Modelling of condensate formation and disposal inside an automotive headlamp

Alberto Deponti[1], Fabio Damiani[1], Luca Brugali[1], Lorenzo Bucchieri[1], Sergio Zattoni[2], Jacopo Alaimo[2]
[1] EnginSoft S.p.A. Via Galimberti 8/D, 20124 Bergamo, Italy
[2] Automotive Lighting Italia S.p.A. Via Cavallo, 18, 10078 Venaria Reale (Torino), Italy

ABSTRACT
An automotive headlamp is an environment with high thermal and low mass exchanges with the external environment; for these reasons humidity can accumulate inside the headlamp and can condensate on the lens. A headlamp design can be produced only if, under severe thermal conditions, all the formed condensate is disposed in a fixed time. The combined use of experimental studies and numerical modelling is an important tool to optimise headlamp design and to produce high performance headlamps. Experimental studies are to be performed in climatic chambers under highly controlled conditions. On the other hand, long transient numerical simulations are to be performed on large meshes in order to capture the relevant physics of the problem. A new numerical method has been implemented in order to study this problem and has been applied to real case headlamp designs providing good agreement between numerical and experimental results.

1. INTRODUCTION

Automotive design has always been driven by aesthetical choices. On this path technology plays the important role to solve all the problems leaded by stylist needs and design solutions. Aerodynamic and curved shapes, new materials and coatings often contrast with economical and productive needs.

Headlamps play a key role: located on the front of the car, lighted, with more and more technological solution such as LED, light-guide, adaptive and smart lighting systems they have always been used by stylists to enhance car lines. On the other hand, mechanical and optical designers have to satisfy many functional requirements. Crash and safety tests, thermal behaviour, and obviously lighting performances are only few of a great number of technical needs. The right solution for conjugating aesthetics and technology with cost and production requirements is not always easy to find and often new problems appear during the project development leading to constant increases of specific requirements.

Something similar happens for the issue of condensate formation and disposal. The increase of moulding capabilities leads to the massive production of large transparent plastic lenses. Until few years ago, lenses were typically designed using glass and covered by optical prism to obtain the correct light distribution (see Figure 1). Curved shapes and transparent surfaces opened a new world for the style solutions, but a transparent lens lets the eye to go into the headlamps (see Figure 1). 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. In Figure 2 an example of condensate on a headlamp lens is presented. The presence of condensate inside the headlamp is perceived by the customer as a lack of quality and reliability.

A possible solution to the condensate formation is represented by the anti-fog coating. This layer of hydrophobic material painted on the inner side of the lens prevents the water to stick onto the plastic walls. Another solution is represented by the use of hydrophobic membrane applied to large vent holes. In this way high air flow rates are allowed to pass through the membrane but the headlamp is kept sealed with respect to humidity. The drawbacks of these methods are the strong impacts on the cost per piece and on the cycle-time. This solution is generally applied for luxury and high-performance cars where cost and production volume are not so relevant. The most used solution for decreasing condensate quantity and disposal time is represented by the optimisation 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 optimise their efficiency, it is important to find their right number and locations by performing numerical and physical tests during the pre-industrialization phase. In Figure 3 an example of vent holes in the headlamp housing is presented. Until today the right solution to condensate formation has always been sought by trials and error. This implies a great increase in time and costs. Under this point of view, the use of appropriate numerical methods and test rooms becomes a strategic tool for decreasing production time and cost and, in the close future, for optimising headlamp design with respect to condensate formation and disposal.

From a fluid-dynamic point of view, an automotive headlamp can be considered as a cavity with low mass-flow 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, in the meanwhile, play a fundamental role in the thermo-fluid-dynamic behaviour of the fluid inside the headlamp which is a mixture of air and water vapour. The headlamp can undergo 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 heating 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 by 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 final analysis, the engine of the motion of the internal fluid, it is important to precisely and accurately characterize all 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. Moreover, the assembly of all components delimits the space where fluid can flow, hence determining the motion field inside the headlamp. All components should be modelled with a geometrical detail adequate to the level of accuracy desired for the fluid-dynamic results. On the other hand, a great geometric detail leads to a large mesh and hence to large computational costs. The right trade off between geometric details and computational costs is 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 important to properly describe the natural convection velocity field due to different density of fluid masses inside the headlamp. For this reason it is important to account for gravity and 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.

