green as it passes over the luminaire. Convection carries the warmed air up and away from the lamp. Is this sufficient dispersion for the lamp itself and any other housings that will be part of the final design? It is a question only the engineer can answer, but frontloading CFD analysis has armed him or her with the data necessary to support an informed judgment.

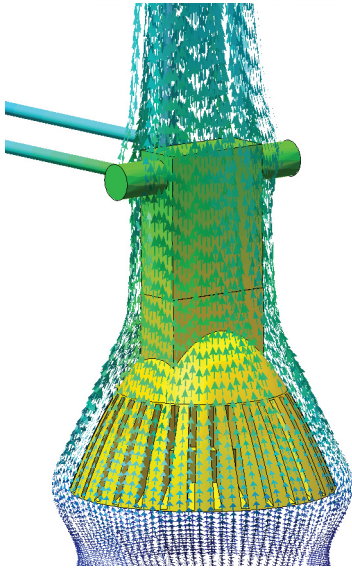


Figure 4: Particle tracks over the lamp, mounted horizontally and facing downwards, showing how the natural convection causes the air to flow smoothly over the exterior of the lamp housing. The thermal plume contracts as the flow accelerates above the lamp.

Figure 5 and 6 show the comparison of the heatsink for an LED Light Bulb Construction in the top view. In this example, the influence of the created core chimney (figure 6) was investigated. The cooling performance of the natural convection has to be sufficiently high to cover also future power dissipations.

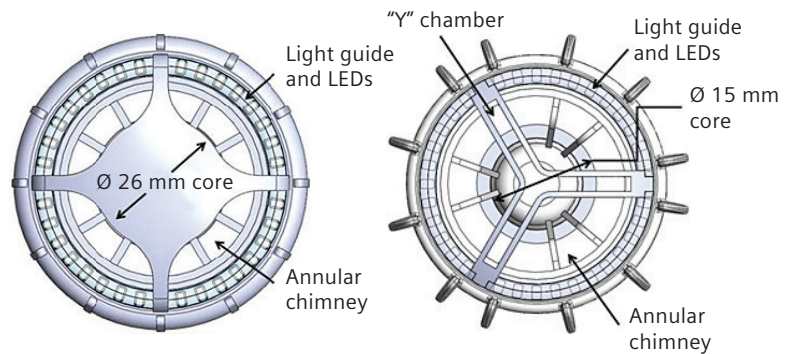


Figure 5

Figure 6

An example of the temperature distribution on the surface is shown in figure 7.

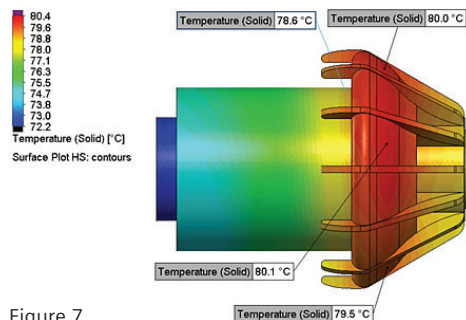


Figure 7

The real orientation of the shown LED light bulbs can be vertical or horizontal (figure 8). The impact on the resulting cooling performance, and thus on the resulting maximum temperatures, can also be carried out very efficiently in frontloading CFD analysis. Figure 8 shows a intermediate design modification in horizontal orientation. This LED light bulb is therefore designed for a reliable vertical and horizontal use.

