Siemens PLM Software

Five hot topics for the automotive lighting industry

Executive summary

Cars have been around for over one hundred years and since the very beginning lamps were installed to ensure visibility at night. Over time automotive lights have gained increasing importance, not only to see the road ahead, but also to spot danger for the driver such as crossing animals or pedestrians. With the increased performance and speed of vehicles increased visibility is required and automotive lighting became one of the key safety features built into the car. Over the last 15-20 years the importance of design to automotive lighting has dramatically changed the way automotive lights are perceived in the industry as well as by the customers.

With this change in perception, perfection in the appearance becomes an important factor, with new light sources the designers are given even more freedom to play with the light as the limitations in space and shape are reduced. Such changes in technology however, bring new or previous marginal problems back on the table.

This white paper discusses the past, current and future ‘five hot topics’ for automotive lighting engineers and elaborates on how thermal simulation, as well as thermal characterization, can help to improve the design cycle and reduce costs in many ways.

Boris Marovic
Technical manager Simcenter FLOEFD products

The five hot topics

There are five major hot topics in automotive lighting design for a mechanical engineer that have an influence on the thermal management and the design cycle. These ultimately influence the product performance, lifetime, costs and of course the customer (OEM and ultimate owner) satisfaction.

1. It's all about the geometry...

Everything starts with an idea, but only once the first geometry is created can the first simulations and prototyping start. Without geometry there will be no 3D computational fluid dynamics (CFD) simulation as it serves as a foundation for every simulation.

The first thermal simulations can actually start as soon as the first drafts of the housing and the basic components are designed and they don't need to be very detailed. Those early simulations help to get the first estimates of temperatures in order to choose the materials necessary to withstand those temperatures. This decision is important as the materials also vary in price depending on their properties, such as melting temperature etc. and of course the price estimate is important for the first offer a Tier 1 supplier needs to provide their prospect or customer. Such an offer can influence the outcome of bidding with a competitor for a new contract, and the faster and better the estimate can be completed the more likely it is to provide the better solution and win the deal.

Figure 1: Exploded view of an example headlight.

After the contract is won, the geometry will evolve quickly and increase in detail and number of parts ranging from screws, heatsinks, PCBs and their copper traces, electronic components on the PCBs, reflectors, bezels, lenses, cables and many other components. The more complex the design becomes, the higher the requirements are for fast and robust meshing times and the simulations between different design iterations are.

With traditional CFD tools the meshing of highly complex systems such as a full LED headlight, with all its components, can take days in order to achieve a high quality mesh for accurate results. With the automatic meshing technology of Simcenter FLOEFD™ software which is based on a Cartesian mesh with an octree refinement and polyhedral cells at the fluid-solid or solid-solid (in case of different material properties) interface, the meshing of most complex geometry is fully automated and only requires CPU time. This frees up time for the engineer to work on other project while the computer handles the otherwise very laborious task. Such a meshing process usually takes from a few minutes to several hours depending on how fine the mesh settings were chosen as well as how complex the geometry is. A small fog light only takes a few minutes whereas a full-blown all LED headlight with all relevant components can take several hours, but not longer than a day, and therefore the meshing can be performed from one day to the next in the worst case and then the simulation can be started.

The major benefit of this automated meshing approach, is that the burden of meshing a model can be completely removed from the user and put onto the CPU. This reduces the costs of an expensive engineer working on a project dramatically and frees up time for other projects. This reduces the pricing of developing such headlights, which flows into the bidding offer to the OEM.

2. Thermal management of LEDs, OLEDs and laser diodes

In the last 10 years light-source technology has evolved the automotive lighting industry significantly. Previously mostly bulb type (Halogen, HID) light sources were used which had low efficiency and created large amounts of waste-heat which the lighting system had to withstand. New technologies such as LEDs, OLEDs and laser diodes generate much less heat and need a different thermal management approach.