Figure 1: comparrison between an old fashione glass headlamp (left) and a new transparent plastic headlamp (right)

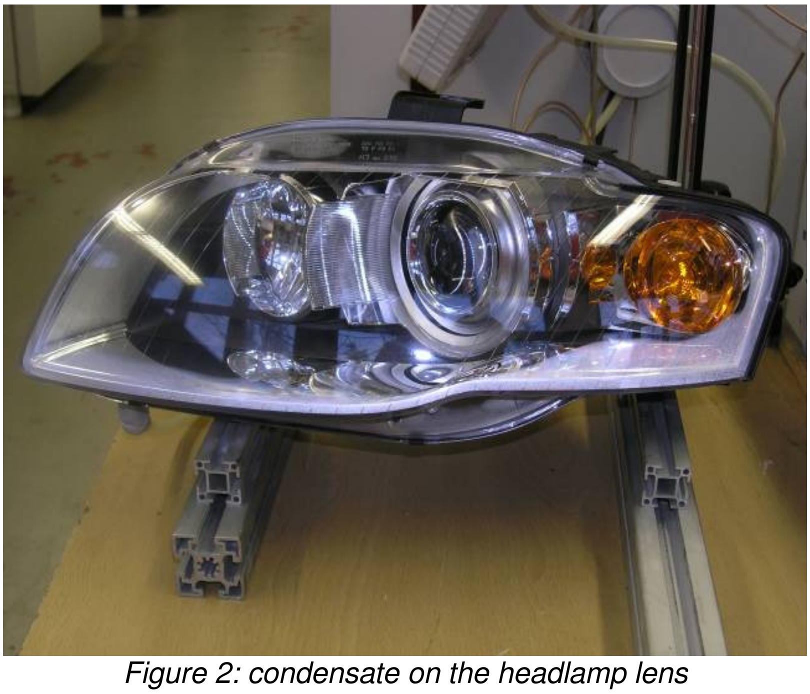


Figure 2: condensate on the headlamp lens

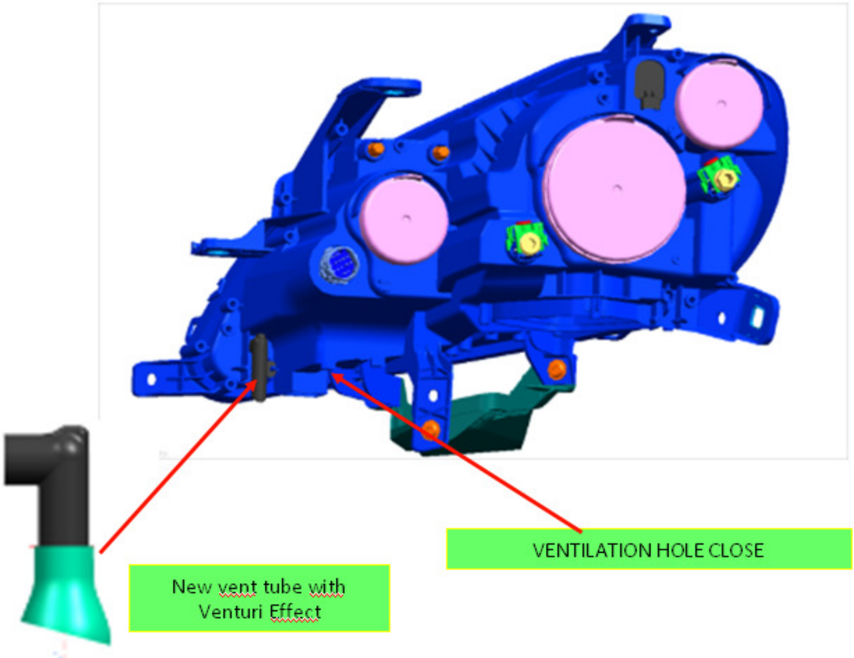


Figure 3. example of vent holes on the headlamp housing

2 EXPERIMENTAL STUDIES

2.1 History of condensate tests

Headlamp reliability verification with respect to the condensate effect started on the early '90 with the introduction of clear lenses and plastic materials. Soon customer specification started to take into account this issue. The first step was the introduction of some verification criteria on the basis of pre-existent tests. These criteria involved the absence of water droplets inside the headlamp during the standard sealing and rain tests. Nevertheless, these tests were not conceived to check the specific worst condition for the condensate formation but usually to test tropical rain and ford conditions. Indeed they were mainly focused on discovering any eventual lack on the headlamp sealing and not on the inner air flux optimization. A typical tropical rain test is performed at ambient temperature higher than 24°C which is very far from the cold and foggy conditions favourable for condensate formation. Consequently, specific tests, more and more severe, have been introduced to understand and prevent any possible defect. Obviously, this process required some years to deeper understand the phenomena and to introduce some technical solution like the introduction of vent pipes, hydrophobic membrane and anti-fog coating.

The first condensate tests were driving-tests. This method is very powerful in taking into account all the variables of the system such as interactions between engine components and headlamp but is hardly reproducible. The influence of environment air properties such as temperature and humidity did not allow to schedule a test campaign. It was then necessary to perform tests in a controlled environment such as a wind tunnel facility using a full scale vehicle. In this way it is possible to control all the key factors of the condensate dynamics looking for the worst condition and, at the same time, without loosing the coupling effects of the car assembly. However, this method is very expensive because of the high cost of facility maintenance and use; the obvious consequence is that only a low number of tests is possible. It was then necessary to find another way for testing different project solutions and prototypes in order to deeply understand the condensate phenomena. Automotive Lighting Italy (ALIT) designed a specific condensate test room able to reproduce and control all the main factors involved in the phenomenon under study. The condensate test room allows for:

