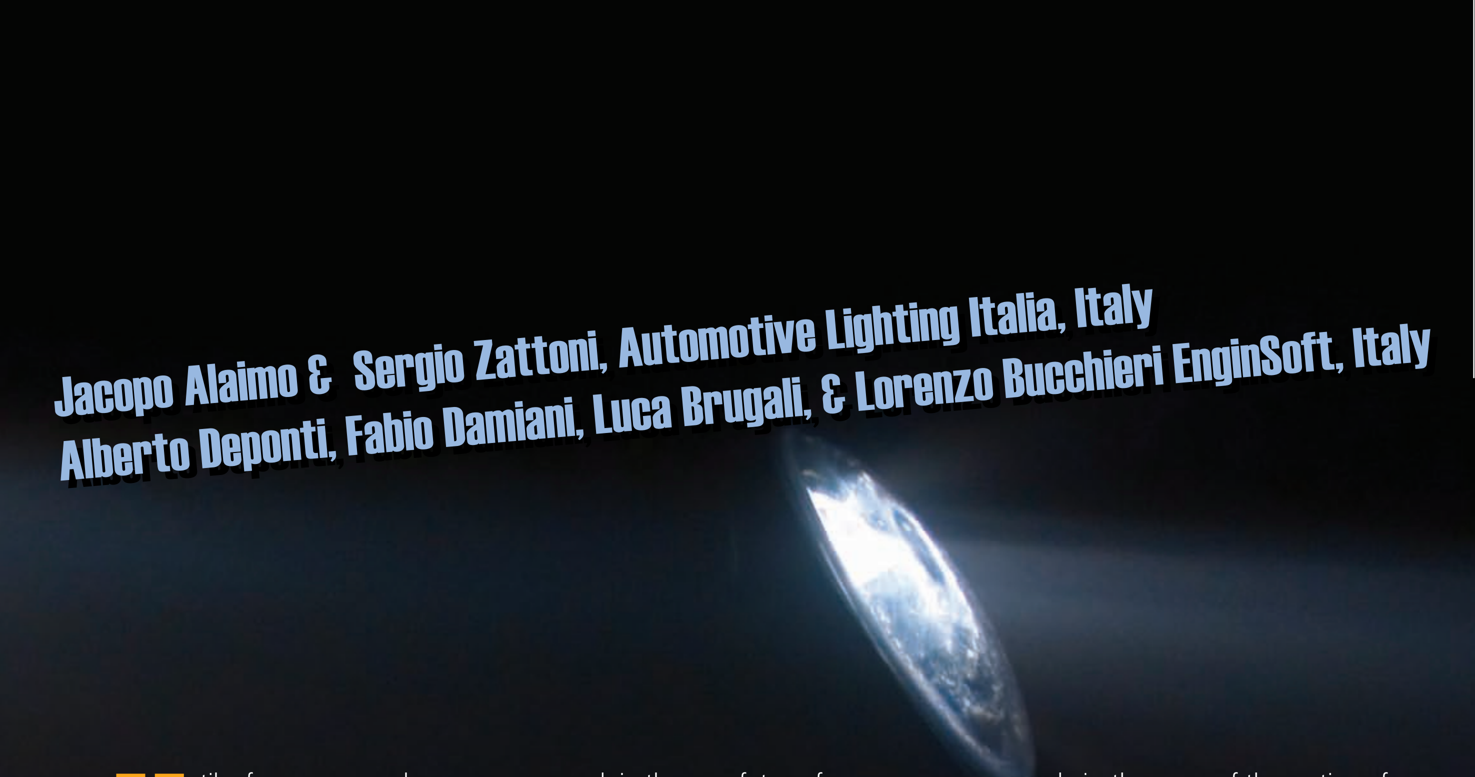
Modelling Condensation in Automotive Headlamps

The environment inside an automotive headlamp has high thermal and low mass exchanges with the external environment, causing condensation on the lens. An acceptable headlamp design can only produced if this condensation can be disposed of in a fixed time under severe thermal conditions.

Experimental studies are performed in climatic chambers under highly controlled conditions, whilst long transient numerical simulations are performed on large meshes in order to capture the relevant physics of the problem. This article outlines a new numerical method which has been used in order to study the problem, and the results obtained when applied to real-world designs.

