Active Moisture Removal Puts Headlamp Condensation Protection on a New Level

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ABSTRACT

Headlamp condensation, a recurring evil for the automotive lighting industry, will be even more prevalent as full LED headlamps further penetrate the marketplace. Current venting solutions are capable of reducing, but not sustainably preventing, such condensation.

In a collaborative innovation effort that leverages each partner's strengths, AML Systems and W. L. Gore are co-creating a new product that actively prevents condensation. This new solution offers an entirely new level of protection.

This paper will present the new technology that provides active moisture removal: AML's Condensation Management Device (CMD) enabled by GORE Condensation Management Products. The CMD leverages electrical power and regenerative desiccants to remove recurring moisture from automotive exterior lamps.

Keywords: Automotive headlamps, condensation, active device, open innovation

1. Introduction

Condensation in automotive exterior lamps occurs when the internal lamp dew point (DP) is higher than the lens temperature. Condensation is omnipresent, and LED technologies, which change the thermodynamic conditions inside the lamps, increase the risk of condensation formation.

Headlamp condensation can lead consumers to believe their vehicle has defective lamps, can result in additional cost to the dealer who must address an unhappy customer, and can negatively impact the brand's quality image through lower initial quality ratings. In addition to these consumer issues, condensation may accelerate the aging of electronic components.

The costs of dealing with condensation can be significant. For example, a premium-vehicle OEM recently incurred a cost of more than EUR 600,000 over a ten-month period, in order to replace xenon headlamps in China due to end-user complaints of condensation and dust ingress. Another premium-vehicle OEM reported that 35% of his end-user complaints about a specific matrix LED headlamp in Europe were due to condensation. Despite great efforts on all sides, the phenomenon of condensation could only be reduced – not yet finally eliminated.

One reason is that even the best current condensation removal or reduction technologies have limitations. All are highly dependent upon ambient conditions. Passive systems (e.g., open tubes, anti-fog coatings, membrane vents) do not work under all conditions, and active moisture removal systems (e.g., desiccants) only work for a finite period of time until saturated – well short of the life of the vehicle.

2. Factors influencing moisture transfer in automotive exterior lamps

The condensation behaviour of automotive exterior lamps is influenced by a wide range of factors, as shown in Figure 1.

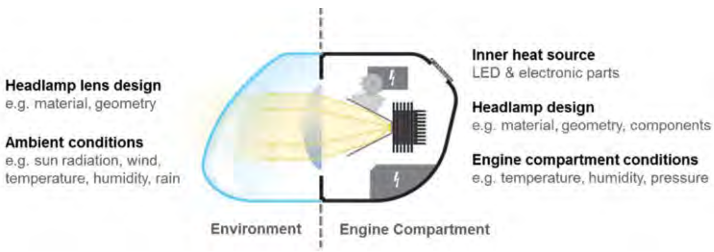

Figure 1: Influencing factors for moisture transfer in automotive headlamps

Moisture, which is what induces condensation to form, can be added to the air inside the headlamp via the following transfer mechanisms, as described in Figure 2:

1. Water vapour sorption of plastic components and housing material,
2. Water vapour permeation through plastic housing material,
3. Convective and diffusive moisture transfer through vent(s).[1]

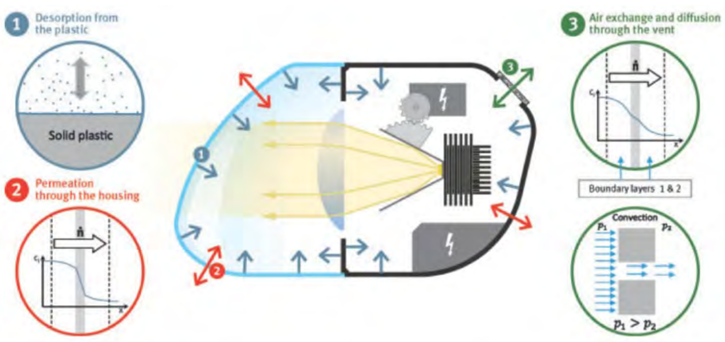

Figure 2: The dynamic interaction of moisture transfer mechanisms in automotive headlamps

Experience shows that LED light sources are negatively affecting humidity formation in automotive exterior lamps, because:

1. LED light sources are emitting less heat.
2. For LED lamps, the heat sources are located at the back of the lamp. For LED lamps (compared to halogen or xenon), this means that less heat is directed towards the lens. This reduces the possibility that direct heat exposure will be able to clear the lens after condensation forms.