- Product Validation – in house HL performances evaluation allows the adoption of corrective actions (if needed) before the test is performed at the presence of the customer;

- Prototype Evaluation – several in house tests are possible in order to test different and/or innovative solutions that could be applicable to new projects;
- Benchmark – in house test are possible in order to evaluate competitors solutions;
- Simulation – full availability for all the necessary tests used for software calibration.

2.2 Test description

Condensate tests are usually divided into three main steps. A first conditioning period is followed by a condensate formation stage; after that, the condense disposal step is performed. In this last step a time threshold is usually fixed. In Table 1 the condensate test steps are described in details.

1. Headlamp conditioning	The prototype, mounted on car or engine-box mock-up, is placed in the room at 5±2 °C and 95% RH	About 12h
2.a. Condensate formation	Headlamp lamps are switched-on	About 20’
2.b. Condensate formation	A rain effect is induced: water at 8°C is spray on the prototype and a wind speed of 30Km/h is introduced. Engine works at low regime with engine box at 30°C. The same air conditions as before are used	About 20’
3. Condensate disposal	External air at 5±2 °C e 95% RH, air speed at 80 Km/h and engine box at 50°C without rain	Until complete disposal

Table 1: condensate test description

Condensate tests are considered successful if, after 60 minutes from the beginning of stage 2, condensate is not visible inside the headlamp or if the percentage of lens surface covered by condensate is lower than a prescribed value.

2.3 ALIT Condensate Test Room

ALIT Condensate Test Room is a metal room with a volume of about $30m^3$ (see Figure 4). Glass windows allow the technicians to follow the ongoing tests. By using a dedicated hardware, it is possible to control all the main variables related to 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.

ALIT condensate 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 axe. Inside the room an engine box mock-up reproduces the effects of the average temperature produced by the engine. Since HTC is influenced by aerodynamic effects too, the engine box mock-up reproduces the car shape (see Figure 4). 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.

