Development of a Software Tool for the Simulation of Formation and Clearance of Condensation in Vehicle Headlamps

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1 Abstract

The use of pattern-free cover lenses in automotive headlamps gives every observer a free view of the insides of the headlamp, which means that even the slightest optical faults become visible. These include thermal damage to the plastic materials used as well as the formation of condensation on the inside of the cover lenses. The use of simulation tools can detect and eliminate possible faults at an early stage.

2 The integration of specular radiation in thermal simulation

The simulation of fogging and de-fogging of a headlamp cover lens makes accurate knowledge of the temperature distribution in this area indispensable. Which is why it is necessary to adapt the commercial CFD programs currently used for temperature simulation to the headlamp system. The heat transported by radiation in particular is not taken into account correctly by most programs. Yet it is exactly this transport mechanism that is particularly important for the temperature load on the cover lens. The following article illustrates a way of eliminating this problem.

2.1 Heat transport in automotive headlamps

When headlamps are in operation, the temperatures in the headlamp are influenced by all three well-known heat transport mechanisms *conduction* (heat conduction), (*free*) *convection* (guidance of heat by air flows caused by temperature-related differences in density) and *heat radiation* (emission of electromagnetic radiation) [2]. In the non-transparent materials of the headlamp (incl. housing, reflectors) only conduction occurs, whereas in the enclosed air the processes of convection and heat radiation dominate. The mechanisms mentioned are available as standard in all commercial CFD tools, whereby the underlying pre-implemented models differ from one another depending on the manufacturer and are more or less suitable depending on the case of application, as will be explained in the following.

Fig. 1: Power balance of an H1 halogen bulb (55 W)

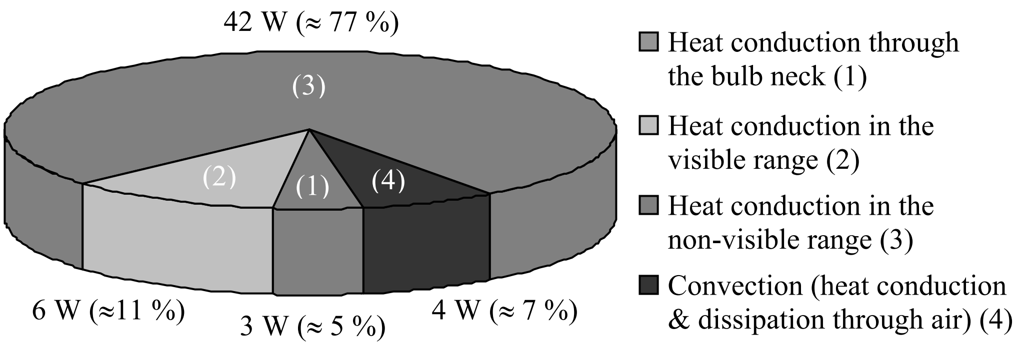


Fig. 1 shows that around 90 % of the electrical energy consumed by the bulb is emitted in the form of heat radiation. This leads to the surfaces affected by the radiation warming up, and in their turn these surfaces dissipate heat by thermal transition to the air and by conduction to other components. It is thus particularly important to take heat radiation into consideration in simulation and in the radiation model implemented in the CFD tool.

2.2 Conventional radiation models for temperature simulation

A well-known method of calculating radiation is based on the use of so-called *view factors*. Using this method, all the surfaces involved in exchanging radiation are divided into individual part surfaces, with a given number of discreet rays being radiated from each. The calculated view factor $F_{i,j}$ then indicates the share of the radiation emitted or reflected from the part surface *j* that reaches the part surface *i*. The calculation of these factors includes the idealisation, however, that all the surfaces reflect the incident radiation in a purely *diffuse* way. *Directed* reflection (*specular radiosity*) according to the principle "angle of incidence equals angle of radiation" does not take place. Fig. 2 shows the principle differences between diffuse and directed reflection.

