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Cooling of LED headlamp in automotive by heat pipes

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HIGHLIGHTS

- Heat pipe based cooling solutions for LED headlamp.
- Heat pipe heat sink provide 40–50% lighter and 2–3 times higher thermal capability.
- Heat pipe merits are ultra-thin form factor, higher degrees of freedom and higher design tolerance.
- Highly efficient, fully passive and compact cooling modules for next generation headlamps.

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ABSTRACT

Trends in automotive headlamps are changing from halogen/xeon towards light emitting diode (LED) type light functions. LEDs have 2 times higher light efficiency, longer illumination distance, 10–15 times longer lifetime and better styling features than halogen lamps. Unlike halogens, LEDs need temperature control to maintain their monochromaticity, light intensity and longevity. A typical LED headlamp can dissipate 25 to 70 W heat load depending on light functions and styling features. Traditionally, aluminum die cast heat sinks are used as cooling solution for LEDs, which are thermally low efficient and structurally heavy and space intensive. In the present investigation, heat pipe based cooling systems for different designs and styles of LED headlamps and thermal capability of up to 20 W/per-module have been proposed, designed and characterized. Heat pipe configurations include 6–8 mm diameter, 200–400 mm length, copper wick/container and water as working fluid. In combination with different heat sink designs and cooling options, heat pipes can provide 2 to 3 times higher heat capability and up to 50% lighter cooling module, as compared to die cast heat sinks. Based on requirements from headlamp manufacturers, different innovative designs of heat pipes, including high-performance cylindrical/flattened copper-water heat pipe for low/high beam cooling, hinge heat pipe for adaptive headlamp with swivel function cooling and flexible heat pipe for remotely mounted heat sink, has been developed. Heat pipes due to their ultra-high thermal conductivity (~5000 W/m.K or higher) can drastically improve heat dissipation capability of heat sink (natural or fan cooled) and allow different heat sink design options (chassis/frame type, die cast type, stacked-thin-fin type). This allows for better space utilizations inside headlamps, possibility of fully passively cooled headlamps and shared heat sinks between different light functions. LED headlamp with heat pipe thermal modules will tend to be cooler, lightweight and compact.

1. Introduction

Headlamps in automotive have lighting functions for occupants and outsiders, and provide specific styling signature to the vehicle. Lights in Automotive provide two main functions: 'seeing function' (e.g. low beam, high beam, front fog light) and 'to be seen function' (e.g. direction indicators, Daytime Running Light (DRL), position/parking light).

As per definition, headlamp refers to low and high beams, however the trend is moving towards incorporating most light functions into headlamps, which provide modular, space-conservative and cheaper design. Headlamps, like wheels and body, provide opportunity to makers to display unique styles and brand signatures. Today, it is easy to identify vehicle maker and even model from its headlamp design and shape.

Headlamps can be classified into four main categories, based on light source (or lamp) type: Halogen, Xeon, Light Emitting Diode (LED) and Laser. Halogen lamp constitute glass housing with tungsten filament in nitrogen/argon gas, Xeon lamp has quartz housing with

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Nomenclature

R	thermal resistance (°C/W)

Subscripts

t	total
i	interface
sp	spreading
tr	transfer
hs	heat sink

tungsten electrode with metal halide mix and Xeon gas, LED lamp has glass window with Gallium Nitride (GaN) semiconductor and laser light is emitted by phosphorous gas heated by laser source. Halogen and Xeon are cheaper but with shorter lifetime and low efficiency. LED [1] has longer lifetime (10–15 times), higher efficiency, longer illumination length (300 m) but expensive than halogen/xeon. Laser lamps have been recently applied in headlamp and provide most superior lighting characteristics, however their high cost have limited them to specific carlines and makers. LED lamps provide best combination of performance, technology, design options and cost. Fig. 1 compares heat load output by different lamp types, which provides direct indication of lamp light efficiency.

Headlamps are often provided by mix of lamps types e.g. Xeon combined with LED. This helps to provide mix of performance and cost to overall headlamp.

Halogen and Xeon headlamp uses tungsten as light source which can withstand high operating temperature without need of any cooling. However, LEDs and laser uses semiconductor, for light generation, that need temperature control, to maintain their reliability, monochromaticity (light colour) and light intensity. An LED headlamp can dissipate anywhere between 25 and 70 W of total heat load depending on light functions and styling features (carline grade). Fig. 2 compares the heat dissipation versus device size for different electronic and electrical systems in automotive.

Heat output by LED headlamp is higher than other LED and processing devices in car but lower than high power electronic/electrical equipment. Here, device characteristic length represents dimension of device which can provide estimate on its size scale. From cooling solution point of view, characteristics length also represents maximum distance for heat transfer for dissipation inside device enclosure or minimum distance up to which heat have to be transported for remote dissipation outside device enclosure. As evident from Fig. 2, headlamp is classified as one of the bulky electronic system in automotive.