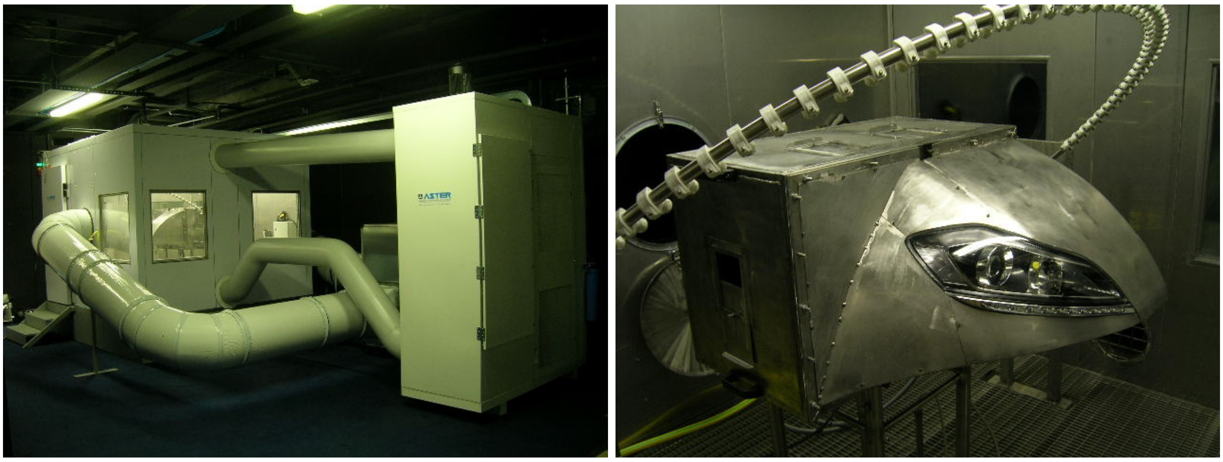


Figure 4: ALIT condensate test room (left) and engine box mok-up inside the room (right)

2.4 Measure devices

A major problem related to the condensate issue is represented by the difficulty of an objective condensate tracking. Indeed large variations in condensate 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 condensate 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 condensate 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 meters inside the headlamp in order to get punctual data. Finally, temperature distribution on the lens is tracked by means of an infra-red camera. Combining these data together with photos and videos of condensate distribution it is possible to track the dew point line. At present it is not possible to measure condensate thickness.

2.5 Test Results

The outputs of the condensate test are:

- thermal maps and videos shot using infra-red camera (Figure 5);
- condensate images and videos shot using photographic camera with flash (Figure 6);
- 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 7).

From Figure 6 it can be noticed that condensate tends to accumulate on the outer side of the headlamp (left side in the figure) which is the coldest part of the lens, as showed by Figure 5.

