Thermal Management of LED's by Liquid Cooling for Automobile Sectors

M .Maniraj, Department of Mechanical Engineering,
Galgotias University, Yamuna Expressway
Greater Noida, Uttar Pradesh
Email ID: m.maniraj@galgotiasuniversity.edu.in

ABSTRACT: With the developments in GaN-based material technology, high visibility white light emitting diodes (LEDs) have flourished over the past few years and have proven very promising in many new lighting applications such as outdoor lighting, mission and decorative lighting as well as aircraft and automotive lighting. LEDs are semiconductors which use the phenomena of electroluminescence that in general refers to the production of light on the recombining electrons and holes within a material. The challenges of thermal management in the automobile sectors are growing wider for large utilization of high-power LED lighting installations. The objective of this paper is to explore an active liquid cooling solution of such LEDs in an application for automotive headlights. In this work the thermal design was carried out from computer to board to system level. Air cooling and passive liquid cooling approaches were tested and ruled out as unacceptable, and an active liquid cooling solution was therefore selected. Many active liquid cooling system configurations were tested, and optimization research was conducted to find optimum thermal performance.

KEYWORDS: Active cooling, GaN-based material, LEDs, optimum thermal performance, passive liquid cooling, semiconductor

INTRODUCTION

Because of the small package size, versatility in styling and superior performance over incandescent light sources, LEDs are nowadays commonly used in many car outdoors, such as brake lights, turn indicators and tail lights. The use of white LED sources for vehicle forward lighting applications is beginning to be considered with the production of higher-light performance packages. Although many LED properties have made them a very promising light source for vehicle forward lighting, the use of white LEDs as headlamps for automobiles is still in its infancy [1]. LEDs actually appear only in some concept cars as forward lighting, and there are no LEDs designed for headlight applications.

The widespread adoption of LED headlamps in Europe depends on the laws that are enforced in all the requirements. One essential LED headlamp specification is the required luminous flux of 1000 lm per lamp (low beam). LEDs currently offer a cost-effective solution with inadequate lumen output for production vehicles [2]. Nonetheless, given that the average current bright LED output is only 40 lm/W, this standard requires more LEDs and higher driving forces. The widespread adoption of LED headlamps in Europe depends on the laws that are enforced in all the requirements [2]. One essential LED headlamp specification is the required luminous flux of 1000 lm per lamp (low beam).

LEDs currently offer a cost-effective solution with inadequate lumen output for production vehicles. Nonetheless, given that the average current bright LED output is only 40 lm/W, this standard requires more LEDs and higher driving forces. To achieve the correct flux of an LED headlamp, configuration of the optics is required. As the demand for light production grows, the LED's driving power continually increases [3]. For these products, thermal management of LED packaging, which greatly affects their quality, performance and reliability, has become increasingly important. A rise in diode junction temperature results in a decrease in the output of the LEDs and a change in the wavelength of emissions.

The LED operating temperature must therefore be held well below its average operating temperature (e.g. < 125 C) for optimal operating performance and minimal variance in colour. The thermal solution must be all-inclusive and resolve thermal problems at all levels-device, box, board, and system level. Bright LEDs are used in this application which are commercially available bare die (unpackaged chip). To help the search for a suitable thermal management solution, thermal simulations using Computational Fluid Dynamics (CFD) were performed at all stages [4]. The design of the thermal management solution has been supported with the commercial Flo-Therm CFD software which calculates the temperature distribution and the pressure and velocity of the surrounding fluids (air, cooling liquid, etc.).

The small scale and distinct presence of LED lighting helps the automotive industry project engineers to be more innovative about how cars work and look how it works with the headlights that in return helps them to consider alternatives examples of headlamps mixing, not only high beams but low beams, flying signs, fog lights and turn signals, but also corner lights, just like the ones on a new Audi A8.

Each of that versatility comes at a rice, though. Brighter LED systems, more practical, need more power, and get hot really quickly [5]. To successfully incorporate LEDs into their designs, design engineers must contend with both power management and heat dissipation.