Headlamps have close enclosure (not air tight) therefore output heat is required to be dissipated inside the casing. Thermal management of LED headlamp is challenging owing to its inherent location (in front of hot engine room and side of radiator), covered frontal area (no possibility of enclosure air exchange for cooling of internal electronic) and trends towards headlamp size compaction (to conserve space for other frontal features).

LEDs have high power efficiency and provide diverse lighting systems in automotive that includes low/high beams, turn indicators, daytime running lights, cornering lights, weather/fog lights, front display panel, head-up display (HUD), back or rear lights and other interior lights. LED based lighting system for automotive is gaining significant attention due to their technical competency and design freedom. Due to its compact size and high heat output, thermal management of the LED systems is one of the main issues.

Fig. 3 shows the 5 LED chip package for headlamp application [2]. LED chips are made from thin GaN which are soldered to the substrate provided with the backside aluminum heat spreader.

Each chip measures 1 × 1 mm^2 and can produce 2.45 W of heat load which accounts to very high heat flux of 245 W/cm^2. LEDs need efficient cooling system which should be able to maintain their junction temperature below 125 °C. Depending on the intended function, LED package can have single chip (low beam, DRL) or multiple chips (high beam, weather light, cornering light). Accordingly, heat output from the package will vary depending on number of chips. Number of LED packages is combined to provide low beam, high beam and other light functions. Placement of these LEDs in headlamp helps to attribute specific styling to headlamps. Typical thermal resistance from junction to package base for such module is 2.65 K/W. Light emitted by the chips is magnified by the reflector for lighting purpose. The top of the chips need access to the optical system therefore cooling is only possible from the backside. Most common cooling system involves die cast aluminum heat sink which is attached to the back side of the LED module and dissipate heat by natural convection or forced cooling using fan. Die cast heat sink are heavy due to their metallic body, and need to be large size due to their high spreading resistance from LEDs to heat sink body.

In this paper, thermal design, technical requirements, advantages and system options for heat pipe based cooling system [3–8] for LED headlamp has been investigated in detail. Current cooling systems for LED headlamp has been outlined and compared to heat pipe based system. Different components of thermal module (namely heat pipe element, heat sink, heat dissipation mechanism) and their possible design options have been discussed. Overall, the paper will provide niche of heat pipe system in headlamps, in particular, and automotive electronics, in general.

2. LED headlamp

Cooling of LED is a necessity owing to their temperature specific performance and reliability.

2.1. Cooling requirements

For an LED, optimum operating temperature range is −40 to 125 °C with maximum allowable junction temperature of 150 °C [9]. In short time applications (100 hr), junction temperature can be maximum 175 °C. At elevated temperature, there are both performance degradation (light color change, flickering light, dimming of light) and structural degradations (package discoloration, wiring melt, chip damage).

2.2. Headlamp thermal control

Headlamp is provided with two type of thermal control: hardware based (heat sink module) and software based (current de-rating). Mostly, LED packages in headlamp have dedicated heat sinks owing to spatial placement of LEDs, distance between lights, package functionalities or light type and package mobility needs (swivel or spin function). Heat sink module is designed to maintain LED package temperature below 125 °C for high ambient temperatures of 40 °C (due to proximity of engine room).

At adverse operating conditions, including high ambient temperatures and full-functions on, the heat sink cooling capacity could be

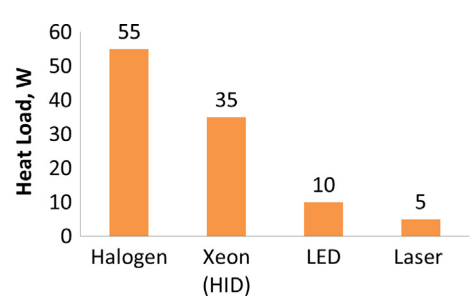

Fig. 1. Heat load output by different lamp types.

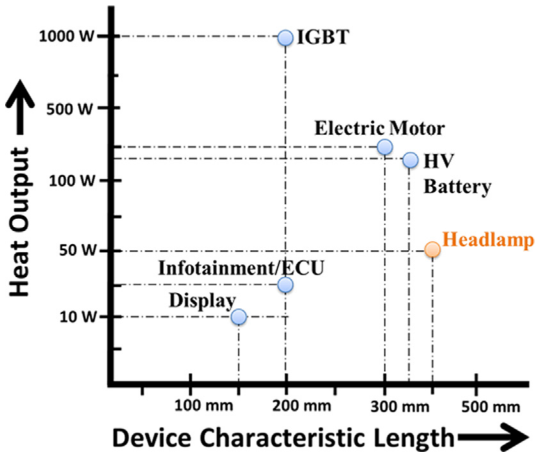

Fig. 2. Heat output versus device length for different automotive electronic/electric systems.