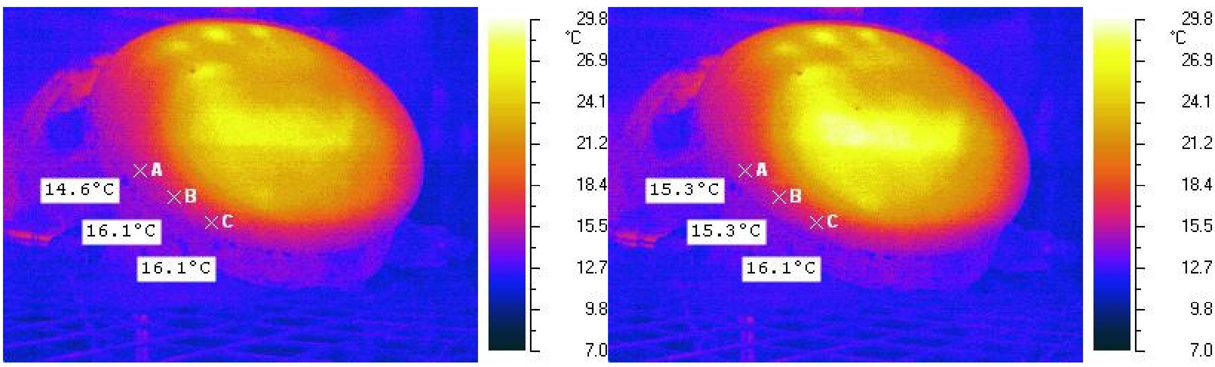


Figure 5: thermal maps on the lens at two different times

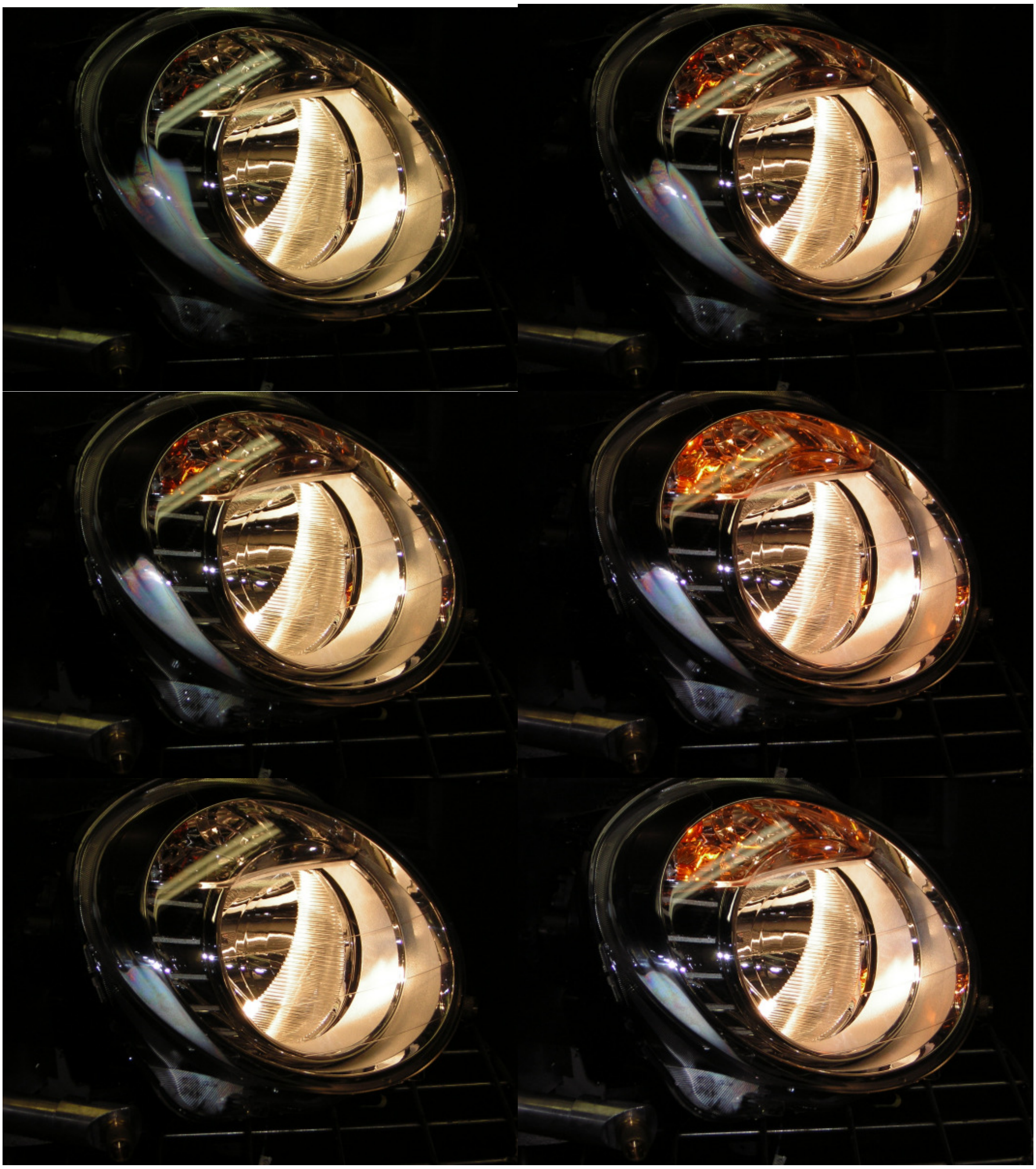
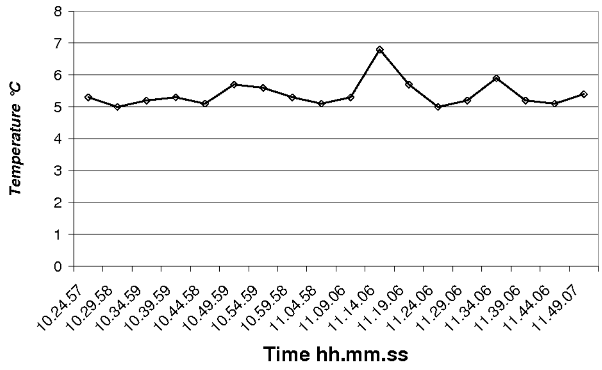