Figure 1: Comparison Between an Old Fashioned Glass Headlamp (top) and a New Transparent Plastic Headlamp (bottom)



Jacopo Alaimo & Sergio Zattoni, Automotive Lighting Italia, Italy
Alberto Deponti, Fabio Damiani, Luca Brugali, & Lorenzo Bucchieri EnginSoft, Italy

Until a few years ago, lenses were typically designed using glass and covered by an optical prism to obtain the correct light distribution (see Figure 1). The increased sophistication of molding capabilities has now led to the mass production of large transparent plastic lenses. Curved shapes and transparent surfaces have opened a new world for style solutions, but a transparent lens lets the eye see all the way inside the headlamps. Today the observer has a free view of the inside of the headlamp, highlighting even the slightest optical fault, any thermal damage of the inner components and the possible presence of water droplets. The presence of condensation inside the headlamp is perceived by the customer as a lack of quality and reliability.

The most common solution for decreasing condensation quantity and disposal time is represented by the optimization of inner air flows and of temperature distribution on the main lens. Typically, at least two vent holes are present on the headlamp housing; in order to optimize their efficiency, it is important to find their optimal number and locations by performing numerical and physical tests during the pre-industrialization phase. Until today the solution to condensation formation has always been sought by trial and error. This leads to a great increase in time and costs. The use of appropriate numerical methods and test rooms therefore becomes a strategic tool for decreasing production time and cost and, in the near future, for optimizing headlamp design with respect to condensation formation and disposal.

From a fluid-dynamic point of view, an automotive headlamp can be considered as a cavity with low massflow interaction but high thermal interaction with the external environment. One wall of the cavity, the lens, is transparent while the others are opaque. Inside the headlamp, there are one or more lamps and a number of components: reflectors, screens, caps, connectors, pipettes, etc. These components are used for the functionality of the headlamp but also play a fundamental role in the thermo-fluid-dynamic behavior of the fluid inside the headlamp which is a mixture of air and water vapour.

The headlamp can undergo the phenomena of heating and cooling because of internal and external heat sources. The external heat sources or sinks are represented by the external environment temperature or by the heat coming from the engine. The internal heat source is represented by the switched-on lamp, which heats up the surrounding fluid and emits radiation. Since the fluid inside the headlamp is composed of a mixture of air and water vapour, it changes density because of thermal evolution. Density differences are the cause of internal convective motions which are always laminar. Since temperature is, in the final analysis, the cause of the motion of the internal fluid, it is important to precisely and accurately characterize all of the components of the headlamp. They are to be characterized both from a thermal and an optical point of view in order to model temperature, heat transfer to surrounding fluid, radiation absorption, emission and reflection. In addition, the assembly of all components limits the space where fluid can flow, hence determining the motion field inside the headlamp.

All components should be modelled with a geometrical detail which is adequate for the level of accuracy needed for the fluid-dynamic results. On the other hand, great geometric detail leads to a large mesh and, consequently, large computational costs. A trade-off between geometric detail and computational cost needs to be achieved. In addition to this, temperature evolution of the headlamp may cause water phase changes; in particular it may cause water condensation and evaporation on the lens which is a main issue for headlamp producers and the target of the present work.

The problem to be studied is a typical multi-phase problem in which it is important to properly describe the phase change between liquid water and water vapour. In this problem it is imperative to capture the natural convection velocity field due to the different density of fluid masses inside the headlamp. For this reason it is important to account for gravity and