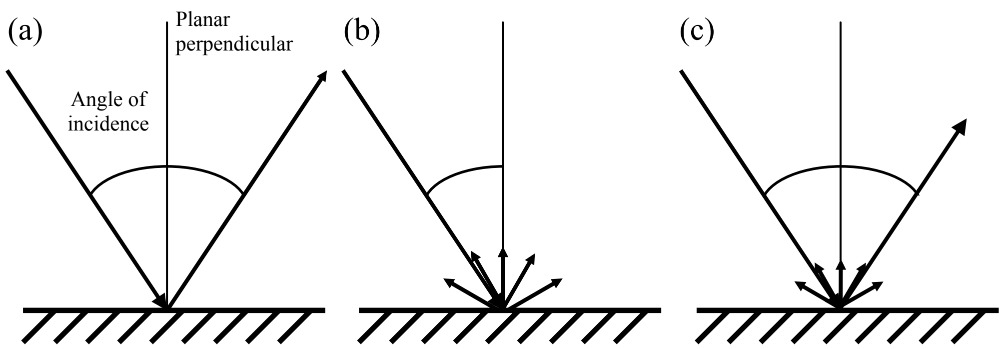


Fig. 2: Comparison of (a) directed, (b) diffuse and (c) superimposed reflection

It must be noted that the reflection of radiation is usually a superposition of diffuse and directed reflection. In addition, there are approaches which integrate directed reflection into the calculation of the viewing factors [1], which leads to a much more complicated calculation, however, and usually presumes knowledge of the fixed part of the emitted radiation power.
The calculation of radiation using viewing factors has been proved in many applications. It can lead to problems, however, if the share of directed reflection is high, which can very well be the case wherever there are large shining surfaces involved. This is the case with automotive headlamps, which use just this principle of directed reflection to produce the beam patterns prescribed by the legislator. For this reason, the radiation model using viewing factors in the thermal simulation of automotive headlamps leads to deviations that cannot be ignored, at least when convective influences are small in comparison with the heat radiation mechanisms.
In such cases, the extension of the CFD software used can improve the simulation results from the point of view of the user. Such an extension will be presented in the following.

2.3 Improved radiation model and simulation results

In order to take the directed radiation of the powerful radiation emitted by the bulbs into account, a so-called *ray tracing* process is carried out before the actual temperature simulation takes place. With this process, some hundreds of thousands of rays are emitted by the bulbs and traced on their path through the simulation model. When a ray meets a grid element of a fixed surface, the share of the radiation power to be absorbed represented by this ray is stored. Then the ray continues on its path, but now with less power (Fig. 3). The direction of reflection can be determined quite easily from knowledge of the previous direction of radiation and the planar perpendicular of the grid element. If the power transported by the ray falls below a certain threshold, it is no longer taken into consideration.