ACTIVE LIQUID COOLING

- *From device to board level*

The chosen LED for this application is a Cree XBright900. This LED is a 900x 900 micrometer chip that is commercially available as bare die. This produces light of wavelengths in 2.5 nanometer range bins between 460 and 470 nanometers, which gives blue colour. It can work with sufficient thermal management producing up to 2.7 W of heat per LED. The proposed system here consists of 15 LEDs placed on 5 boards each with 3 LEDs. Consequently the entire *system dissipates 40.5 Watts. The LED's had to be individually packed to ease the mounting* process. In addition, the LED must contain a phosphorous coating to transform the blue light from the Gallium Nitride based LED into a white (visible spectrum) light emitter. The heat is directly dissipated from the device's active region into the packet.

A high thermal conductivity ceramic must therefore be chosen to simultaneously provide a low thermal resistance path and electrical insulation to the package. In this case, aluminum nitride (k = 200 W / mK) was chosen as it suits the function very well in providing high-power operation with thermal conduction and heat distribution [6]. The determined thermal resistance is less than 2 C/W between the LED and the bottom of the Aluminum nitride bag. The box of Aluminum nitride is then placed on an insulated metal substratum (IMS) as illustrated in Figure 1. IMS implementation provides both heat spreading and a good thermal path to the sink or cold plate and significantly simplifies the design of the device. IMS consists of three layers:-a layer of copper film circuitry bonded with a thin dielectric layer and an aluminum metal base plate.

Several various materials that make up the dielectric layer were compared, as there were different combinations of the thickness of the three layers of IMS. The thermal simulations illustrate that the ideal board should have a thick layer of circuitry to disperse the heat while a very thin layer of di-electricity made of a material with higher thermal conductivity to reduce the resistance. Therefore, the thicknesses of these layers are constrained only by the IMS's manufacturability. The chosen 'IMS' structure comprises a copper layer of seventy micrometres, a dielectric layer of 75 micrometers with a thermal conductivity of 2.23 W/mK and a core board of 1 millimeter aluminum as represented in Table 1.

- *Thermal Management in system level-cooling of air*

Application with headlight requires forward light emission. The optical design is based on a transparent mirror and therefore includes mounting of the IMS boards at forty five degrees facing the mirror at the back of the headlight assembly. The heat sink has to be mounted directly behind the IMS board for passive air refrigeration. The entire system is placed inside the headlamp enclosure in the actual application which minimizes heat dissipation through convection to the surrounding environment.

Additionally, the size of the heat sink is limited due to the space constraints inside the headlamp. The figure 2 as illustrated below represents a cross section of the model air-cooled headlight where the temperature of the LED junction (hottest point) well exceeds its maximum allowed value of 125 C. Here, also aggressive air cooling was investigated. Nonetheless, it is not a feasible solution for cooling since the limitations on space and enclosure will require a large number of high flow fans. From a reliability, cost and assembly point of view this is impractical.

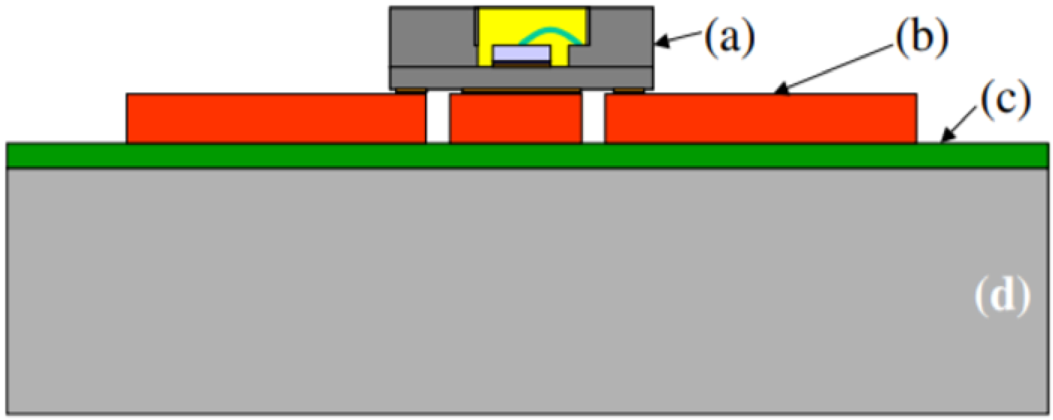

Figure 1:- Insulated assembly of metal substrate. (a) AIN cup with wire bonded LED, (b) circuit layer (c) dielectric layer and (d) aluminum substrate