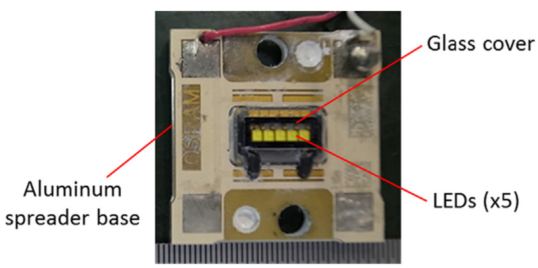

Fig. 3. LED package for automotive headlamp.

insufficient. In such circumstances, current de-rating is activated to keep LED temperature within permissible range. Current de-rating refers to software based reduction in input current to LEDs to control their temperature. Software takes its feedback from a thermistor installed on the LED package. Extent and rate of de-rating depends on rate of change of temperatures of LED package. Typical, LED operating at 3.15 V with 1 A max current will start de-rating current as package temperature approaches 125 °C. Current de-rating is limited to 15 to 20% of max value, due to safety aspect related to reduction in visibility with LED current reduction. Headlamp manufacturer try to avoid or minimize current de-rating as much as possible by oversizing heat sink. Here, oversize heat sink will have additional weight penalty. Therefore efficient heat sink is a requirement in headlamps.

2.3. Headlamp cooling module

Fig. 4 shows schematic of typical thermal module for LED package cooling. LED package constitutes of LED mounted on ceramic substrate that is attached to aluminum base, which behaves as local heat spreader for LED source. This LED package is installed on one side of metal base with natural or forced convection cooled fins on other side of metal base. It should be noted that package is not shown installed directly on top of heat sink because in most cases there is not enough space available in the vicinity of package to mount heat sink directly on top of it. Heat spreader and sink is generally made from aluminum die cast due to its acceptable thermal conductivity, lightweight and cheaper cost.

Waste heat release by LED package is first spread on heat spreader base, then transferred to heat sink base, followed by dissipation from sink fins to ambient via natural convection, in most cases, or forced convection, in very specific high-end headlamps. Total thermal resistance (R_t) for heat flow from LED package to ambient, as shown by thermal resistance diagram at the bottom of Fig. 4, can be expressed by:

$$R_t = R_i + R_{sp} + R_{tr} + R_{hs} \quad (1)$$

where, R_i is interface resistance between LED package and metal sink base, R_{sp} is conduction spreading resistance inside metal base, R_{tr} is heat transfer resistance due to conduction along heat spreader base and R_{hs} is heat sink resistance for heat dissipation from metal sink base to ambient. For temperature limits of 125 °C on LED package side, and 40 °C on ambient side, a single LED package with heat load of 2.45 W will have total available thermal resistance of 34.7 °C/W.

Interface resistance (R_i) depends on the quality of contact and thermal conductivity of thermal gap filler (normally limited to 1 W/m.K). Heat spreading (R_{sp}) and heat transfer resistance (R_{ts}) depends on the thermal conductivity of the thermal module (90 W/m.K for typical aluminum die cast: ADC12). In case of heat sink resistance (R_{hs}), mechanical properties (thermal conductivity), geometrical properties (fin thickness, fin gap, fin height) and heat removal conditions from heat sink (natural or forced convection) are important. Aluminum die cast material has limited thermal conductivity and casting process allows limited control over geometrical properties of heat sink (e.g. fin thickness and fin gap cannot be easily reduce below 5 mm). As a result of these limitations, die cast heat sink have to be made thick (to reduce their spreading/transfer resistance) and need fan to improve heat dissipation from heat sink. Die cast fins have limited natural convection heat removal due to lower surface area to volume ratio. In this regard, heat pipe heat sink, with ultra-high thermal conductivity of heat pipes (> 5000 W/m.K), and superior conductivity (~210 W/m.K) and geometrical properties of stacked fins, can offer to reduce heat transfer and heat spreading resistances dramatically thereby improving performance to weight ratio of heat sink.

Heat sink dissipates heat from LED packages to the inside ambient of the headlamp enclosure from where heat is transferred to outside ambient via enclosure wall. This is possible due to larger surface area of headlamp casing. Locating heat sink outside headlamp is generally difficult due to assembling issues and severe engine room ambient.

3. Test method

Different cooling solution design options, investigated in this research work, were characterized based on their steady state thermal performance (i.e. operating temperature and thermal resistance). Temperatures (specific and average) were measured using T-type thermocouples with accuracy of +/- 0.1 °C. Output from thermocouples was read and recorded using Agilent datalogger (HP34970A). Heat load was provided to thermal simulators using power meter with current and voltage accuracy of +/−0.01 A or V respectively. Thermal grease with heat conductivity of 1 W/m.K was used at dry interfaces to