Figure 2: Opel Astra IntelliLux LED matrix light (© Adam Opel AG).

Those new light sources are far more efficient and continue to improve as the technology advances. It took a few years until the LEDs were powerful enough to provide sufficient light output to fulfill the requirements of the automotive industry, initially they weren't very cheap. But as those LEDs reached mass production the prices decreased, today we can see full LED headlights in mid-range cars such as the Opel Astra, Audi A3 or Seat Leon.

The next LED evolution for automotive lighting is Matrix and Pixel LEDs which enable a glare free high beam that automatically deactivates the LED elements that project light onto the oncoming traffic or the car in front. This provides a dark spot for the other car so the driver is not grared by the high beam. This improves driving visibility and at the same time ensures safety not only through visibility for the driver but also the other traffic participants.

While LEDs are a spot light source, OLEDs provide a new opportunity to have a surface light source for interior as well as exterior lighting applications. The first appear-ances of OLEDs in tail lights are planned and BMW released the M4 GTS with OLEDs in its tail lights already.

Figure 3: BMW M4 GTS OLED tail lights (© BMW AG).

And finally laser diodes as a light source. In automotive headlights they are currently used only for far distant spot illumination for around 600m visibility and first introduced by Audi and BMW. The way they work is based on the concept of Laser Activated Remote Phosphor (LARP), where blue laser diodes bring a small phosphor element to react on the laser light causing the blue light of the phosphor to become white light. The advantage is an even higher efficiency than LEDs with more light output and a smaller design space necessary. As with every new technology, it is still expensive and only available in premium cars currently. However, the technology is advancing fast and in future we will see LARP systems that will be able to illuminate the whole road and not just a distant spot. In order to do so, the Digital Light Processing (DLP) technology from Texas Instruments might be a solution. Here tiny mirrors in Microelectromechanical Systems (MEMS) control the reflection direction of the light extremely fast. Such systems are already used in consumer electronics such as video projectors and can be used with LEDs as well as LARP systems.

That's the technology, but what about the thermal management for these three light source types? Well, all of these light sources could be categorized as cold light sources compared to halogen and HID light sources. Halogen and HIDs emit a large amount of thermal radiation as their actual source of light has a very high temperature of over 2000 Kelvin, and with a low efficiency the waste heat is massive compared to LEDs.

But before we explore this further, let's first define two terms, **efficiency** and **efficacy**, as they are often used in a wrong way.

Efficiency = the ratio of the radiant flux (in Watt [W]) the light source produces to the electrical power (in Watt) put into the light source.

Efficacy = the ratio of luminous flux (in Lumen [lm]) to the electrical power (in Watt) put into the light source.

While LEDs have an efficiency of around 30 percent or more, HID lamps are around 5-8 percent and Halogen lamps are also around 5 percent efficiency. A big difference between LEDs, OLEDs and laser diodes is the way the heat is dissipated and therefore influence the thermal management design. Where bulb type of light sources radiate most of the heat through infrared (IR) and have some convection and conduction portion due to contact to the fixture as well as the air and bulb gas, modern light sources conduct most of the heat and therefore need heatsinks and possibly active cooling through a fan for example. This of course can make the very small, almost point like, light sources such as LEDs and laser diodes hard to cool and their thermal management is critical as the lifetime depends strongly on their maximum temperature. Whereas OLEDs have a large surface, cooling is therefore easier and sometimes not even needed, they are however currently more sensitive to higher temperatures.

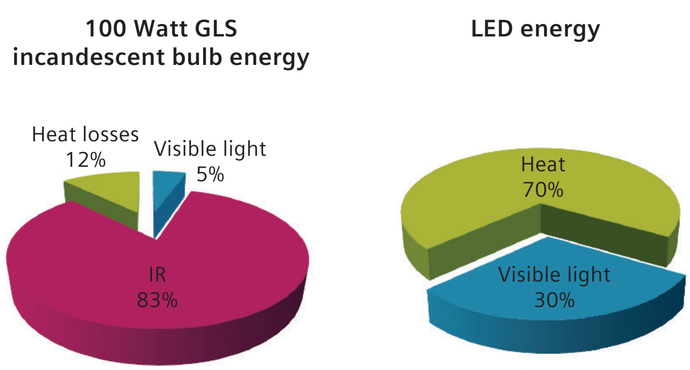


Figure 4: Incandescent bulb and LED energy dissipation modes.