Layer	Material	Thickness	k(W/mK)
Circuit	Cu	72 micrometer	386.2
Metal Substrate	Al	1.2 millimeter	199.6
Dielectric	Ceramic/polymer	75.6 micrometer	2.23

Table 1:- Board Structure of IMS and materials employed in thermal modelling

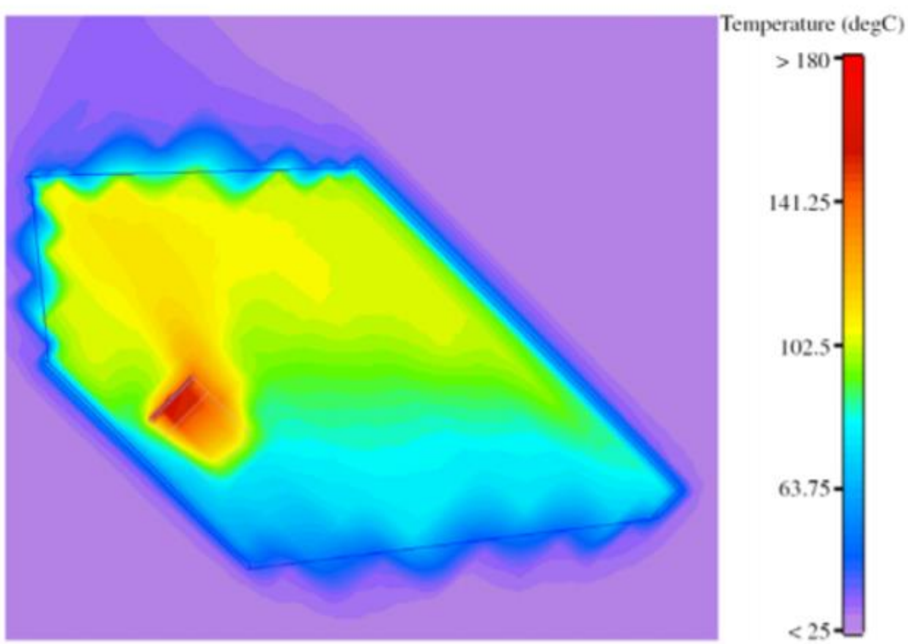

Figure 2:- Profile of temperature variations across the headlight assembly for passive air cooling (Tj= 200 degree Celsius)

- *Submissive liquid cooling*

Two different configurations of passive liquid cooling were explored: passive closed-loop and heat tubing.

The close-loop design is based on indirect cooling (fluid is not in contact with the LED's or any other electrically active components), so any material with good heat transfer properties, such as water, can be used effectively. Thermal simulations have shown that a passive closed-loop can achieve the necessary cooling rates to maintain the temperatures of the LED junction well below their maximum operating temperature. In passive systems, however, the motion of the fluid is achieved through the forces of buoyancy. Such systems also demand that the heat exchanger be mounted above the heat source, so that the hotter and lighter cooling fluid (water) flows upwards against the gravity to be cooled [7]. Nonetheless, although it is feasible from the thermal point of view, it is not an appropriate solution for the cooling of headlamps, since the headlight configuration allows the heat exchanger to be located below the LED modules.

To pass the heat from the IMS boards to the heat exchanger a loop heat pipe device was considered for the heat pipe solution. Nevertheless, since each individual LED board needs to be mechanically flexible for proper light beam alignment in this application, it is therefore important to bend the heat pipe which significantly increases the cost of the cooling solution. The price could be as expensive as $1000 per package, from the commercially available flexible heat pipe items (e.g. Thermotek, Dau). Once, while feasible from a thermal point of view, due to technical and cost considerations the versatile heat pipe device is not an appropriate solution. Hence, in the automotive application, the cooling solution of high brightness LED's transforms into active liquid cooling.