In addition, heating of the surrounding plastic leads to increased moisture desorption, which increases the likelihood of condensation forming within the lamp.

The growing number of sensitive electronics in the lamps increases the amount of plastics in lighting enclosures, leading to an even greater increase in the amount of water released during heat-up.

Finally, as lamp designs become more complex, the open pathway between the front and back of the lamp is restricted. This creates new challenges for achieving appropriate venting/condensation reduction.

Figure 3 illustrates the massive influence of lamp design (amount and kind of plastics, lamp volume, surface area of plastics, etc.) on the moisture pick-up of three different headlamps. The headlamps were completely dried at 70 °C for 6 days. Afterwards they were exposed to 22 °C / 50% rH ambient conditions for several weeks. The mass increase due to moisture sorption in the materials was logged by gravimetric measurement.

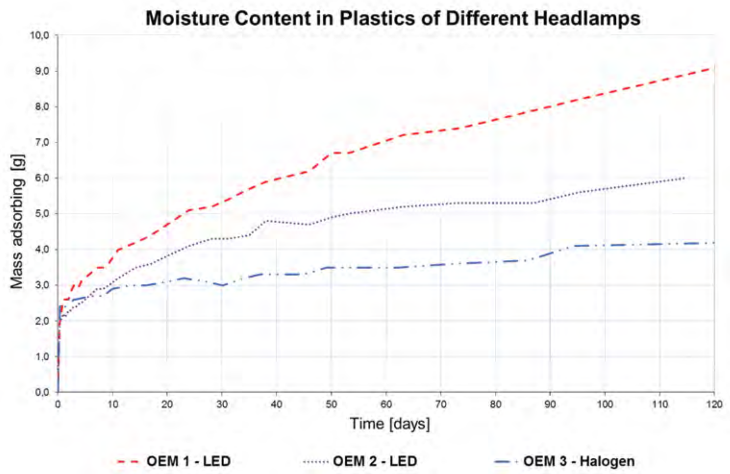

Figure 3: Mass increase of closed headlamps at 22 °C / 50% rH (pre-conditioning: 6 days at 70 °C / 10% rH)

3. Common Condensation Reduction Technologies

In Europe, three major types of venting systems are currently used to reduce condensation in exterior automotive lamps. All work passively – either by pressure differentials (convection) or moisture concentration disequilibria (diffusion):

1. Rubber tubes and caps with labyrinths or open-cell foam,
2. Cap vents with non-woven or PTFE membranes,
3. Adhesive vents with porous membranes (typically ePTFE).

Some of these solutions provide benefits beyond condensation reduction: they also equalize pressure and prevent water and dirt ingress. Convective systems featuring rubber tubes and non-wovens are neither dust-proof nor waterproof, while diffusive ePTFE membranes are both dust-proof and waterproof. Whereas rubber tubes and cap vents provide almost no diffusive moisture transfer, ePTFE membranes balance the disequilibria of water vapour concentration between a lamp's interior and the exterior engine compartment / environment. Further, for convective systems to function, the vehicle has to be in motion. As the typical car is stationary 96.5% of the time[2], convective systems cannot provide sufficient and sustainable lens clearing.

To reduce the perceived amount of visible condensation, some lamp manufacturers supplement venting technologies with additional measures. *Anti-fog coating* increases the surface energy of the lenses, reducing the contact angle between the water droplet and the surface. This causes the water droplet to disperse into a continuous thin film. However, the coating reduces the freedom of lens design. Moreover, its camouflage effect has a limited lifetime. The coating degrades over time until droplets are formed and water spots and stripes appear inside the headlamp.

LED headlamps or their packaging can contain non-regenerating *desiccant bags* to protect lamps during transit and storage against the harmful effects of humidity and moisture. The bags are available in a range of different types and weights. Moisture removal performance is dependent on the size of the bags and the relative humidity, and active moisture removal can last from a few weeks to several months. Once saturated however, these bags cease to function.