In general we can say that LEDs and laser diodes need a good heat spreading either in the PCB they're mounted on, or into a heatsinks and possibly active cooling, depending on their power rating. OLEDs on the other hand can often hang freely without a big heatsink attached and therefore can also utilize a better effect in the design of being almost transparent when deactivated. They are on the other hand more temperature sensitive and solar radiation can influence their lifetime if their maximum temperature is reached.

Radiation however still plays a role as a cooling mechanism, just not as big as for bulb type light sources. For high power LEDs that are mounted very close to a lens or light guide, a good radiation model becomes important as the absorption inside those optical elements can influence their temperature.

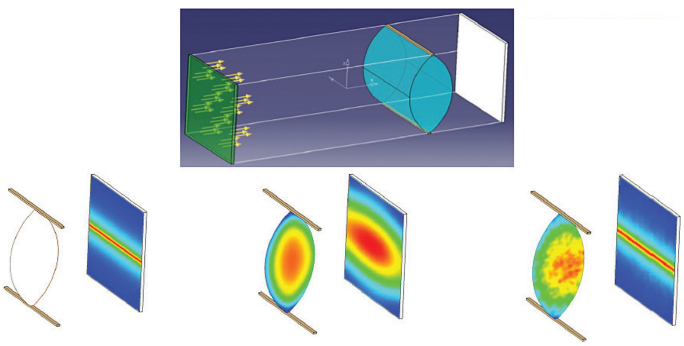
3. Radiation and solar exposure

As mentioned before it depends heavily on the utilized light source if and how radiation plays a role in the simulation as well as what conditions are considered.

If we take the bulb type light sources for example, the radiation is the main heat dissipation method and surrounding components are then, of course, strongly influenced and appropriate materials have to be chosen which can cope with the resulting temperatures. Here reflectors and lenses can reach their limiting temperatures quickly and the styling is influenced greatly. Smaller sizes are often not achievable with the high amount of energy emitted. As materials change coping with a higher maximum temperature the costs for a headlight increases.

With LEDs usually only high power LEDs require a more advanced radiation model such as the Monte Carlo model as here. Close by optical elements such as light guides can absorb a large amount of the optical power emitted by the LED. Also in LARP systems the laser beam carries all the optical power and is usually a very narrow beam and reaches therefore a high power density as a radiation source. As a comparison, the standard laser pointer used in presentations or to drive a cat crazy, usually has a power of <1mW. The automotive grade high power blue lasers have a overall power of around 1.5W and with an efficiency of around 30 percent the beam still has around 0.45W. If we consider the solar radiation density on earth, we can measure around 1000W/m² which will give us around 0.001W/m² which is roughly the size of a laser pointer spot. Even with a laser spot of 4mm² the power of a blue automotive laser is still in the order of 0.1125W and therefore 112.5 times stronger than the sun. The radiation power of such lasers can therefore seriously damage any remote phosphor if not properly cooled.

In general radiation will contribute a lot in a thermal simulation, a thermal simulation without radiation is not advised as it also is a heat transfer mechanism in reality. However, the choice of the radiation model will depend on the radiation mechanisms that need to be considered. For example, some radiation models cannot consider absorption in semi-transparent material such as plastic or glass, some might be capable of absorption but don't offer a high accuracy for refraction effects or any focusing through lenses or due to a reflector. Especially if solar radiation needs to be considered, a good radiation model should be chosen if the simulation goal is to determine any hotspots created by a lens such as in a Xenon module. These hotspots can create temperatures of several hundred degrees Celsius and simply burn a hole into a plastic housing.