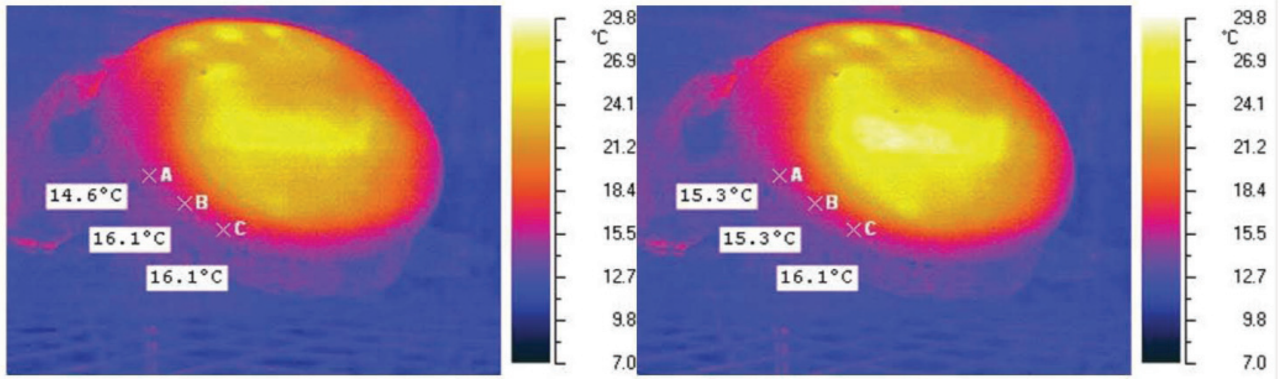


Figure 2: Thermal Maps on the Lens at Two Different Times

buoyancy effects in the fluid. Since the motion field is driven by natural convection, the flow is laminar and no turbulence model is used. Another important phenomenon to be modelled is the heat transfer between walls and fluid, between different fluid masses and, particularly, the latent heat absorbed by water evaporation and released by vapour condensation. Finally, when a switched on lamp is considered, thermal radiation is to be accounted for.

Experimental Studies

ALIT Condensation Test Room

ALIT (Automotive Lighting Italia) Condensation Test Room is a metal room with a volume of about 30m^3. Glass windows allow the technicians to follow the ongoing tests. By using dedicated hardware, it is possible to control all the main variables related to the condensate disposal process such as:

- Heat Transfer Coefficient (HTC) on headlamp boundary walls;
- Internal and external air relative humidity (RH);
- Internal and external air temperature;
- Pressure and air flow fields in the proximity of ventilation pipettes;
- Mission profile reproduction accounting for engine induced temperature and wind speed;
- Interaction between headlamp-engine assembly.

The ALIT condensation test room is projected to control all the main factors involved in the HTC distribution. It is possible to control external air RH and temperature; moreover, an air speed of up to 80Km/h can be produced along the longitudinal car axis. Inside the room, an engine box mock-up reproduces the effects of the average temperature produced by the engine. Since the HTC is influenced by aerodynamic effects too, the engine box mock-up reproduces the car shape. At present the effects not reproducible are represented by pressure and air flow fields inside the engine box. Indeed, geometric and thermodynamic effects of the engine are still too complex to be reproduced. Nevertheless, a good approximation is obtained by using an average temperature inside the engine box mock-up.

Measurement devices

A major problem related to the condensation issue is represented by the difficulty of an objective condensation tracking. Indeed large variations in condensation layer thickness as well as in water droplets diameters may occur, and this has a direct influence on the human eye perception. The use of a standard photographic camera with flash usually highlights even the smallest traces of condensation which may not be visible by human eye. At the same time, it is not possible to measure a continuous distribution of the dew point. Several temperature and humidity probes are present inside ALIT condensation test room, these are located in the free-area zone and inside the engine box mock-up. Moreover, it is possible to place thermal couples and moisture

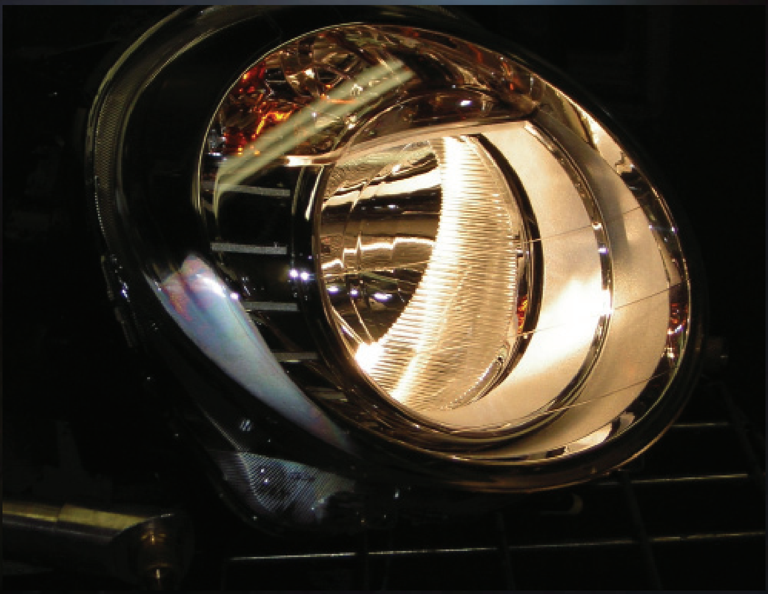


Figure 3: Condensate on a prototype specifically designed for enhancing condensation