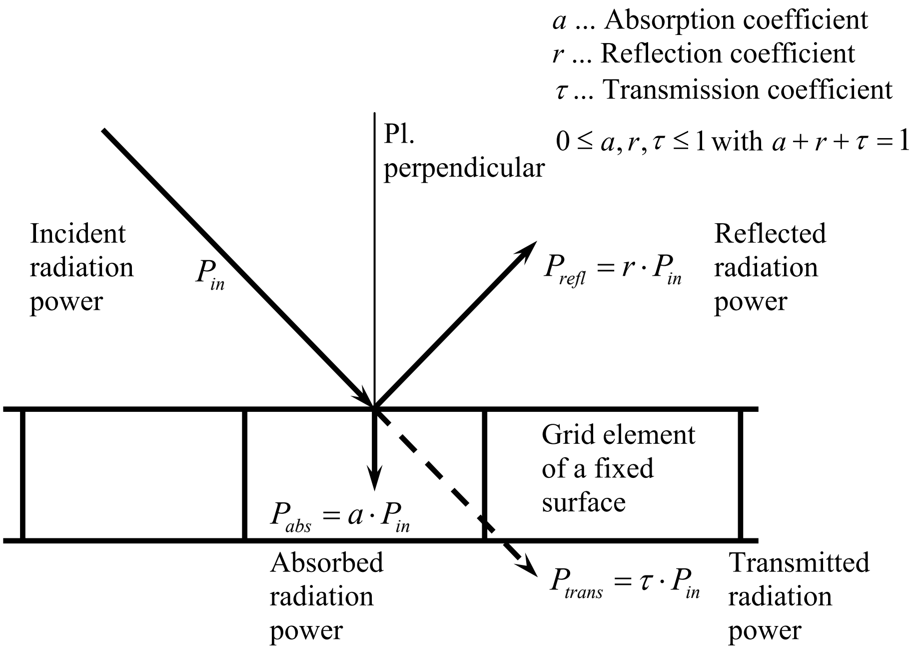


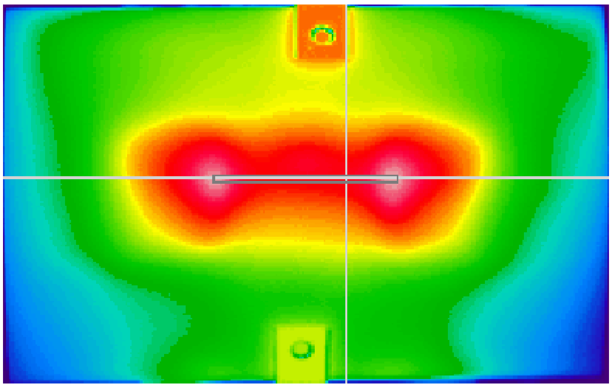
Fig. 3: Calculation of power in the case of directed radiation reflection

The result of the calculations is the distribution of the radiation emitted by the bulbs on the individual surfaces of the grid model. This distribution is available in the form of the radiation energy to be absorbed and is taken into account in the temperature simulation by the definition of additional source terms in that the energy to be absorbed is applied to the corresponding grid element.

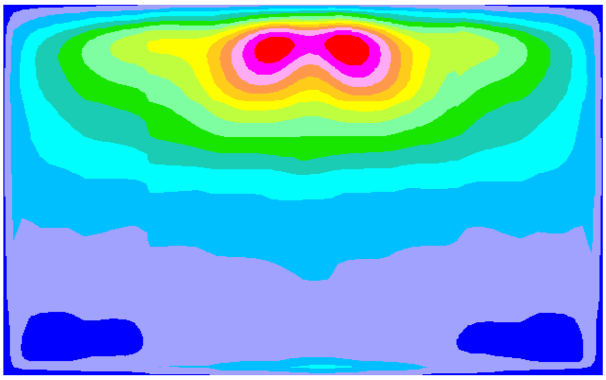
The temperature radiation of all other bodies is still considered on the basis of the radiation model based on viewing factors due to the comparatively low error influence. Since, following the Stefan-Boltzmann law, this radiation power is dependent on temperature, an application of the new method on this part of the emitted radiation would make the calculation of the distribution of radiation necessary in every iteration step of the temperature simulation and cause a lot of complicated calculations.

This method can be improved further by using a CAL program (**C**omputer-**A**ided-**L**ighting). These programs have the advantage of already containing the exact characteristic curve of the bulbs, and representing the technically relevant surfaces to a greater degree than in the discreet finite volume model. The result of these tools is then the distribution of illuminance on the cover lens, which can be transformed into heat flow density with the aid of the thermal parameters of the bulb [7].

Fig. 4 finally compares the measured and simulated surface temperature and distribution of radiation on the cover lens of a sample headlamp used to verify and validate new methods of simulation.



a)



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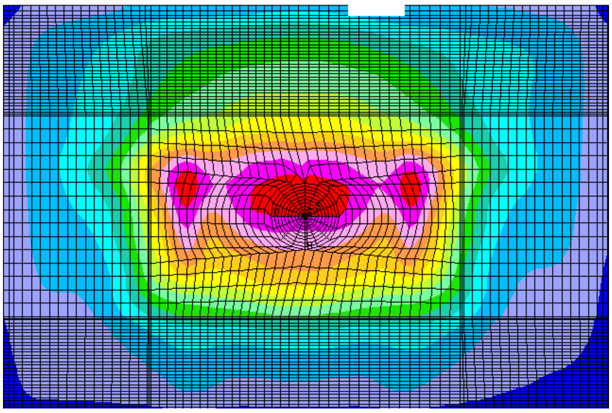

c)

Fig. 4: Comparison of the results of simulation and measurement
a) Thermography
b) Calculated temperature distribution using a conventional radiation model
c) Calculated temperature distribution taking directed reflected radiation into consideration