Figure 6: condensate images at different times



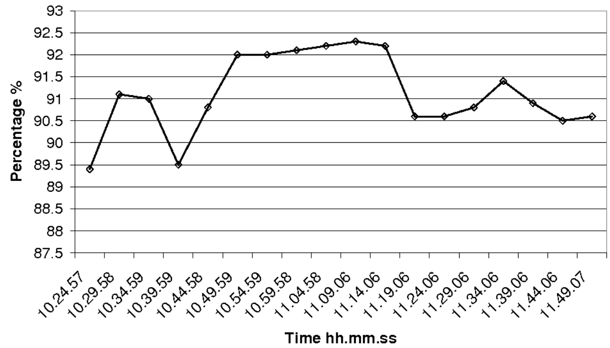


Figure 7: temperature and relative humidity graphs in ALIT Condensate Test Room

3. NUMERICAL SIMULATIONS

3.1 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 the present work 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 superficial temperature of the lamp bulb; surface temperature data come form experimental measurements.

In the considered evaporation/condensation model, the liquid phase is not directly modelled. 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:

$$S_M = \dot{m}A = \frac{\pi L \mu \mathrm{Sh}\left(e\text{-}m_f\right)}{A_l} A. \tag{7.2}$$

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:

$$S_E = -\dot{m}C_p, \qquad (7.6)$$

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 laying on the lens as:

$$m_W(\mathbf{x},t) = m_W(\mathbf{x},0) - \int_0^t S_M(\mathbf{x},\tau)d\tau. \qquad (7.8)$$

Here the space and time dependency of the water mass per unit area is explicit. This variable allows for a precise tracking of the condensate amount laying 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 upwind advection scheme and first order backward Euler transient scheme. Moreover, the time step and the convergence criteria were chosen in order to minimize the computational time without compromising result quality and method robustness.

3.2 The Computational Mesh

Solid and fluid domains were discretized using a thetra-prism mesh. In particular, prism layers were used inside each 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.

3.3 Initial and Boundary Conditions

At the initial time the lamps are switched off, the temperature is 6℃ and the relative humidity 95%. At the beginning of the simulation lamps are switched on. After 20 minutes rain starts. After 40 minutes rain stops and a wind at 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 2.

0 min	Temperature = 6℃ Relative Humidity = 95%
0 min → 20 min	Uniform temperature distribution on the lamps and radiation model External temperature = 6℃ External relative humidity = 95% HTC on the lens = 10 W/m^2 K
20 min → 40 min	Uniform temperature distribution on the lamps and radiation model External temperature = 6℃ External relative humidity = 100% HTC on the lens = 500 W/m^2 K
40 min → 60 min	Uniform temperature distribution on the lamps and radiation model External temperature = 6℃ External relative humidity = 95% Variable HTC on lens

Table 2: initial and boundary conditions

3.3 Results

The simulation was run on 32 parallel CPUs with OS Linux CENTOS. The computational time was roughly 12 days. In Figure 8 velocity vectors on a vertical plane passing through the lamps is presented; note that vectors are coloured with temperature distribution. In Figure 9 the time evolution of condensate per unit area on the lens is presented. The strong buoyancy effect caused by the switched on lamps can be appreciated form Figure 8. From the same figure the complexity of the geometry of the inner part of an automotive headlamp can also be appreciated: this is made up by a number of parts that strongly affect the inner velocity field. Moreover, from Figure 9 it can be noticed that condensate tends to accumulate on the outer side of the headlamp (left side in the figure), where heating from the lamp is limited as well as natural convection.