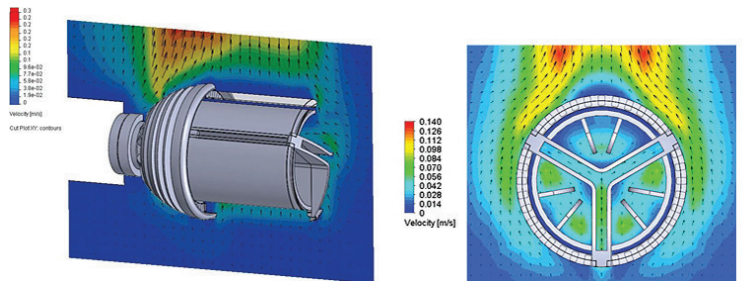


Figure 8

The design was improved by increasing the outer diameter for the shown annulus outer core, external fins were added outside the light guide section and the heatsink was redesigned for a better air inflow and distribution (figure 9). These design modifications enabled performance improvements of about 25 percent for the shown example (figure 10).

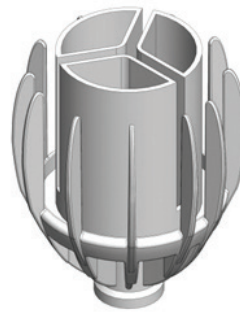


Figure 9

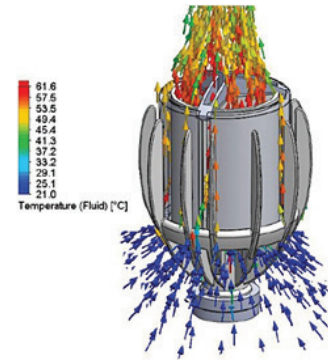
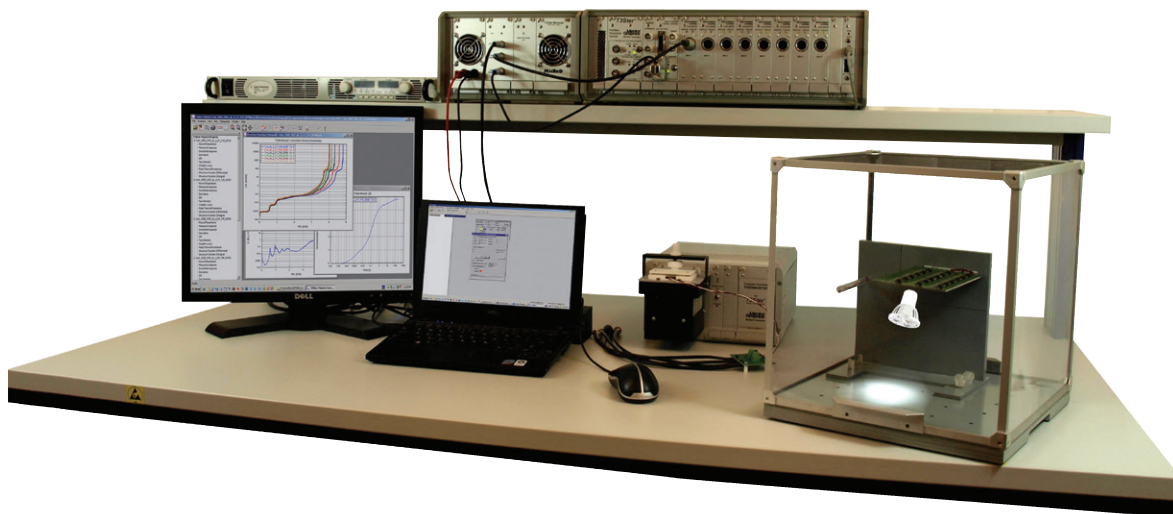


Figure 10

Conclusion

The frontloading CFD flow simulation/analysis step as performed by Simcenter FLOEFD is indispensable for refining design proposals. It is far less costly than building and testing a succession of physical prototypes, and the automation built into frontloading CFD means that preparation for the first evaluation cycle is brief and for every subsequent attempt, even faster. It is an environment that encourages experimentation until the design is truly optimized.

For example, frontloading CFD can be used to quickly determine the optimum number slots in the bell-shaped housing and the thickness of the metal between them to maximize the heat loss to the surrounding air.



The Simcenter T3STER thermal measurement system by Siemens PLM Software characterizes critical LED thermal parameters.

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