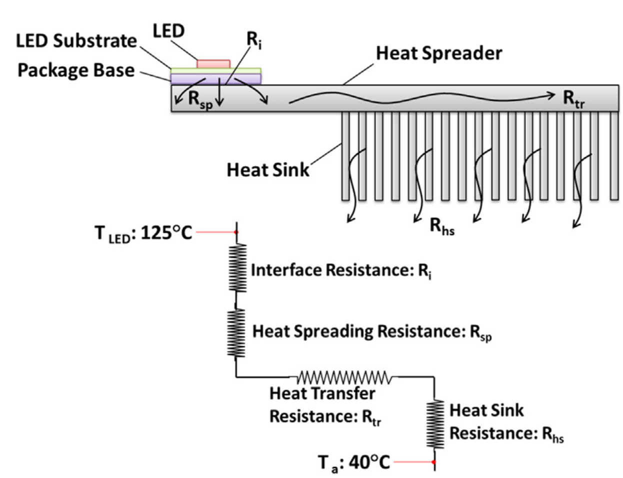

Fig. 4. Schematic of LED package with thermal module (top), and system thermal resistance network (bottom).

facilitate in heat flow.

4. Heat pipe based cooling for headlamp

Thermal module for headlamp should be thermally efficient (high performance to weight ratio) and structurally lighter and robust (to withstand severe vibrations and shock in automotive operating environment).

4.1. Benefits

Heat pipe module provides number of advantages related to design and performance. Thermal conductivity of heat pipes is significantly higher (50 to 100 times) than die cast material, as a result they can provide highly efficient thermal transfer link between LEDs and heat sink. In addition to this, heat pipe help to spread heat over heat sink fins, thereby improving fin-stack efficiency.

In electronics, mostly, it is not possible (due to space issues) or recommended (to control ambient temperatures) to dissipate heat around the area where it is produced. Similarly, in headlamps, space is available towards the back of enclosure rather than near LED where wiring and holding mechanism is installed. In this case, heat pipes offer an efficient heat transfer device and help to use available space inside headlamp for heat sink installation. Positively, the space utilization character of heat pipe helps to provide fully passive cooling solutions for headlamp. Die cast heat sink are more of local coolers and needs fan for heat dissipation, if LED package heat load is high (e.g. high beams). Reliability of fan in headlamp is serious issue due to rigorous working environment. Generally, headlamp is sealed plastic enclosure. Fan cooled headlamps should be easy to dismantling to replace damaged/faulty fan which increases headlamp assembly cost significantly. In this context, heat pipe heat sink provides reliable and passive thermal solution for headlamps.

With die cast solution, each LED package need to have dedicated heat sink which increases the number of parts and thus cost of the headlamp. Heat pipes provide an innovative design approach for headlamp by combining heat sink for certain light functions. For example, there can be a common heat sink for high beam and weather light as either one of them would be used at a time. This will help to reduce heat sink quantity as well as material, which will compliment weight reduction attribute of heat pipe heat sink. With die cast heat sink, this is not possible due to longer distances between different lights.

With heat pipes, it is possible to use die cast heat sink or stacked fins. Stacked fins can be made from high conductive aluminum sheet (~210 W/m.K) that helps to further improve heat sink performance. Also, stacked fins have more design flexibility than die cast stack, thus providing customized high performance heat sinks.

Stacked fins provide heat transfer area 2 to 3 times higher than die cast heat sink. As for efficiency, stamped fins can be 3 to 5% better than die cast fins. There is limited increase in efficiency with stacked fins as die cast fins are very thick (~5 to 7 mm) therefore their efficiency is good. Combined effect of fin area and efficiency increase provides efficient heat dissipation characteristics to stacked fins. Thermal module using heat pipe and stacked fins can be 40 to 50% lighter than die cast heat sink for similar cooling requirements. Weight advantage of heat pipe solution comes from low material quantity in hollow heat pipes and thin stacked fins.

Heat pipe heat sinks are generally more expensive than die cast heat sink, however, at system level, the combined effect of reduction in parts, less material quantity, no fan assembly and efficient heat sink (that provide LED lifetime longevity) tend to offset the added cost.

4.2. Design options

Heat pipe based thermal module consists of heat pipe, heat sink and optional fan, depending on thermal requirements. There are different design options for heat pipe and heat sink, depending on thermal and structural requirements.

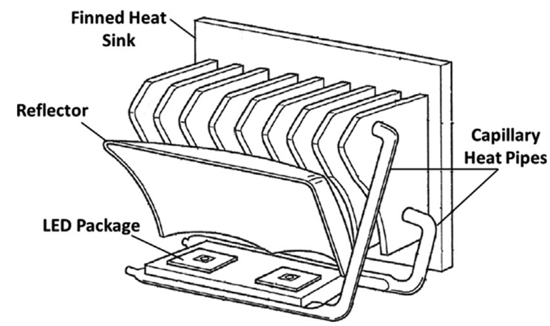

Fig. 5a. Cooling module design for automotive headlamp.

