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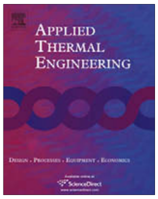

Liquid cooling of bright LEDs for automotive applications

Yan Lai [a], Nicolás Cordero [a,*], Frank Barthel [b], Frank Tebbe [b], Jörg Kuhn [b], Robert Apfelbeck [b], Dagmar Würtenberger [b]

[a] *Tyndall National Institute, Theory, Modelling and Design Centre, Lee Maltings, Prospect Row, Cork, Ireland*
[b] *Odelo GmbH, Alfred-Schefenacker-Strasse 1, D-71409, Schwaikheim, Germany*

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ABSTRACT

With the advances in the technology of materials based on GaN, high brightness white light emitting diodes (LEDs) have flourished over the past few years and have shown to be very promising in many new illumination applications such as outdoor illumination, task and decorative lighting as well as aircraft and automobile illuminations. The objective of this paper is to investigate an active liquid cooling solution of such LEDs in an automotive headlights application. The thermal design from device to board to system level has been carried out in this research. Air cooling and passive liquid cooling methods were investigated and excluded as unsuitable, and therefore an active liquid cooling solution was selected. Several configurations of the active liquid cooling system were studied and optimisation work was carried out to find an optimum thermal performance.

1. Introduction

Due to the small package size, styling flexibility and superior performance over incandescent light sources, LEDs are widely used in many automobile exteriors nowadays, such as brake lights, turn indicators and tail lights. With the development of higher light output packages, the use of white LED sources for vehicle forward lighting applications is beginning to be considered. Although many properties of LEDs have made them a very promising light source for vehicle forward lighting, the use of white LEDs as automobile headlamps is still in its infancy. Currently, LEDs have appeared as forward lighting only in some concept cars, and there are no LEDs customised for headlight applications.

The widespread introduction of LED headlamps in Europe is dependent on legal regulations, which are enacted in all specifications. One important specification of a LED headlamp is the required luminous flux per lamp (low beam) of 1000 lm. At present, LEDs offer a high cost solution with insufficient lumen output for production vehicles. However, since the average current bright LED output is only 40 lm/W, more LEDs and higher driving powers are needed to meet this standard [1]. In order to attain the required flux of an LED headlamp, the optics must be customised. As the demand for light output increases, the driving power of the LED increases continuously. The thermal management of LED packaging, which has great effect on their efficiency, performance and reliability, has become more and more important for these devices.

An increase in diode junction temperature leads to a decrease in the LED efficiency and a shift in the emission wavelength. Therefore, the LED operating temperature must be kept well below its maximum operating temperature (e.g. <125 °C) for optimum efficiency operation and small colour variation. To achieve this, the thermal solution must be all-inclusive and must address thermal issues at all levels – device, package, board and system level. Commercially available bare die (unpackaged chip) bright LEDs are used in this application. Thermal simulations using Computational Fluid Dynamics (CFD) were carried out at all levels to support the search for a suitable thermal management solution. The design of the thermal management solution was supported using the commercial CFD software FloTherm [2] which calculates the temperature distribution and the pressure and velocity for the surrounding fluids (air, cooling liquid, etc.).

2. Choice of active liquid cooling

2.1. From device to board level

The chosen LED for this application is a Cree XBright900. This LED is a 900 × 900 μm chip that is commercially available as bare die [3]. It generates light of wavelengths between 460 and 470 nm in 2.5 nm range bins, which gives the colour of blue. With appropriate thermal management it can operate generating up to 2.7 W of heat per LED. The system proposed here consists of 15 LEDs mounted on 5 boards with 3 LEDs each [4]. Therefore the whole system dissipates 40.5 W.

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[*] Corresponding author. Tel.: +353 21 490 4073; fax: +353 21 427 0271.
E-mail address: nicolas.cordero@tyndall.ie (N. Cordero).

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To simplify the mounting process, the LEDs had to be individually packaged. Furthermore, the LEDs need to incorporate a layer of phosphor to convert the blue light from the GaN based LED to a white (visible spectrum) light emitter. The heat is dissipated directly from the active region of the device to the package. Therefore, a high thermal conductivity ceramic must be chosen to provide the package with a low resistance thermal path and electrical insulation simultaneously. Aluminium nitride ($k = 200$ W/mK), was chosen in this case as it fits the role very well in providing thermal conduction and heat spreading for high power operation. The calculated thermal resistance between the LED and the bottom of the AlN package is less than 2 °C/W [5,6].

The AlN package is then mounted on an insulated metal substrate (IMS) (Fig. 1). Adopting IMS provides both heat spreading and a good thermal path to the heat sink or cold plate and greatly simplifies the system design. IMS consists of three layers: a copper foil circuitry layer bonded together with a thin dielectric layer, and a metal base plate made of aluminium [7].