ACTIVE COOLING OF LIQUID

- *Structure regarding the Modified System*

The selected liquid cooling system comprises of a pump, thermally attached cold plates to the heat sources (IMS boards), a liquid reservoir and a heat exchanger also associated with the system. The cold plates are connected to the heat exchanger using flexible silicone hoses which create a closed loop. Seek out a more detailed description of the entire headlight system. Since each board has to be mechanically adjusted individually, a separate cold plate is placed on each surface. Heat should be available near the front lenses in vehicle headlamps to defrost them and keep them from steaming up. The heat exchanger is therefore placed directly behind the front lens, without shadowing the luminous flux. Due to the limitations in weight and volume, and the fact that the high and low beams are never on at the same time, the high beam (HB) and low beam (LB) LEDs will share a single heat-exchanger.

The heat exchanger consists of a liquid-cooled base along with a heat sink. Thanks to its good thermal properties and quality, water with a variety of additives (e.g., antifreeze-glycerol, anti-algae, anti-fungal, etc.) is the most suitable liquid for the cooling solution. Many closed loop architectures were considered. The pump only sees' cold' liquid to reduce damage to the pump and thereby increase its efficiency. First, it explored a solution of five LB-HB circuits in parallel as illustrated in Figure 3.

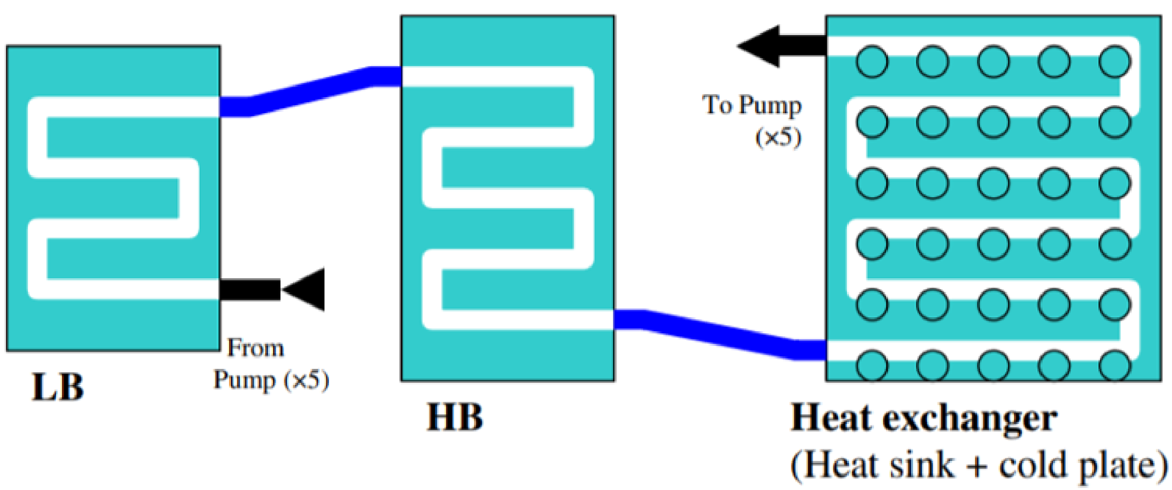

Figure 3:- Cold plates and Heat Exchanger design and their hose connections

While ideal from a thermal point of view (all cold plates cooled at the same temperature and lower pressure head), this solution requires two manifolds plus two separate pipe parts, which makes the system far too complex and therefore not the best option in this situation. A second solution comprises of the same five cold plate circuits as the LB-HB but connected on a single loop in sequence. As the circuit is longer, therefore the decrease in pressure is higher. In addition to this the final cold plate temperature is higher than the first plate. However, CFD calculations show that (a) the temperature differential between the first and last boards is less than 5 C; and (b) the pressure drop in the circuit is far below the pressure head of normal pumps and should have no detrimental impact on the liquid cooling solution's thermal efficiency.