Another way to try and avoid condensation is to use a *fan* that blows hot air from the heat sink to the lens. This helps to dry the lens faster – however, it doesn't reduce the DP or the moisture content inside the headlamp.

In summary: Due to the complexity of moisture transfer routes and the broad variety of lamp designs, at present there is no commercially-available "one size fits all" solution that keeps lenses 100% free of condensation. The effectiveness of all existing solutions greatly depends upon the specific ambient conditions and the DP inside the lamp.

A new technology aims to answer these challenges. Even in extremely humid weather conditions, it *actively removes moisture* from headlamps, and at the same time provides dust- and water-ingress protection as well as pressure equalization to the headlamp. For the first time, this technology enables us to partially decouple the headlamp conditions from the ambient conditions.

4. New AML Condensation Management Device (CMD) enabled by GORE Condensation Management Products

4.1 CMD overview

CMD is an electromechanical device installed on the headlamp housing, with a portion of the device extending into the headlamp enclosure. The CMD is designed to actively reduce the humidity level inside the headlamp and significantly reduce the risk of condensation.

This device, equipped with a breathable membrane and a radial seal, allows the headlamp to remain completely sealed. At the same time, it provides pressure equalization, so that no other venting system is needed. Because the CMD is screw-mounted, it is easily installed and can be a serviceable component as opposed to replacing an entire headlamp assembly.

Figure 4: CMD view from inside the headlamp / from outside the headlamp

The CMD can be electrically connected to the headlamp's internal harness. All components of the CMD are designed to endure for the lifetime of a vehicle. No maintenance of the device is required.

4.2 CMD function

AML and Gore co-developed a technology that *actively removes moisture* from the headlamp through adsorption and desorption processes, lowering the lamp's internal DP. As the internal lamp DP drops, the difference between the internal lamp DP and the lens temperature increases, reducing the risk of condensation occurring inside the lamp.

The CMD works as a moisture pump and is operated in cycles. It incorporates a desiccant material that adsorbs the moisture from the inner headlamp and desorbs (releases) it to the external environment when saturated.

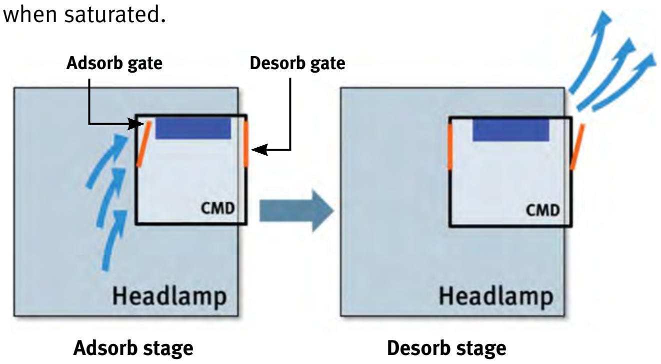

Figure 5: CMD operation principle

In the adsorb stage, the adsorb gate is opened to the inner headlamp and the desorb gate is closed. The desiccant adsorbs moisture from the inner headlamp, lowering the DP inside the lamp.

In the desorb stage, the adsorb gate is closed and the desorb gate is open to the environment. In parallel, the desiccant is regenerated.

The breathable GORE® Vent on the outside of the CMD reliably allows pressure equalization in each stage, and provides continuous protection from dust and water ingress into the headlamp.

4.3 Desiccant

The CMD contains a regenerable desiccant specifically developed for headlamp applications. It adsorbs[3] the H_2O molecules from the air and the plastics by physisorption.

Furthermore, this desiccant is capable of being regenerated thousands of times, to endure and function for the lifetime of a vehicle.

4.4 Pump-down cycles

One adsorption stage followed by one desorption stage is called a "pump-down" cycle. Repeated pump-down cycles remove moisture and continuously lower the lamp's internal DP.

A desorb stage typically takes 30 minutes, and usually happens in driving conditions which provide the electrical power for the desiccant regeneration. During regeneration, the moisture removed from the desiccant is expelled through the diffusive membrane vent to the environment.