Several different materials making up the dielectric layer as well as different combinations of the thickness of the three layers of IMS have been compared. The thermal simulations show that the optimum board should have a thick circuitry layer to spread the heat while a very thin dielectric layer made of a material with higher thermal conductivity to reduce the thermal resistance. The thicknesses of these layers are therefore only limited by the manufacturability of the IMS. The chosen structure of IMS includes a 70 μm copper layer, a 75 μm dielectric layer with thermal conductivity of 2.2 W/mK and a 1 mm Al core board (Table 1) [5,6].

2.2. System level thermal management – air cooling

The headlight application requires forward light emission. The optical design is based on a reflective mirror and therefore requires the IMS boards to be mounted at 45° facing the mirror placed at the back of the headlight assembly. For passive air cooling, the heat sink has to be mounted directly behind the IMS board. In the actual application, the whole system is placed inside the headlamp enclosure, which reduces the heat dissipation to the surrounding ambient by convection. Furthermore, due to the space constraints inside the headlamp, the size of the heat sink is limited. Fig. 2 shows a cross section of the modelled air-cooled headlight, where the LED junction temperature (hottest point) far exceeds its maximum permitted value of 125 °C.

Active air cooling was also investigated here. However, it is not a feasible cooling solution since the space and enclosure constraints would necessitate a large number of high flow fans. This is impractical from reliability, cost and assembly viewpoints. Therefore, liquid cooling solutions were chosen for further analysis.

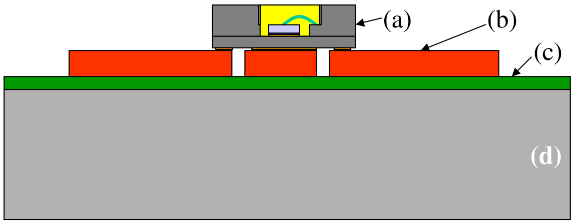

Fig. 1. Insulated metal substrate assembly. (a) AlN cup with wire-bonded LED, (b) circuit layer, (c) dielectric layer and (d) aluminum substrate.

Table 1
IMS board structure and materials used in thermal modelling

Layer	Material	Thickness	k (W/mK)
Circuit	Cu	70 μm	385
Dielectric	Ceramic/polymer	75 μm	2.2
Metal substrate	Al	1 mm	200

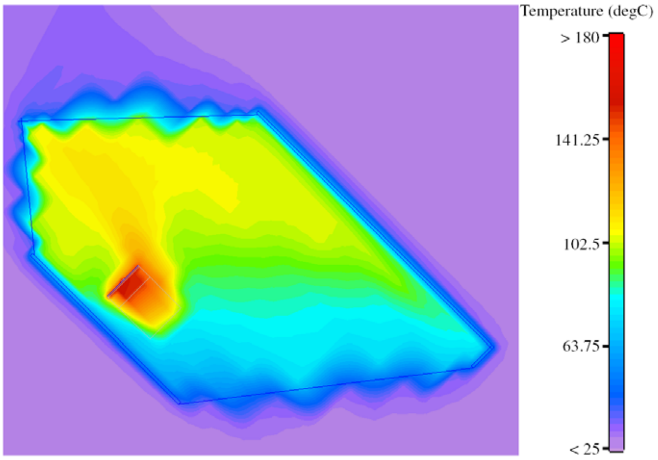

Fig. 2. Temperature profile across the headlight assembly for passive air cooling ($T_j = 200$ °C).

2.3. System level – passive liquid cooling

Two possible passive liquid cooling configurations were investigated: passive closed-loop and heat pipe.

The close-loop configuration is based on indirect cooling (fluid is not in contact with the LEDs or any other electrically active components), and therefore any liquid with good heat transfer properties, such as water, can be used [8]. Thermal simulations showed that a passive closed-loop could achieve the required cooling levels to keep the LED junction temperatures well below their maximum operation temperature. However, in passive systems the motion of the fluid is achieved by buoyancy forces. Therefore, these systems require the heat exchanger to be placed above the heat source, so that the hotter and lighter cooling fluid (water) will travel upwards against gravity to be cooled. However, although feasible from the thermal point of view, it is not a suitable solution for the cooling of headlamps, as the headlight design requires the heat exchanger to be positioned below the LED modules.

For the heat pipe solution, a loop heat pipe system was considered in order to transfer the heat from the IMS boards to the heat exchanger. However, since in this application each individual LED board needs to be mechanically adjustable for proper light beam alignment, the heat pipe is therefore required to be bendable, which significantly increases the cost of the cooling solution. From the commercially available flexible heat pipe products (e.g. Thermotek, [9], Dau [10]), the price could be as expensive as $1000 per unit. Again, although feasible from the thermal point of view, the flexible heat pipe system is not a suitable solution due to engineering and cost considerations.

Therefore, the cooling solution of high brightness LEDs in the automotive application turns to active liquid cooling.

3. Active liquid cooling

3.1. System structure

The chosen liquid cooling system consists of a pump, cold plates thermally connected to the heat sources (IMS boards), a liquid reservoir, and a heat exchanger. The cold plates and the heat exchanger are connected using flexible silicone hoses which create a closed loop. See [11] for a more detailed description of the complete headlight system.