Lastly, since the LB and the HB LEDs are never on (generating heat) at the simultaneous time for which an alternative design is proposed, including a liquid loop through all the cold LB plates is placed in series followed by the HB in series and then the heat exchanger as represented in Figure 4. This version has the advantages of having fewer hoses than the previous one (14 instead of 17), shorter hoses enabling separate mechanical adjustment of both columns, and being easier to install. The thermal simulations demonstrate once again this the temperature of the junction of the last set of three LEDs (the last board in the loop) is less than 5 degree Celsius greater than that of the first set.

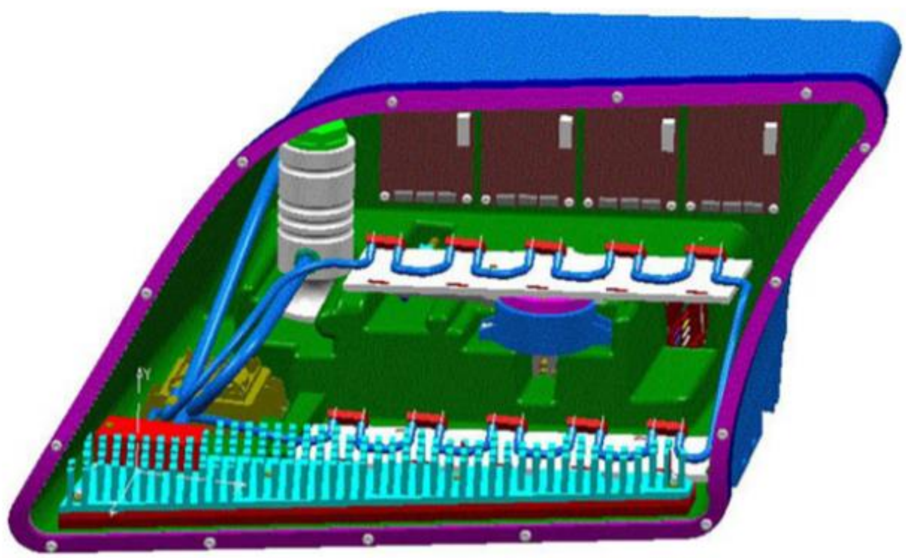

Figure 4:- Active Liquid Cooling configuration- the liquid loop connects all the LB cold plates in series followed by the HB in series and then into the heat exchanger

The system configuration is shown as designed using Flo-therm that is illustrated in Figure 5. The model includes only a set of fifteen LED's (five boards with three LED's each), because at the simultaneous time only one of the beams (either HB or LB) is turned on. In addition, the heat-exchanger (heat sink in conjunction with a cold plate) was designed at an angle of 45 degrees, while it is horizontal in the actual system as already illustrated in Figure 4 to simplify the finite volume mesh.

THERMAL OPTIMIZATION

- *Optimized liquid flow:*

The calculated LED conjunction temperature as the function of a nominal (‘0’ pressure) flow of pump. As the insignificant flow of the pump enhances results in the decrease in the temperature of the LED junction. Figure 7 illustrates the measured ratio of the chosen closed loop circuit between the marginal and real flows. With small marginal flows the pressure drop effect is negligible. However the pressure decrease in the liquid cooling system limits the actual flow as the temperature increases. Figure 8 illustrates the relationship between the loop pressure drop and the loop flow characteristics of a linear pump with a marginal flow of' 0.12' l/s and a nominal loop pressure head (no-flow) of 25 kg. The results show that the pump chosen would work within its recommended range of operation.

➢ *Optimized Heat Exchanger (Heat-Sink):*

The design of the heat sink is based on the outer condition of the heat sink, such as the type of airflow and the operating environment that determines the placement of components and the rate of air flow.