In the adsorb stage, the CMD is turned off so the desiccant can pick up moisture from inside the headlamp. Depending on the conditions, it can take several hours to saturate the desiccant. The adsorb stage can take place while parking or driving, provided the CMD is turned off. During this adsorb stage, the DP gets reduced as moisture is drawn from the plastics of the headlamp, into the CMD. Once the car is started again or when the CMD is turned on, the CMD is re-activated and a new pump-down cycle is initiated. These CMD pump-down cycles can be adapted, if appropriate and required by the OEM or headlamp manufacturer.

CMD contains an actuator[4] that closes the adsorption gate and opens the desorption gate within 100 ms. This actuation is adapted from the AML smart actuator that is already used to switch from low to high beam.[5] Repeated pump-down cycles continuously remove moisture from the headlamp plastics. The more the CMD operates, the lower the DP inside the headlamp. The number of pump-down cycles initially needed to bring a lamp to a steady "dry" state depends on the lamp size, its plastic(s) and the environmental conditions (see section 2).

Figure 6 illustrates the CMD working principle. We assume an initial amount of 3 g moisture in the headlamp plastics. At 22 °C and 50% rH, the air inside an 11 litre lamp holds ~100 mg of moisture. Further, we assume the first 30-minute pump-down cycle removes 400 mg of moisture trapped in the headlamp air and plastics. After an adsorb phase of 6 hours, the second pump-down cycle will remove slightly less than 400 mg of moisture. Another 6 hours of regeneration are required, after which the third pump-down cycle will remove additional moisture, but slightly less than the previous cycle.

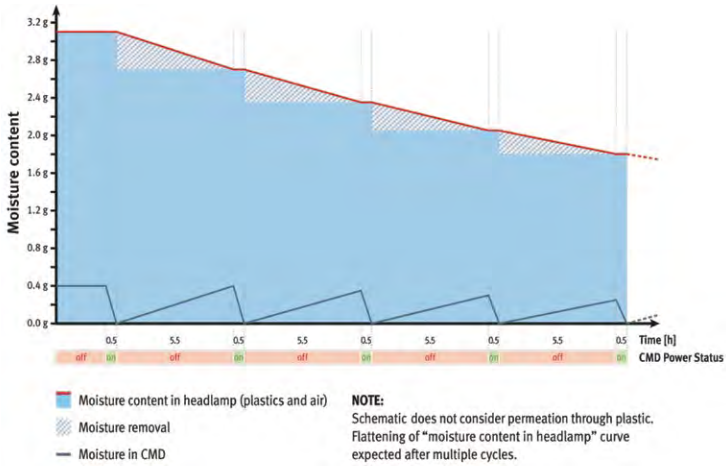

Figure 6: Principle of moisture removal from headlamp by pump-down cycles

This sequence of pumping down and desiccant regeneration will go on until a steady state is reached: i.e., when moisture permeation through the lens and housing into the headlamp is equivalent to the CMD's moisture removal rate per pump cycle.

Figure 7 displays a representative CMD pump-down curve in a headlamp at 30 °C / 70% rH. In this typical curve, the CMD is operated for 30 minutes, in which the desiccant is regenerated; followed by a 5.5 hour adsorb stage.

The small dew point spike at the beginning of each pump down cycle is due to heating of the CMD and heating of the surrounding lamp plastics.

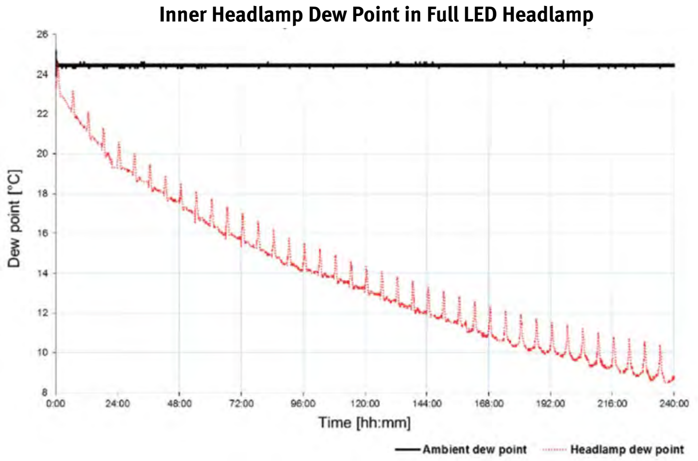

Figure 7: Representative pump-down curve for a CMD-equipped full LED headlamp at 30 °C / 70 % rH (pre-conditioning: 24h at 30 °C / 70% rH)

As shown, the headlamp DP (red) quickly reduces with each cycle, compared to the ambient DP of 24.5 °C (black). The inner headlamp DP curve starts to get flatter towards the end of the pumping cycles, as the difference in moisture concentration (inner headlamp to environment) increases.