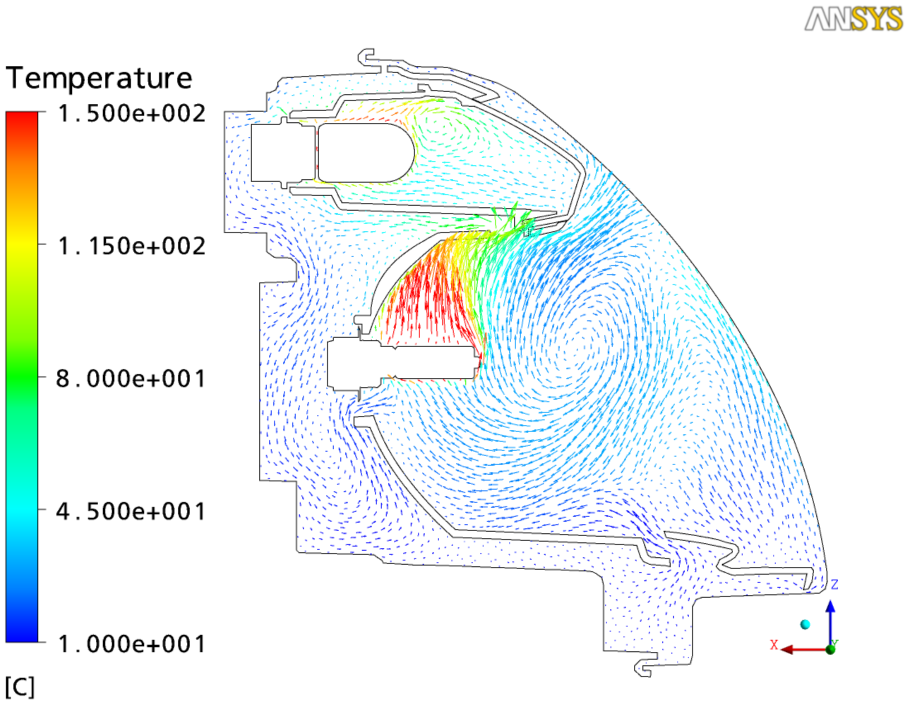


Figure 8: velocity vectors on a vertical plane passing through the lamps (note that vectors are coloured with temperature distribution)