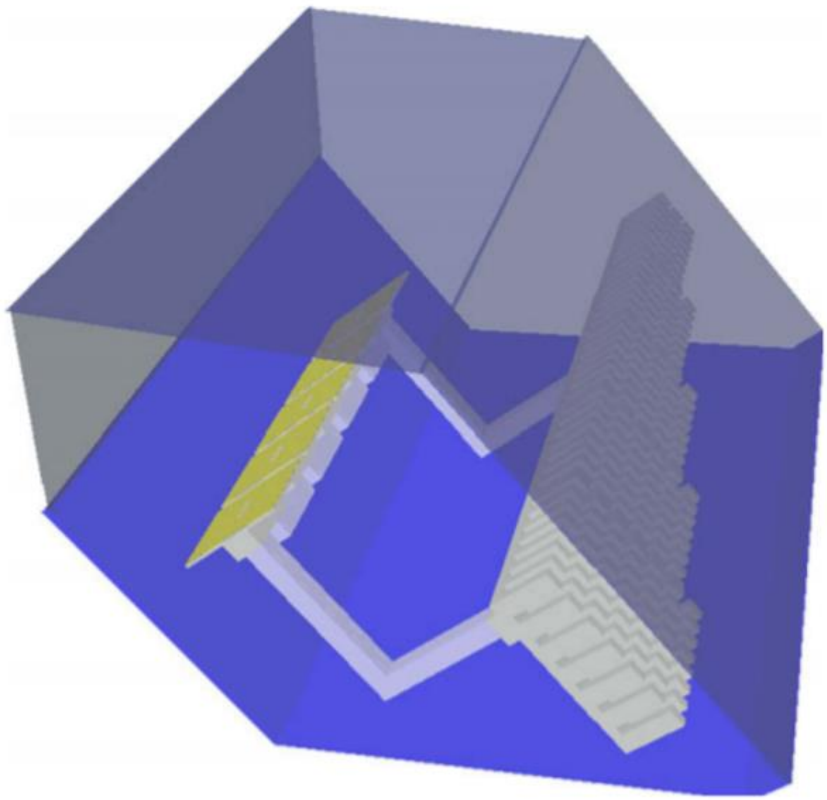

Figure 5:- Full model of active liquid cooling of complete low beam system inside the headlamp enclosure

In this case, since the heat sink is mounted horizontally, there is no preferential direction of flow, and thus a heat sink with pins was preferred to one with fins for order to reduce the total weight. In designing the optimal heat sink, there are a number of parameters to consider, such as pin length, pin numbers, base thickness, etc. Because of the conflicting effects of some of the parameters on the LED temperature, an iterative procedure is used to investigate those parameters.

RESULTS

The optimized headlight was realized and characterized thermally. The headlamp and front lens is put in a thermal chamber thirty degree Celsius ambient temperature. The temperature measurements were initially performed only with the LB in operation, as seen in the simulations. The LED's were driven though their heat dissipation was half of that considered in CFD simulations, with lower forward current. Since the LED heat generation with the electrical parameter selected was considerably lower than originally thought in the simulation, the HB and the LB were worked concurrently to match the heat input to the actual installation.

Inside the enclosure, between the LEDs and the heat exchanger, fourteen thermal test points were placed along the thermal path. The temperature in all fourteen test points inside the enclosure reached stable-state values after approximately two hours. The thermal resistance measured between the different test points along the thermal track is in close alignment with the simulated results. The only difference between heat exchanger and ambient was observed. This was attributable to the fact that the enclosure was recognized as an optimal insulator in the thermal computations while some heat dissipation by conduction occurred in the actual system.

CONCLUSION

This paper shows the process for selecting and optimizing an active liquid cooling system designed for new headlight applications for high brightness LEDs. It was found that air and passive liquid cooling were either inadequate to keep the temperature of the LED junction below its maximum permissible rate or unpractical for the actual application. While some of these solutions would be suitable from a strictly thermal point of view, this is not the case when account is taken of the optical and mechanical designs. Therefore all aspects of headlight design need to be taken into consideration when looking for an appropriate thermal management solution.

Accordingly, under these conditions active liquid cooling is chosen as the optimal cooling method. In this paper we research and compare many different system structures of active liquid cooling. And to optimize thermal performance, thermal optimizations of the liquid flow and heat sink are made. Thermal control is not the only aspect to concentrate on when looking for the optimal thermal solution; all related problems such as manufacturability and product specifications are also taken into consideration. The driving power required for a certain light output will decrease continuously in the future with the development of brighter white LED's. Hence heat dissipation will also decrease. With reduced system power requirements and lower heat dissipation, it is again possible to simplify the cooling solution to just passive air cooling.

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