4.2.1. Heat pipe design

Capillary heat pipe is the most viable heat pipe type which can be used in cylindrical and/or flattened form for heat transfer and heat spreading function inside headlamp. The characteristic length scale, as outlined in Fig. 2, provides an important indication on maximum possible lengths of heat pipe required in each device. For headlamp thermal control, length of heat pipe between 200 and 400 mm can be required, depending on headlamp size and available space. Fig. 5(a) shows typical design of heat pipe heat sink for cooling high beam inside headlamp. In Fig. 5(b) actual prototype for high beam with heat pipe heat sink that was fabricated and tested inside headlamp is displayed. Heat pipe is made from copper with copper powder wick and water as working fluid. Two capillary heat pipes, 6 mm outer diameter, transfer approximately 20 W of heat from two LED packages to finned heat sink from where heat is dissipated inside headlamp ambient, with 40 °C air, using natural convection [10]. Heat sink consists of 12 Aluminum fins, each with approx. area of 81 × 31 mm^2 and 0.5 mm thick. It should be noted additional cooling area is provided by holding frame structure of headlamp. Heat pipes were solder attached to the nickel plated Al die cast frame and stacked fins. Total thermal resistance available from LED junction to ambient was 7 °C/W.

In Fig. 6, heat pipe heat sink is shown installed inside the headlamp. Two LED packages were mounted on the spreader plate with two embedded heat pipes (Fig. 5(b))

Fig. 7 shows test results on actual headlamp using heat pipe cooling with one LED and two LED turned ON. It is evident that heat pipe system is able to maintain LED package temperature below 80 °C for 25 °C ambient. This translates to overall thermal resistance from LED

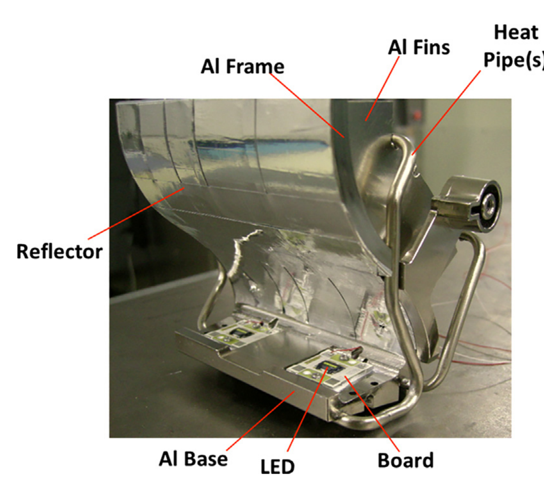

Fig. 5b. Heat pipe heat sink for cooling high beam LED package inside headlamp.

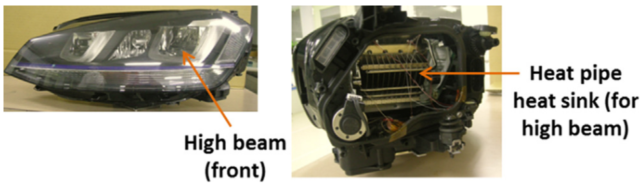

Fig. 6. Heat pipe heat sink for headlamp high beam cooling.

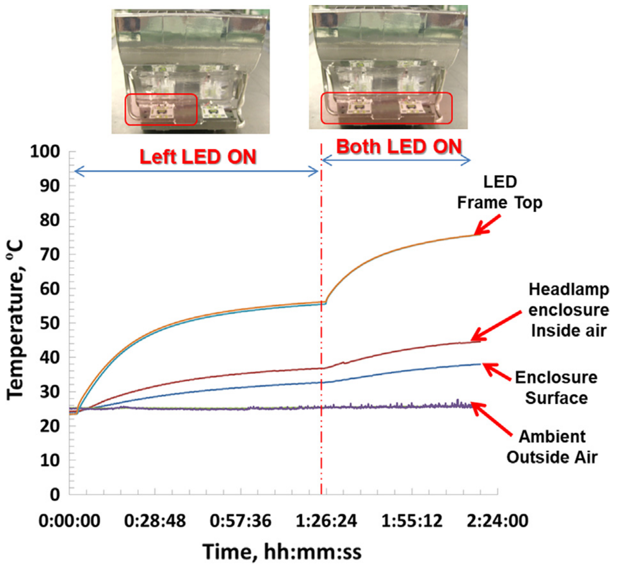

Fig. 7. Thermal test on LED headlamp with heat pipe based cooling of high beam.

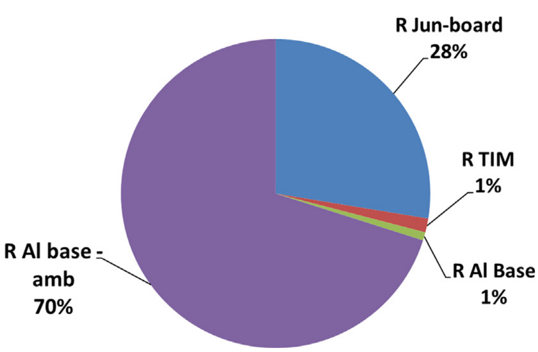

Fig. 8. Breakdown thermal resistance for different components from LED junction to ambient air.