This representative curve is characteristic of CMD performance, although individual results will be specific to a given headlamp's type, pre-conditioning, environmental conditions and pumping cycles.

4.5 Initial on-car test results

In laboratory tests, the environmental conditions surrounding the headlamp are usually kept stable. This does not represent the real-life conditions of a car, where environmental factors (wind, sun, rain, temperature, humidity, etc.) and different usage patterns (parking, driving, engine compartment temperatures, etc.) add variations to the external conditions. Those variations significantly affect the climate inside the headlamp, as previously described.

Therefore, on-car tests are an essential factor in verifying laboratory test results.

Figure 8 shows on-car test data for a commercial car (test car #1) equipped with full LED headlights. The passenger-side headlamp retained the vehicle's standard (open-tube) venting system as a reference. The driver-side headlamp was equipped with a CMD. (The open-tube system was removed and this headlamp was sealed.)

The car was operated twice a day (morning and evening) for about 30 minutes at a time. During this time the CMD was operated for thirty minutes. Adsorb was realized while the car was parked. The data plots in Figure 8 show the DP in the reference lamp (blue), the CMD lamp (red) and the environment (black). Both headlamps started at the same humidity and DP level.

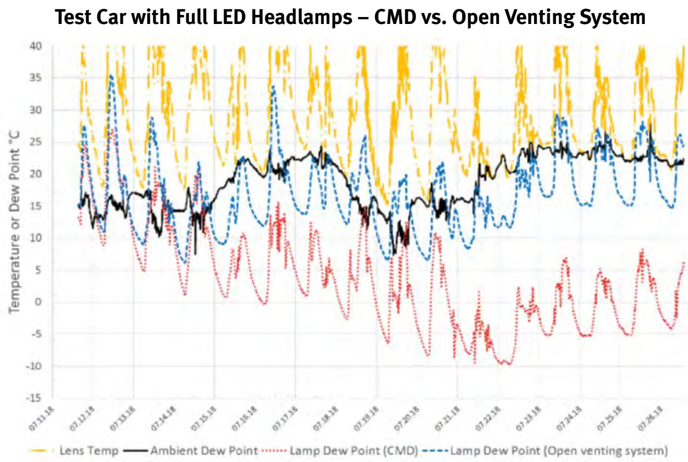

Figure 8: On-car test data (test car #1)

As shown, the DP of the reference headlamp follows the ambient DP. The DP of the CMD-equipped headlamp separates clearly from the reference headlamp after a couple of pump-down cycles.

The plot also shows the lens temperature (yellow). As soon as the lens temperature falls below the headlamp DP (blue), condensation may occur. Therefore the CMD-equipped headlamp provides a higher level of protection against condensation, as its dew point is kept at a significantly lower level compared to the reference headlamp.

Another car (test car #2) was equipped and operated in the same way. To compare the level of protection in the headlamp with CMD versus the reference headlamp with two open tubes, a condensation event was triggered and evaluated. After driving, the engine compartment and the headlamps heated up to ~ 65 °C. Both headlamp lenses were then sprayed with 20 °C water for 5 minutes, to simulate a rain shower or a car wash.

The relevant plot is displayed in Figure 9. The initial DP of the headlamps differs, due to the above-mentioned driving and CMD operation pattern. In both headlamps, the DP increases as rising engine compartment and lamp temperatures cause the plastics to release moisture. The spray event can be identified by the significant drop in the lens temperatures (from 50 °C to 22 °C). Condensation occurs in the reference headlamp when the lens temperature drops below the DP of the reference headlamp. The DP of the CMD-equipped headlamp remains below the lens temperature. No condensation occurs.