Fig. 4a shows the thermography of the cover lens with Fig. 4c, the result of simulation coupling CAL and CFD results, shown in comparison. A high-quality correlation between simulation and measurement can be clearly recognised and is also reflected in the quantitative results. The maximum deviation is around 5 K.
This development is an important step on the path to simulating condensation and de-condensation, since it allows temperature distribution to be simulated more accurately.
In the meantime, temperature and flow simulation on the CFD basis are standard technology, a fact documented by numerous publications in this field (e. g. [3], [4], [5], [6]). In addition, it is often used as a preventative quality assurance measure and a customer pre-condition. It can be used to carry out temperature analyses even in the very early stages of the technical design process. Thermal problems such as so-called *hot spots* on the cover lens, for example, are discovered early, enabling counter-measures to be taken (e.g. use of a different reflector design), thus avoiding an expensive and time-consuming return to earlier design phases.

3 Simulation of fogging and defogging processes

Fogging is the term used for the formation of a film of water inside automotive headlamps, in particular on the inside of plastic cover lenses (Fig. 5) and results from the condensation of steam in the air. Analogously, the inverse process (evaporation) is termed defogging.

Fig. 5: Headlamp with condensation (light-coloured areas on the PCL)

3.1 Causes of condensation

Condensation is formed in headlamps on account of their structure as an open system that exchanges not only heat but also mass with its environment. This leads to a continuous exchange of humidity in the form of steam [8].

Completely closed headlamps cannot be produced at justifiable costs. In addition, the diffusion behaviour of the plastics mainly used contributes to the occurrence of humidity, which means that all in all, humidity penetration cannot be prevented.

If the partial pressure of the steam exceeds the saturation steam pressure when it cools down, the result is the condensation of the steam and the formation of water films on solid surfaces in zones prone to condensation in headlamps. These are usually characterised by low temperatures even with the lights switched on and are usually in the area of the cover lens. It is here that the condensation temperature is reached first when the whole system cools down. On account of the fact that nowadays pattern-free cover lenses are usually used for design reasons, this condensation can be seen directly and is felt to be a quality deficit not only in the headlamp but in the complete vehicle.

Since the penetration of humidity and thus condensation cannot be prevented, the primary objective must be to limit the condensation locally or displace it to uncritical areas and to find suitable measures that can be used to speed up the evaporation of the water films that have formed as far as possible.

3.2 Measures to speed up de-condensation

Ventilation or aeration of the headlamps represents one possible measure. This can be carried out actively by using a fan or passively by introducing ventilation openings on the back of the headlamp body, between which pressure drops are created during vehicle movement, thus forcing air through the headlamp. This allows humid air to be transported out of the headlamp and speeds up the evaporation of the film layers [9].

Aeration with the aid of ventilation openings is less expensive and its effectiveness depends on the position of the openings to a large extent, since the flow must be achieved as far as possible in the areas prone to condensation. Up to now, favourable positions have been determined according to the trial-and-error method, which is both time-consuming and cost-intensive (Fig. 6).

Fig. 6: Trials on a test track

Particularly negative is the fact that relevant environmental parameters such as humidity and temperature are known and can be influenced only in expensive wind channel tests and not during drives on conventional test tracks, which means the comparability of test results is questionable.

In conclusion it must be stated that the specific design of the headlamp as an open system is usually sensible. This design means that humidity can penetrate more quickly, but it can also be transported away more quickly, too. In contrast, once humidity has penetrated an almost closed system, it will hardly be able to escape again.

3.3 Calculation of fogging and defogging

The simulative determination of condensation and evaporation processes allows the limitation of complicated experiments. In addition, investigations can be carried out on new technical products at early stages of development without having to fall back on prototypes.

Of particular interest is the location of the areas prone to condensation as well as the intensity of the condensation that occurs there. While statements about sensible positioning of the ventilation openings can be made using the location, the intensity of the condensation is decisive for the time required until the water films have been evaporated completely.

An exact thermal simulation forms the basis for determining the location of the areas of condensation, since air flow and temperature relationships play a decisive role in determining the processes. Thanks to the directed reflected radiation being taken into consideration, the forecast of the temperatures particularly in the area of the PCL satisfy the stringent requirements of a correct simulation of condensation and evaporation. Building on the results of the stationary thermal simulation, critical areas can be determined quite accurately on the basis of limiting temperatures gained from experimental values. With this method, those areas of the plastic cover lens are classified as prone to condensation where the temperature is below the limiting temperature in a stationary state. Fig. 7 shows the comparison between experimentally produced (Fig. 7a) and forecast (calculated) (Fig. 7b) areas prone to condensation and reveals good correlation.