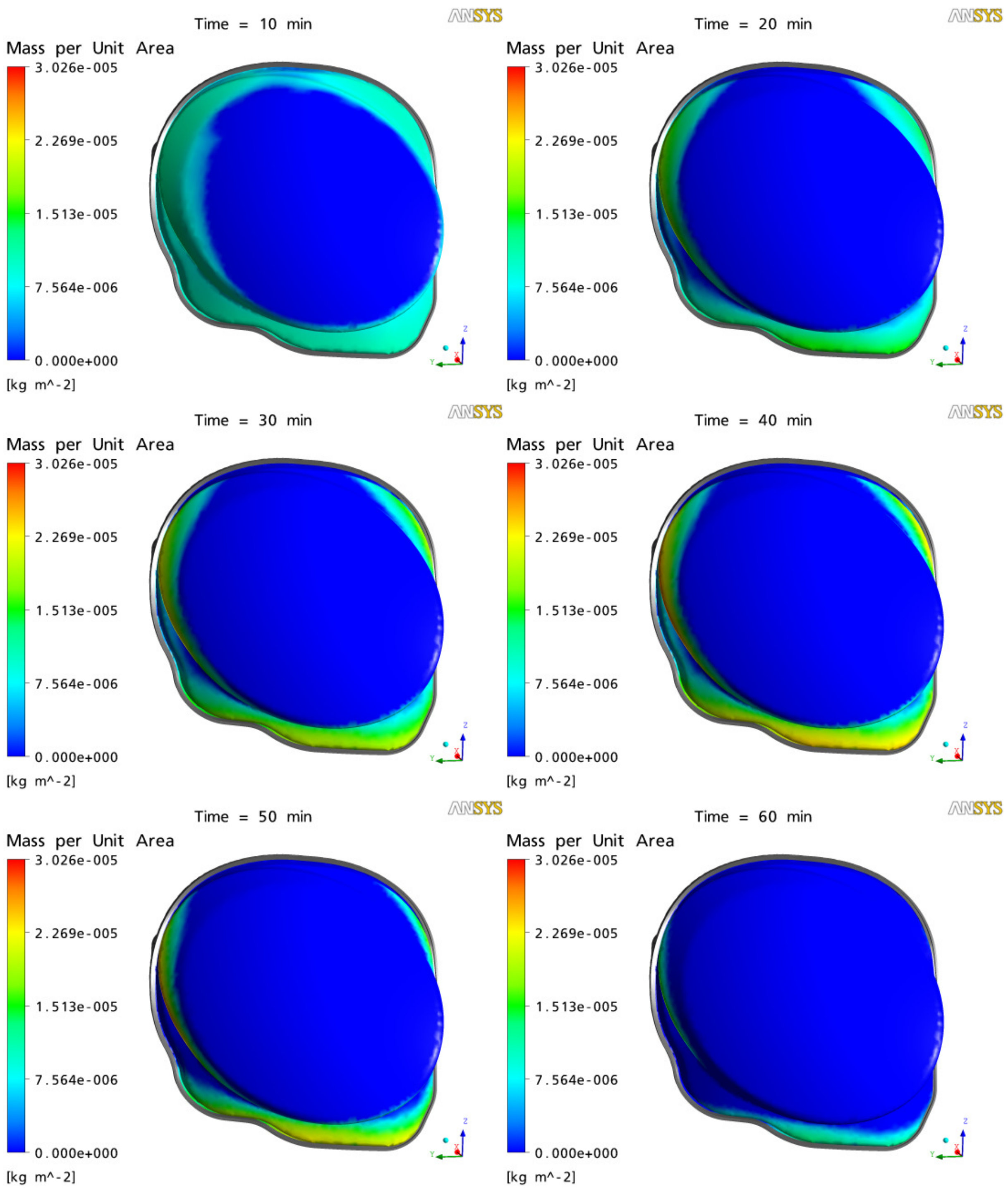


Figure 9: time evolution of condensate mass per unit area

4. CONCLUSIONS

Because of difficulties in measuring condensate mass on the lens, at present, only a qualitative comparison can be made; in Figure 10 such a comparison is presented. It can be noticed that the two results are in good agreement highlighting a region of condensate 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, numerical simulations are to be performed on long time period and on large meshes, so that a high computational power is needed. Nevertheless, numerical simulations are capable 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. In particular, numerical simulations clearly highlight the critical areas of a headlamp design with respect to condensate formation and disposal. These information can be made available before any real headlamp is produced thus reducing the number of prototypes. Moreover, by superimposing numerical results and condensate images taken from the experimental tests, it is possible to correlate results and to get important information about the condensate issue in terms of distribution and thickness of the water layer. The combined use of numerical and experimental studies is a powerful tool for optimising headlamp design and obtaining high performance headlamps.

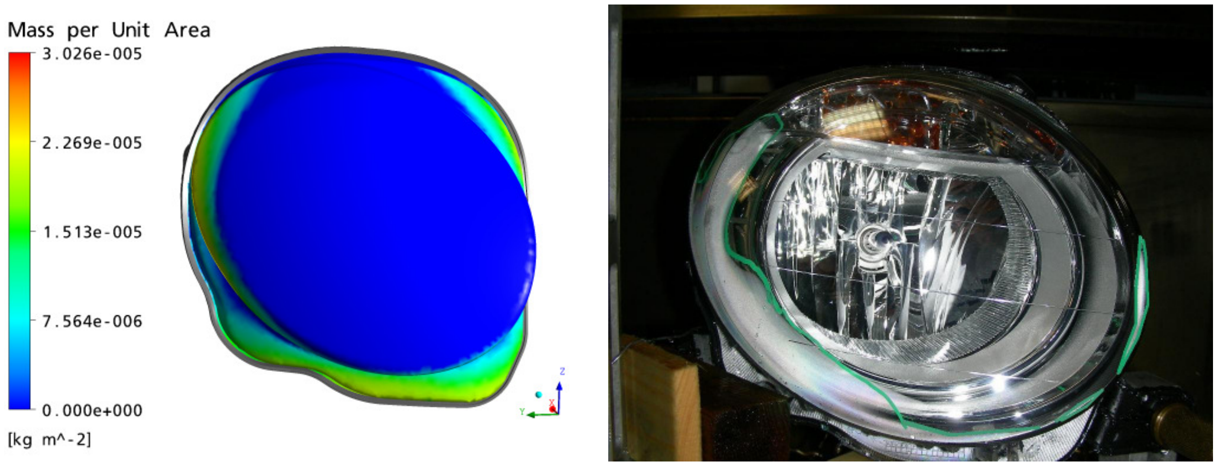


Figure 10: qualitative comparison between numerical and experimental results

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