DTRM model

- No absorption in lens
- Good focus
- Only correct focus with forward ray tracing and only for solar sources
- No wavelength dependency

DO model (Lvl 7, 2nd order)

- Absorption in lens
- No good focus
- Band based
- Wavelength dependency

MC model (1M rays)

- Absorption in lens
- Good focus
- Noisy with few rays
- Band and ray based
- Wavelength dependency

Figure 5: Radiation model calculation results and differences.

The most advanced radiation models a simulation software should offer for any automotive lighting application is the Monte Carlo model. But even within this model there are different capabilities when it comes to effects such as the spectral definition. Most thermal simulation tools only offer a band definition for the Monte Carlo model, such a band definition can be very coarse or it takes some time for the user to define the correct band limits. The reason for this shows as soon as multiple materials are stacked with different absorption properties. In order to calculate the absorption correctly, the bands have to be placed accurately and when multiple materials are used with different absorption curves, the whole definition of bands can become messy, quickly. Here a bandless, or ray based, definition has the advantage that the full spectrum is resolved and not split into bands, in which only an average absorption is used within that band. In the bandless definition each ray represents a single wavelength. It is then necessary to use more rays for the Monte Carlo model, but this only influences the CPU time for the calculation and not the users time to determine the correct band limits manually. A bad definition of the band limits can easily influence the accuracy of the simulation results drastically.

4. Condensation, evaporation and icing

In a thermal simulation of automotive lamps it is not simply about heat transfer alone or keeping the components under their maximum temperature in order to achieve a high reliability and lifetime. Now that there is an increased design focus on head and tail lights, effects such as condensation inside these lamps are a pain for every automotive lighting engineer.

Often the condensation is not a big problem to the system itself, although with PCBs built into them, condensation can lead to corrosion on the components or in the worst case to a short circuit. Often the bigger focus of the engineers lies on the front lens of the lamp and the components directly behind that and therefore visible to the car owner. Most people not familiar with the technical aspects of an automotive headlamp would think the system has a defect as water is getting into the lamp. In reality however, automotive lamps are not sealed systems and the laws of Diffusion such as Fick's law define the diffusion of mass concentrations. Even with membranes that are supposed to keep humidity out of a lamp, over time the diffusion will let some humidity into the lamp.

It is simply natural that some humidity will get into a lamp and the scenario is a car that is driving through a humid and rainy night with lights on, when it gets into the garage the lights are switched off and as the lamp cools down, the air contracts and the lower pressure inside the lamp sucks in humid air from the surrounding environment. When the driver drives out of the garage in the morning, the car is exposed to the colder temperatures outside. This cold temperature on the outer side of the front lens and the warm and moist inside of the lamp causes the humidity to condensate on the inside of the front lens as the air reaches the saturation pressure near the inner front lens surface.

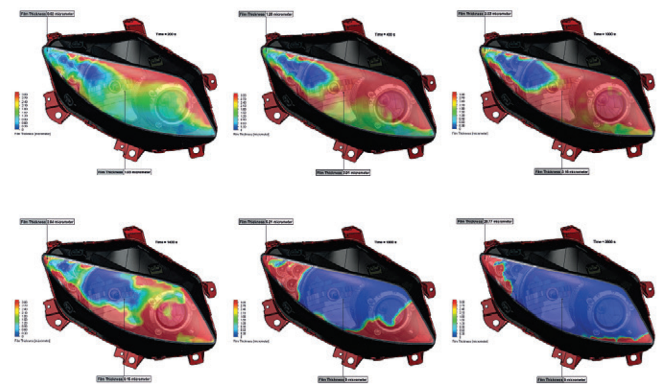


Figure 6: Condensation film thickness results of a transient simulation over 3600 seconds.