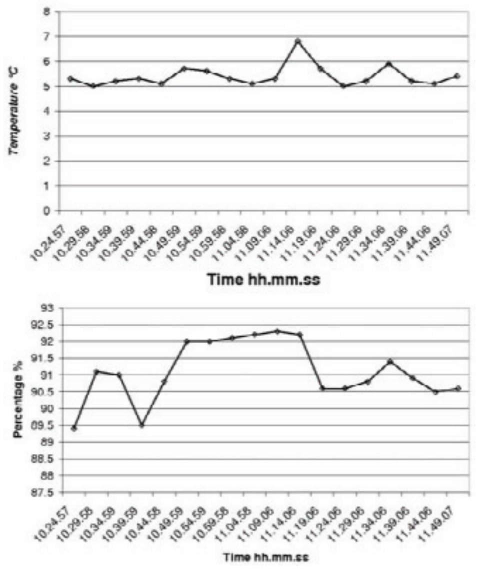


Figure 4: Temperature and Relative Humidity Graphs in ALIT Condensation Test Room

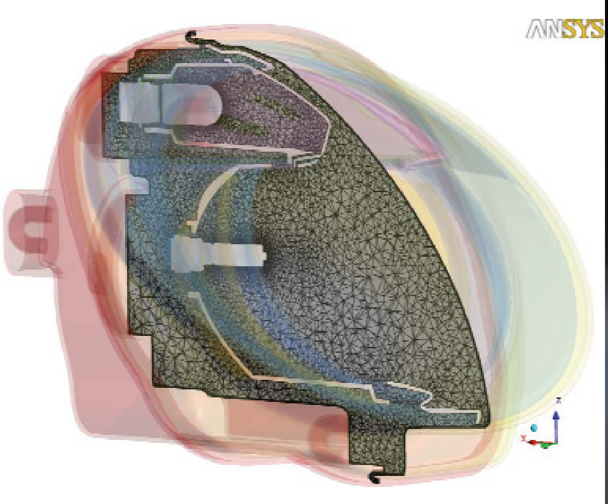


Figure 5: A Typical Tetra-Mesh Optimized for Thermal and Condense Simulations.

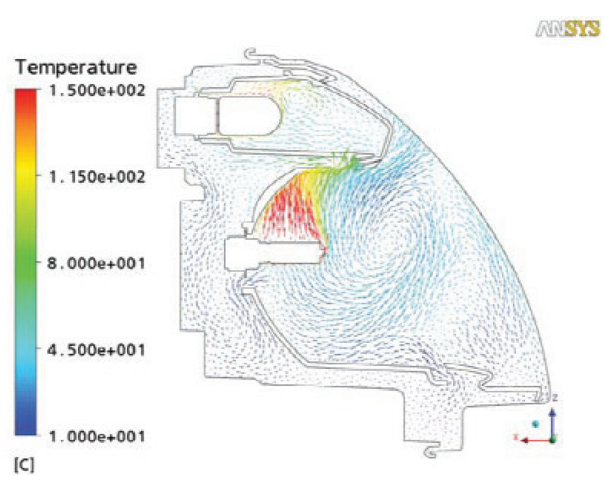


Figure 6: Velocity Vectors on a Vertical Plane Passing Through the Lamps (note that vectors are colored with temperature distribution)

meters inside the headlamp in order to get data. Finally, the temperature distribution on the lens is tracked by means of an infra-red camera. Combining these data together with photos and videos of condensation distribution it is possible to track the dew point line. At present it is not possible to measure condensation thickness.

Test Results

The outputs of the condensation test are:

- thermal maps and videos shot using infra-red camera (Figure 2);
- condensation images and videos shot using photographic camera with flash (Figure 3);
- temperature and relative humidity graphs measured by the thermal couples and moisture meters placed inside the headlamp, inside the engine box mock-up and in the external environment (Figure 4).