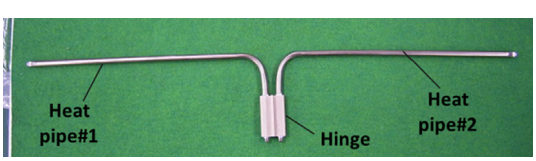

Fig. 9. Hinge heat pipe assembly.

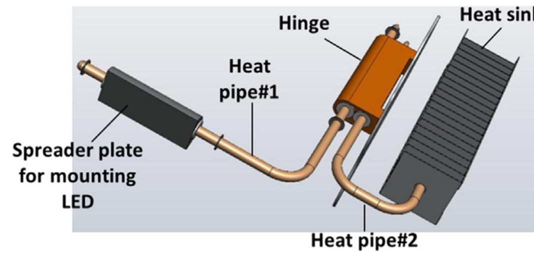

Fig. 10. Hinge heat pipe assembly for cooling LED package with swivel function.

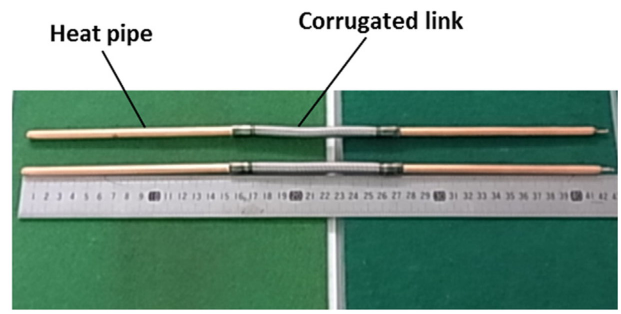

Fig. 11. Flexible heat pipe.

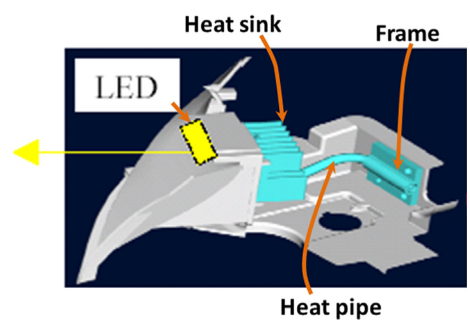

Fig. 12. Heat pipe assembly with frame as heat sink.

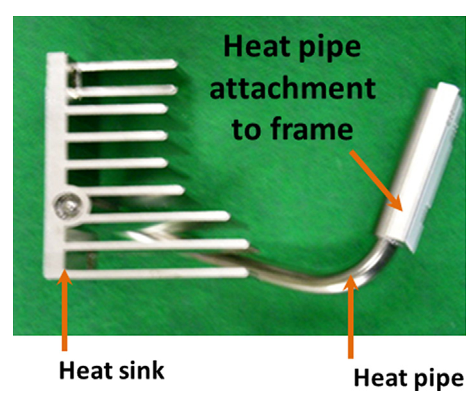

Fig. 13. Heat pipe assembly for cooling fog light LED package in headlamp.

junction to ambient ~ 6.89 °C/W, which is less than maximum permissible resistance value of 7 °C/W.

Fig. 8 presents the breakdown thermal resistance for different elements as identified by resistance type and per Fig. 5(b) locations, where thermocouples were installed for active measurements. Most dominating thermal resistance is from Al base to ambient due to natural convection heat dissipation from frame to outside ambient air. As evident from Fig. 7, almost 20 °C temperature difference exists between air inside and outside of headlamp due to limitation of heat flow via natural convection through plastic headlamp wall. Here, heat pipes with thin snap fins will mainly contributing to reduce thermal resistance from Al base to inside headlamp ambient. In the current investigation, primary target is weight reduction of heat sink, therefore heat pipe heat sink is designed to provide similar thermal performance as die cast heat sink (i.e. R total $<$ 7 °C/W limit).

It should be noted that for original design of die cast heat sink, such resistance values was achievable with heat sink weight two times of heat pipe heat sink, and with active cooling option using fan. For

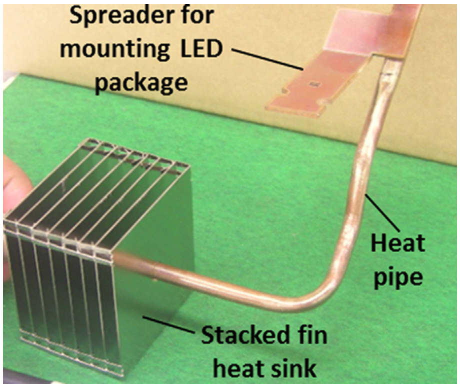

Fig. 14. Heat pipe heat sink for low beam LED package cooling.