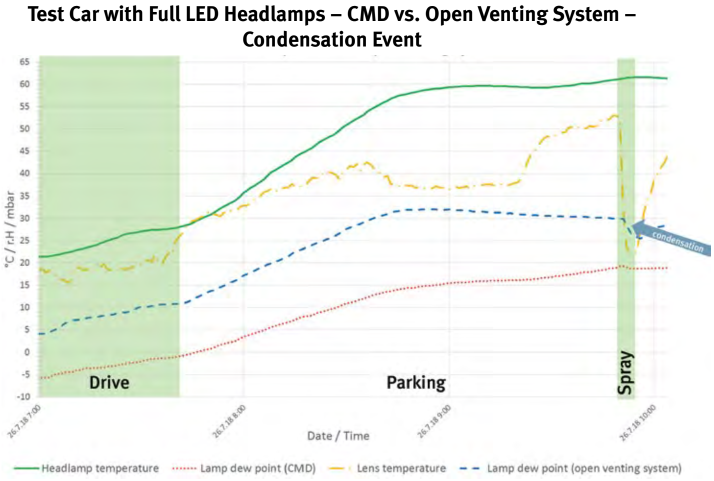

Figure 9: Plot of forced condensation event on test car #2

The condensation prediction from the measured data correlates with the visible condensation that was observed on the lens of the reference headlamp (Figure 10).

Figure 10: Top – Reference headlamp (no CMD) with condensation; Bottom – Headlamp with CMD with no condensation after spray event.

4.6 Water and dust protection

The CMD is equipped with a GORE Membrane that provides headlamp pressure equalization, fine dust and water protection, and high moisture diffusion.

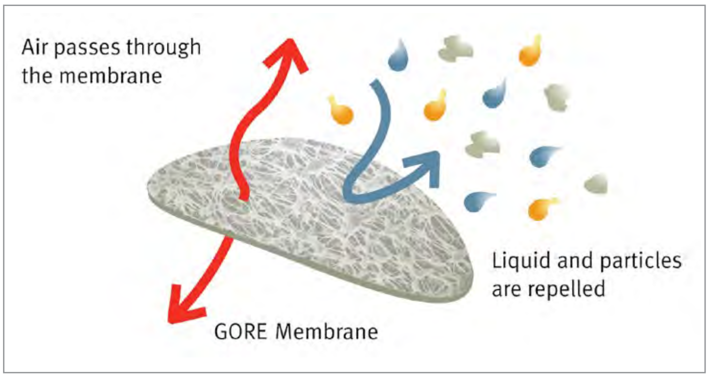

Figure 11: ePTFE GORE Membrane prevents fine dust and water ingress into the headlamp, and enables pressure equalization

4.7 Systemic embeddedness

The CMD's performance cannot be assessed in isolation, as the device is systemically embedded in its environment. A pump-down cycle's effectiveness depends upon the kind and quantity of plastics used in the headlamp, the plastics' permeation rates, the heat generated by the headlamp, the car driving pattern, the CMD control algorithm, fan usage, and – last but not least – upon environmental characteristics like relative humidity and temperature cycles. Extensive simulations and testing have been performed in order to define the most appropriate parameters for efficient CMD operation – whatever the conditions.

4.8 Device storage and operating conditions

The CMD and its components have been designed to withstand a temperature range of -40 °C to +120 °C without any degradation – and without impacting the lighting performance.

CMD offers a high level of protection against condensation in all weather conditions. Tests have been conducted in various ambient conditions to optimize the efficiency even in more severe (warm and humid) climates.

5. Summary

Condensation and fogging, a recurring challenge for the automotive lighting industry, will be even more frequent with the general adoption of full LED headlamps. Unlike currently-used approaches which are not able to sustainably minimize condensation, the CMD actively removes moisture from both headlamp air and plastics.

CMD combines the benefits of both desiccant and membrane solutions, and introduces a unique attribute: it prevents condensation by actively removing moisture from, and lowering the DP inside, a headlamp.

Compared to the current venting and anti-fog technologies on the market, the CMD is a durable, active moisture-removal device that provides a high level of protection against fogging of headlamp lenses. Moreover, it prevents ingress of fine dust, dirt and water while enabling rapid, responsive pressure equalization of the headlamp. The CMD is easy to install, and allows service replacement if required.

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8. Glossary

CMD: Condensation Management Device enabled by GORE Condensation Management Products

DP: Dew point

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