The task for engineers is to reduce the water content inside the headlamp, and reduce the evaporation time as soon as the car is started again and the lamps are switched on. But it is not only the humidity in the air that has an influence on the amount of condensation and the speed of the evaporation, but also the humidity stored within the plastic of the headlight components. Although plastic is not as absorbent as our typical bathroom sponge, it can still store a certain amount of humidity in its molecular structure, similar to wood.

As soon as temperatures drop below zero, ice will also form as the condensation film freezes. Considering the condensation effects as well as the phase change into ice and back to liquid, the evaporation into the air becomes important in condensation simulations of automotive lights. Some simulation tools offer a free surface calculation approach but this approach can be extremely CPU intense and create more solver stability issues than necessary. A condensation film model is required for such calculations as they can predict the film thickness, temperature, growth rate, mass, phase and many more parameters that are necessary for any simulation of that kind. A free surface or two phase simulation of a few micro-meter film thickness would be similar to shooting at sparrows with cannons, not the best choice.

5. Design cycle speed

After all the simulation tasks and important mechanisms discussed so far, one of the major limiting factors for every engineer is the time he has to get the design right and out to the customer/market. Especially in areas where the design and reliability plays such a big role, the number of design iterations can be numerous and the design cycles can require only a few minutes or hours to create a change that might improve, but might also worsen a design based on a decision made on simulation results.

With such short design cycles, the speed of realizing results on a certain design change is important and long model preparation and meshing times to get to the simulation results are a major hurdle to every engineer. An engineer not only needs to decide what simulations, and in particular what physics, he needs to consider for the result he is looking for but he also needs to have a fast model preparation time. For example if a condensation simulation shows that the evaporation is too slow and the engineer finds the airflow near the inner surface of the front lens is too little, a change in the airflow path that guides the air provided by a fan of the low beam LED to the front lens might solve the issue. Such a change can be done within an hour in modern CAD tools and starting the simulation again quickly would lead to a fast proof of concept or rule that concept out and might require a different approach. If the engineer would have to spend a lengthy period preparing the geometry provided by a neural exchange format and mesh the headlight for another few days in order to finally start the simulation, the design decision may have already moved on due to some other ideas or requests by the customer or another department such as the structural analysis team. Such decision should be analyzed faster and a CAD embedded CFD approach with a fully automatic mesher, capable of handling the most complex geometries, is the ideal solution to simply change the geometry start the meshing process without any need to prepare the model again and then as soon as the CPU completes the meshing work, start the solver. The whole process of preparing the model for the creation of the mesh and then the laborious creation of the mesh can be reduced to just some clicks and some CPU time delivering a high quality mesh no matter how complex the geometry is getting.

If only specific improvements are required, such as a higher airflow near the front lens' inner surface, then it doesn't necessarily require more CPU consuming condensation simulation in order to see if the goal was reached, a simplified simulation of just the airflow might suffice to give a go or no-go result for the design change.

Conclusion

Automotive lighting engineers face one of the most complex geometries with a wide range of boundary conditions and physics to consider. As automotive lighting advances, the design elements bring so much complexity into the systems, but also reduce the design space necessary for automotive lamps. But the simulation task doesn't get any easier, to the contrary, more and more simulation tasks need to be considered. Transient simulation cases with condensation, with switching of certain light functions as well as a mix of high temperature components such as HID modules right next to low temperature components such as LEDs are sensitive to the maximum temperatures they can reach. And of course tiny swiveling mirror elements of DLP systems that contribute to the complexity of the luminaire.

Siemens PLM Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 314 264 8499

Europe
Stephenson House
Sir William Siemens Square
Frimley, Camberley
Surrey, GU16 8QD
+44 (0) 1276 413200

Asia-Pacific
Unit 901-902, 9/F
Tower B, Manulife Financial Centre
223-231 Wai Yip Street, Kwun Tong
Kowloon, Hong Kong
+852 2230 3333

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