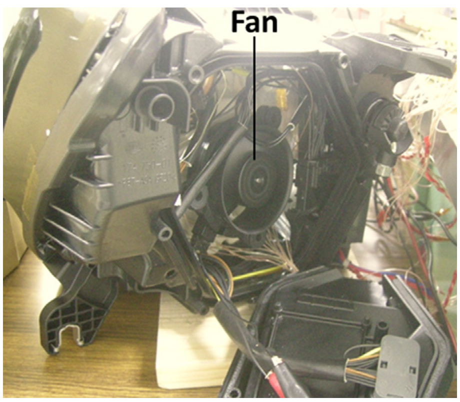

Fig. 15. Axial fan installed inside headlamp for forced convection cooling.

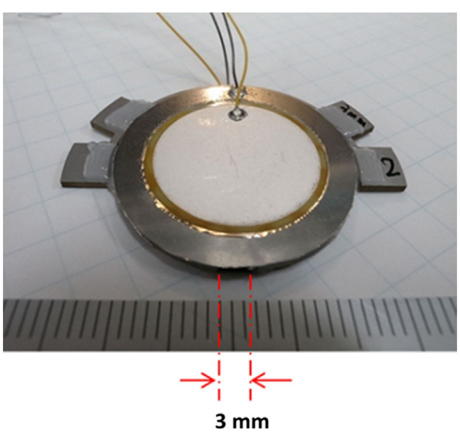

Fig 16. Round type Piezo fan.

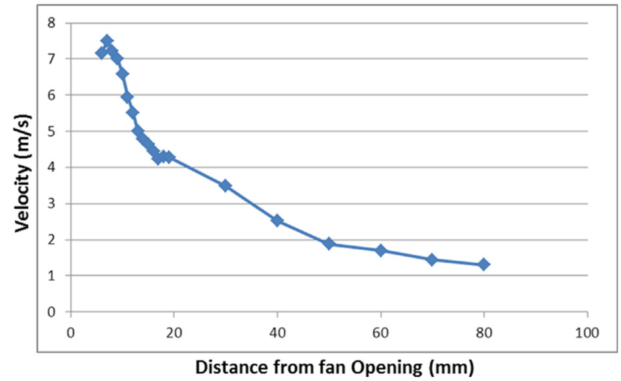

Fig 17. Velocity profile of round piezo fan.

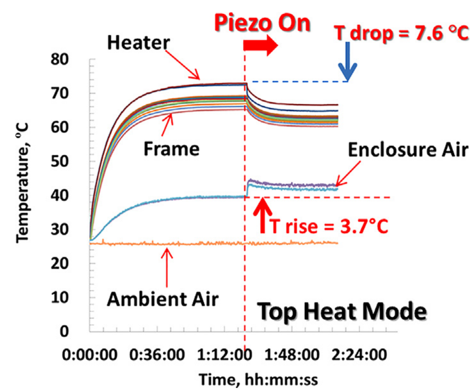

Fig 18. Cooling enhancement for LED headlamp using piezo fan.

adverse operating conditions (40 °C ambient, all light functions ON), heat pipe thermal module was able to maintain LEDs temperature below 110 °C which is well below maximum permissible limit of 125 °C. As stated earlier, heat pipe heat sink was ~50% lighter than die cast heat sink for similar thermal capacity.

In adaptive headlamps, low and high beams have swivel or rotate function that require either direct back mounting of heat sinks or flexible link between LED package and heat sink. For high power LED packages, back mounting is not possible due to weight issues. In order to address this problem, hinge heat pipe assembly, as shown in Fig. 9, was developed.

Hinge heat pipe consists of two heat pipe which are connected by copper hinge. Here, hinge provided the thermal link between two heat pipes and single degree of freedom to move/rotate. To increase degree of freedom further, additional hinge with either or both heat pipes can be added. Based on experiments, it was determined that hinge resistance was approximately 1 °C/W, which was acceptable based on available thermal resistance from LED package to ambient air inside headlamp. Fig. 10 presents heat pipe heat sink with thermal hinge for cooling LED with swivel function.

In compact headlamps, there is limited space inside the headlamp to install heat sink for all light functions. In that case, heat sink can be mounted externally on the wall of the headlamp. Due to assembling tolerances and light beam setting requirements, thermal link (i.e. heat pipe) between the LED package and wall mounted heat sink need to have certain level of flexibility. Such requirements can also exist for compact headlamp where space is not available near LED package for installing heat sink. Fig. 11 shows flexible heat pipe which was developed to thermally connect LED with remotely mounted heat sink. Flexible heat pipe consists of bendable corrugated metal link hydraulically connected by normal heat pipe on both sides. The corrugated link can be made from copper or steel depending on compatibility with heat pipe working fluid. For flexible heat pipe, wire wick with spring retainer to hold wick to the inner circumference of container was used. It should be noted that flexibility in such heat pipes is achieved at the expense of thermal performance which can degrade by 2 to 3 times, as compared to rigid capillary heat pipe, made from similar container and working fluid combination. Such differences in thermal performance can results from different reasons including loose contact between wick and container wall, displacement or clustering of wick during heat pipe movement and high non-uniformity of loose wire wick.