From Figure 3 it can be noticed that condensation tends to accumulate on the outer side of the headlamp (left side in the figure) which is the coldest part of the lens, as shown by Figure 2.

Numerical Simulations

The Numerical Method

When a switched-on lamp is to be modelled, a radiation model has to be used in order to compute the source term for the energy equation and the radiative heat flux at walls. In this case, the Discrete Transfer model is used for the directional approximation and the Grey model is used for the spectral approximation. The Gray model assumes that all radiation quantities are nearly uniform throughout the spectrum, consequently the radiation intensity is the same for all frequencies. The Discrete Transfer model assumes that the scattering is isotropic. The switched-on lamps are modelled by imposing the temperature data coming from experimental measurements. In the evaporation/condensation model considered, the liquid phase is not modelled directly. Instead, the evaporation/condensation processes occurring on the lens are modelled by means of suitable mass and heat sources for the continuity and thermal equations. The mass source term applied to the conservation law for water vapour mass in the gas is:

$$S_M = \dot{m}A = \frac{\pi L \mu \mathrm{Sh}(e\text{-}m_f)}{A_l} A.$$

Here $\dot{m}$ is the water mass per unit area transferred between liquid and gas, A is the area of the element face where evaporation and condensation processes occur, A_l is the total area of the surface where evaporation and condensation processes occur, L is the typical length scale of the process, μ is the diffusivity of water vapour in the air, considered equal to the air dynamic diffusivity, e is the water mass fraction at equilibrium, m_f is the water mass fraction and Sh is the Sherwood number. The air volume fraction is the complement to unity of the computed vapour volume fraction. The energy source due to phase change applied to the conservation law for internal energy is:

$$S_E = -\dot{m}C_p,$$

where C_p is the water latent heat for vaporization/condensation. Mass and energy sources are applied only at surfaces where evaporation/condensation processes occur. In the framework of this evaporation/condensation model, it is possible to define the water mass per unit area lying on the lens as:

$$m_W(\mathbf{x},t) = m_W(\mathbf{x},0) - \int_0^t S_M(\mathbf{x},\tau)\,d\tau.$$

Here, the space and time dependency of the water mass per unit area is explicit. This variable allows for precise tracking of the amount of condensation lying on the lens. Moreover, in the case of evaporation, the local mass source has to be null where local water mass per unit area is null; this is achieved by a local control of the mass source term. Mass and energy sources are implemented in ANSYS CFX by means of properly defined functions and variables using the CEL language. The analyses were run using an upwind advection scheme and the first order backward Euler transient scheme. The time step and the convergence criteria were chosen in order to minimize the computational time without compromising result quality and method robustness.