The experimental results are from condensation tests where headlamps are operated over a longer period first for 15 minutes with the light functions switched on and then left for 5 minutes to cool down with the light functions switched off. The areas that showed a relatively low temperature even with the lights switched on are the first to fall below the condensation point when the headlamps cool down. This experiment reproduces the case where a vehicle is parked in cool and damp environmental (weather) conditions having been driven with its lights on. Verification of the experimental and simulative results can be carried out very easily visually.

Fig. 7: Condensation zones a) experimentally produced and b) forecast by simulation.

A particular advantage of the determination of critical areas using stationary thermal simulation is the comparatively short time required for calculation in comparison with a transient simulation corresponding to the experiment, since calculation using conventional computers with stationary simulation takes several hours, whereas with transient simulation it can take several weeks.

The exact calculation of the development of the thickness of the film layers over time and thus the time required for de-condensation makes transient simulations necessary. Here, a validation of the results acquired using the measured results is only possible if there is a sufficiently reliable possibility available for measuring film thicknesses and humidity, particularly in compactly designed and thus inaccessible lighting systems.

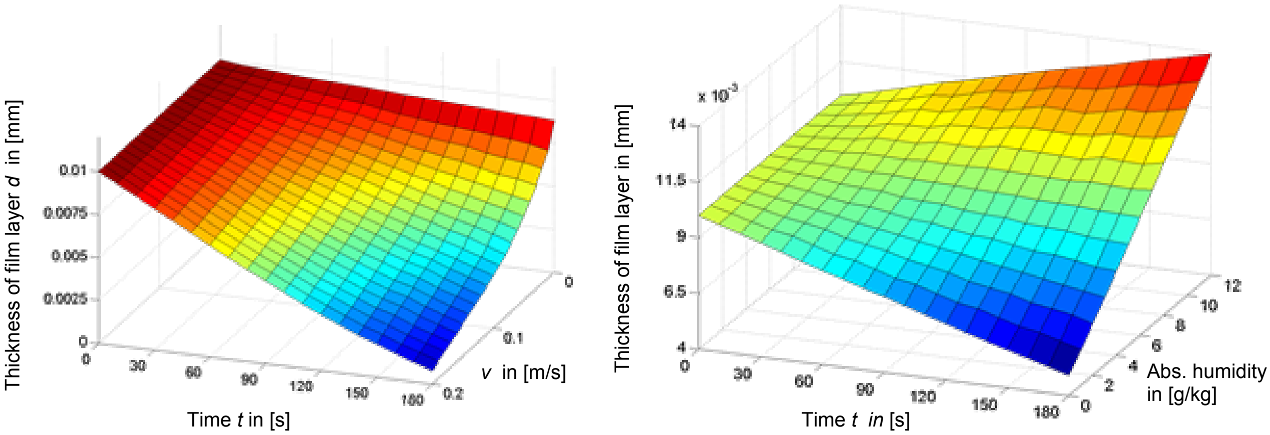

Fig. 8: Development over time of the average thickness of the film layer with
a) Variation of air speeds and
b) Variation of air humidity.

Fig. 8 shows the results of a simulation study using a simple simulation model. This is a vertical flat plane which has a constant water film at the beginning of the simulation and has air directed at it. The results show the transient development of the thickness of the film layer over the surface when the flow speed (Fig. 8a) and the air humidity (Fig. 8b) are varied. This model was used to be able to verify the plausibility of the calculation method used on the basis of a simple approximate calculation [10].

4 Summary

The thermal simulation of automotive headlamps has become standard procedure in the development process of new products. The integration of directed reflected radiation has increased the reliability and accuracy of the calculation method and now also satisfies the demanding requirements of fogging and defogging simulation. This is still in the development stages, but even today, important knowledge about the location of areas prone to condensation can be gained and integrated in the development process. Condensation simulation as well as thermal simulation will form fixed parameters in future and be able to significantly shorten the development process (time to market) of new products.

5 Literature

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