4.2.2. Heat sink design

Heat pipe heat sink for headlamp can have different types of sink designs and cooling options. Design possibility for heat sink includes headlamp body/chassis as heat sink, die cast or extrusion heat sink, and stacked/stamped fins as heat sink. Cooling options include natural convection cooled or fan cooled heat sink. It should be noted that such design options as chassis heat sink are only possible with heat pipes.

Fig. 12 shows heat pipe assembly using headlamp frame as heat sink. There are two heat sink arrangements including extrusion heat sink which is mounted at backside of LED and frame heat sink with heat pipe as thermal link from LED to frame.

In Fig. 13, actual sample is presented that consists of aluminum heat sink and copper-water heat pipe as remote heat transfer device. Here, heat was dissipated from heat sinks to 40 °C ambient using natural convection. The assembly was able to dissipated 15 W heat output by LED package and maintained LED temperature below 90 °C.

Fig. 14 shows an example of heat pipe module with high conductive stacked thin-fin heat sink for low beam LED cooling in headlamp. Heat pipe heat sink, with 6 mm diameter copper-water heat pipe, was able to dissipate 10 W heat from LED package using natural convection to 40 °C ambient. Thermal module was able to maintain LED package temperature below 80 °C.

In high-end headlamps like matrix LED headlamp, natural convection is not sufficient to dissipate output heat from the heat sink. In such cases, forced cooling using electric fan is inevitable. For forced convection cooling, centrifugal or axial fan similar to electronics cooling can be used. Fig. 15 shows the axial fan installed inside the headlamp for cooling heat sink by forced convection. Such a fan can enhance heat transfer coefficient inside headlamp to as high as 35 $W/m^2.K$ which is almost 7 times higher than heat transfer coefficient for natural convection (5 $W/m^2.K$). However, as discussed before, there are long term reliability issues with fan and lack of available space for the installation of fan inside headlamp.

Forced convection using piezo fan with very thin form factor can address integration issues incurred by normal large size fans. Fig. 16 shows the impingement type round piezo fan [11–12] with 26 mm blade (or disk) diameter, 19.7 mm piezo disk diameter, fan thickness of 2 mm and flow aperture of 3 mm.

Fig. 17 presents the outlet air velocity plot of piezo fan as function of distance from flow aperture. It is noted from graph that at 10 mm distance from aperture, flow velocity as high as 7.5 m/s is possible. As the distance from aperture increase to 80 mm, flow velocity trails off to 1.5 m/s.

Two round piezo fans were installed inside LED headlamp with heat pipe heat sink for high beam cooling, as shown in Fig. 6. High beam with two LED packages have total heat load of 20 W. Piezo fan provided two functions: directly impinging high velocity air over the LED package and move the air inside the headlamp thereby increase heat transfer coefficient from heat pipe heat sink to inside ambient.

Fig. 18 presents the realtime temperature profile obtained during the test. It is evident from the temperature graph that piezo fan manifest thermal improvements in two different ways (1) direct impingement of the LED package that reduces the source temperature by 7.6 °C (31% improvement as compared to natural convection case) and (2) increase in the heat transfer coefficient inside the headlamp enclosure that increase the inside air temperature by 3.7 °C (48% improvement in heat removal from heat sink due to enhancement in the internal air heat transfer coefficient).

Using piezo fan, heat transfer coefficient inside headlamp enclosure increases from 5 $W/m^2.K$ (natural convection) to 15 $W/m^2.K$ (3 times improvement). Here, increase in the enclosure air heat transfer coefficient will facilitate heat removal from heat sink inside headlamp as well as heat dissipation from enclosure air to the outside ambient air. These enhancements by piezo fan helped to increase the heat dissipation capacity of heat sink. Alternatively, this can reduce the mass of the heat sink for the same cooling rate, which is very contributing for the automotive applications.

It should be noted that heat sink design and cooling options, as discussed above, is better realized with heat pipes, due to their high thermal conductivity that improve the heat spreading and heat removal from heat sink stack, and their remote heat transfer feature which is not possible with traditional heat sinks. It is evident from the assortment of design options possible with heat pipes and heat sink arrangements that heat pipe heat sink system can provide innovative and high performance cooling systems for LED headlamp cooling.

5. Conclusions

Heat pipe based cooling solutions for LED headlamp has been proposed, designed and characterized. As compared to die cast heat sink, heat pipe thermal modules are 40–50% lighter and have 2–3 times higher heat removal capability. High thermal conductivity, design flexibility and technological development in heat pipes will qualify them as most potential candidate for cooling of new headlamp types like adaptive and matrix headlamps. Heat pipes can be made ultra-thin and flat, flexible with required degrees of freedom and with higher design tolerances. This allows efficient combinations of heat pipes with different types of heat sink designs and cooling arrangements. With these design attributes, heat pipes will be able to provide highly efficient, fully passive and compact cooling modules for high-end headlamps with complicated styling features.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.applthermaleng.2019.114733.

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