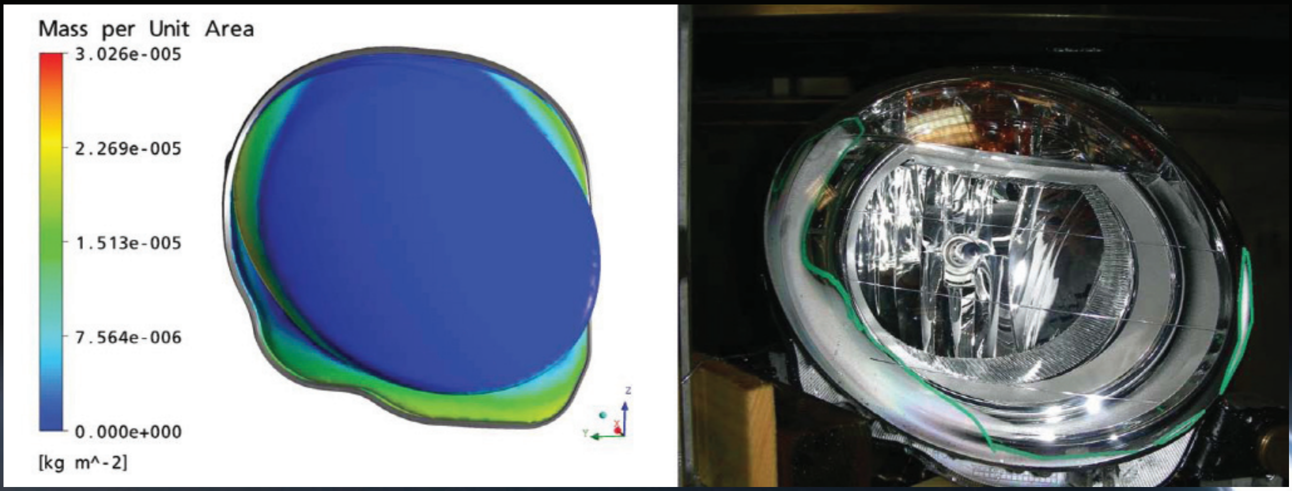


Figure 7: Qualitative Comparison Between Numerical and Experimental Results

Conditioning – 1 step	Temperature = 6°C Relative Humidity= 95%
Conditioning – 2 step	Uniform distribution on the lamps and radiation model External relative humidity = 95% HTC on the lens = 10 W/m^2 K
Condense development (20')	Uniform distribution on the lamps and radiation model External relative humidity = 100% HTC on the lens = 500 W/m^2 K
Condense disposal (40')	Uniform distribution on the lamps and radiation model External relative humidity = 95% Variable HTC on the lens

Table 1: Initial and Boundary Conditions

The Computational Mesh

Solid and fluid domains were discretized using a thetra-prism mesh. In particular, prism layers were used inside each of the solid domains and outside of the rear body, the lens and the lamps. A total of about 1.750.000 elements were used to discretize the entire headlamp. (Figure 5)

Initial and Boundary Conditions

At the start the lamps are switched off, the temperature is 6°C and the relative humidity is 95%. At the beginning of the simulation, the lamps are switched on. After 20 minutes rain starts. After 40 minutes rain stops and a wind of 30 km/h starts blowing until the end of the simulation at 60 s. These conditions are simulated by varying external temperature and relative humidity together with HTC on the lens. The initial and boundary conditions used in the simulation are summarized in Table 1.

Results

The simulation was run on 32 parallel CPUs with OS Linux CENTOS. The computational time was roughly 12 days. In Figure 6 velocity vectors on a vertical plane passing through the lamps is presented; note that vectors are colored with temperature distribution. The strong buoyancy effect caused by the switched on lamps can be appreciated.

Conclusions

Because of difficulties in measuring condensation mass on the lens, at present, only a qualitative comparison can be made; in Figure 7 such a comparison is presented. It can be noticed that the two results are in good agreement highlighting a region of condensation accumulation in the outer side of the headlamp. It has to be highlighted that some sensitivity analyses showed a strong dependency on initial and boundary conditions demonstrating the complexity of the phenomenon under study and the need of strongly controlled experimental conditions. Due to the complexity of the problem, and the fact that numerical simulations are to be performed over long time period and on large meshes, high computational power is needed. Nevertheless, numerical simulations are able to give detailed information on the thermo-fluid-dynamics of the headlamp, taking into account the condensation/evaporation phenomena that may occur on the lens. Moreover, by superimposing numerical results and condensation images taken from the experimental tests, it is possible to correlate results and to get important information about the condensation issue in terms of distribution and thickness of the water layer. The combined use of numerical and experimental studies is a powerful tool for optimizing headlamp design and obtaining high performance headlamps.

References

- ANSYS CFX-Solver Modelling Guide.
- ANSYS CFX-Solver Theory Guide.
- Perry, R.H. and Green, D.W. (Editors) (1997). Perry's Chemical Engineers' Handbook, 7th Edition, McGrawhill.
- Kreith, F. and Bohn, M.S. (2001). Principles of Heat Transfer, Thomson Learning.
- Chenavier, C. (2001) Thermal Simulation in Lighting Systems - 5 Days / 5 Degrees. PAL Symposium Darmstadt, 2001.
- Preihs, E. (2006). Analytic Solution Measurements of Condensation in a Headlamp, COMSOL Conference 2006.
- Nolte, S. and Maschkio, T. (2007). Development of a Software Tool for the Simulation of Formation and Clearance of Condensation in Vehicle Headlamps, LLAB.
- Schmidt, T. (2008). Nanotechnologies surface modifications for anti-fog applications in automotive lighting and sensor serial production, SAE 2008

AUTHOR INFORMATION

Jacopo Alaimo I Automotive Lighting Italy
jacopo.alaimo@al-lighting.com

Alberto Deponti I EnginSoft Italy
a.deponti@enginsoft.it