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Analysis of Factors Influencing on Heat Transfer Characteristics of Automobile LED Headlamp

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Abstract

Light Emitting Diodes (LEDs) are being considered for use in the automobile headlamps for front side illumination in the place of halogen and xenon headlamp systems. Although LEDs provide larger service life and better power efficiency, they generate considerable amount of heat. It is desirable to develop an advanced cooling system to effectively dissipate heat generated for a stable, continuous and reliable LED operation. The objective of this investigation is to experimentally study the factors influencing the cooling performance of the air cooled heat sink model used in an automobile LED headlamp system. The cooling performance of the heat sink model under consideration was assessed by measuring temperature and thermal resistance at significant locations. The input power, fan output and ambient temperature were varied and corresponding effects were observed. The effect of power variation on illuminance was observed. In addition, a comparative study was carried out to determine the effects of forced and natural convection, which indicated the necessity of forced convection for effective cooling of an automobile LED system.

Keywords: *Cooling performance, LED, automobile, headlamp*

1. Introduction

An automobile headlamp is a safety device attached to a frontal area of an automobile to provide sufficient illumination during night or insufficient lighting conditions. Xenon and halogen headlamp systems are predominantly used for forward lighting applications in an automobile. Although LEDs were developed about 40 years ago, significant uses for various lighting applications were observed only in last 10-15 years. Current lighting technologies are apparently inefficient and LEDs are being thought as promising technology for energy saving and reduction in greenhouse gas emission associated with it. Almeida *et. al.* [1] reviewed the potential and challenges of solid state lighting (SSL) in Europe and projected that SSL will become dominant efficient light source by 2020. Current developments in LED technologies have resulted in various applications including the usage of LED in an automobile headlamp for forward lighting. With improved electrical to optical power efficiency and low-carbon economy, LEDs are promising option for fourth generation illumination. However, thermal management is one of the key issues which needs attention in order to develop stable LED operation and long lifecycle.

Currently LED chip for lighting purpose are available with input powers from as low

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as 1W to as high as 25W with area less than 1 mm^2, corresponding to the heat flux of more than 100W/cm^2 [2]. Arik *et. al.* [3] discussed about thermal challenges of solid state lighting applications and stressed that the efficiency of the solid state lighting products decreases with the increase of junction temperatures. The main objective of a thermal management system of LED headlamp is to maintain the temperature of the LED junction and nearby area as low as possible for the stability, reliability and longevity of LED operation. It is interesting to compare the heat dissipation methods for LED and traditional headlamp. As LED headlamp has higher electro-optical efficiency than traditional headlamp system, heat generated by LED headlamp is smaller than the traditional headlamps for same input power. But, in traditional headlamps only 10% of the heat generated is dissipated by conduction, whereas in case of LED headlamp almost all the heat is dissipated by conduction from junction to heat sink, and finally heat sink to air by convection [4]. This creates a necessity to transfer heat effectively by both conduction and convection. The power loss by LEDs in terms of heat dissipation must be transferred effectively out of the LED chip to the environment. Hence, the heat sink model and the active air cooling are being used.

Long *et. al.* [5], in his review on light emitting diode based automotive headlamps cited important clues for future developments including energy-efficient thermal management. Park *et. al.* [6] optimized the heat release performance of LED headlamp using a heat pipe and a fan. Donahoe [7] surveyed about the thermal aspects of LED automotive headlamps by thermal design approach and also reviewed power budgets of automobiles, lighting history, lighting technologies and patents regarding an automobile LEDs. Lee *et. al.* [8] conducted study on cooling device of LED lighting system. Bullough [9] discussed about the energy and environmental implications of LEDs in an automobile industry along with key differences between LED and filament sources in terms of visual responses. Lai *et. al.* [10] discussed about optimum cooling solution for LED heatsink with respect to fin number, fin thickness, fin height and base plate area. Pohlmann *et. al.* [11] discussed about the requirements of LEDs in vehicle lighting applications. Seo *et. al.* [12] conducted the numerical investigation on cooling performance of the heat sink for LED headlamp for automobile. Heat dissipation has been the major bottleneck for developing thermally stable LEDs. So it is important to address the thermal issue using effective cooling systems for stable working of LED headlamp. Choi *et. al.* [13] conducted a numerical analysis to evaluate the cooling performance of automotive LED headlamp for different heat sink structures and fin shapes. Although for different heat sink structures, a similar numerical investigation for improving the performance of high power LED lighting system was conducted [14]. Patil *et. al.* [15] carried out the experimental study on the cooling performance of the LED headlamp of a commercial passenger vehicle and studied the effects of the various parameters affecting the cooling performance of the heatsink of LED headlamp.

For developing the effective cooling devices with an active air cooling, it is important to evaluate the parametric effects on the cooling performances of the LED headlamp. There are four important parameters which impact the variation of junction temperature of LED headlamp. These are: input power, ambient temperature, the thermal resistance between the LED junction and ambient environment and the external active air or liquid cooling. The objective of this investigation is to experimentally study the effects of various parameters on cooling performances of the heat sink model of LED cooling system for the passenger vehicle headlamp. To evaluate cooling performance, the temperature and thermal resistance at critical points have been measured. The input power, fan output and ambient temperature were varied and corresponding effects were analyzed. In addition, comparison between natural and forced convection was carried out.

2. Experimental Setup

The experimental setup schematic is shown in Figure 1, which consists of a glass container, an automobile headlamp LED chip, a heat sink model, a fan, power supply, thermocouples (T-type), microcontroller board (Arduino MEGA 2560) for input power and fan output variation, data logger (GRAPHTEC midi LOGGER GL820) and a computer for data processing. One thermocouple is attached to LED junction to measure the junction temperature. The other thermocouples are attached to measure the temperature of heat sink surfaces, air temperature near the LED heatsink surface and ambient temperature. Figure 1 shows the relative positions of the different thermocouples. The heat sink model has been mounted on the Aluminum plate with the point support.

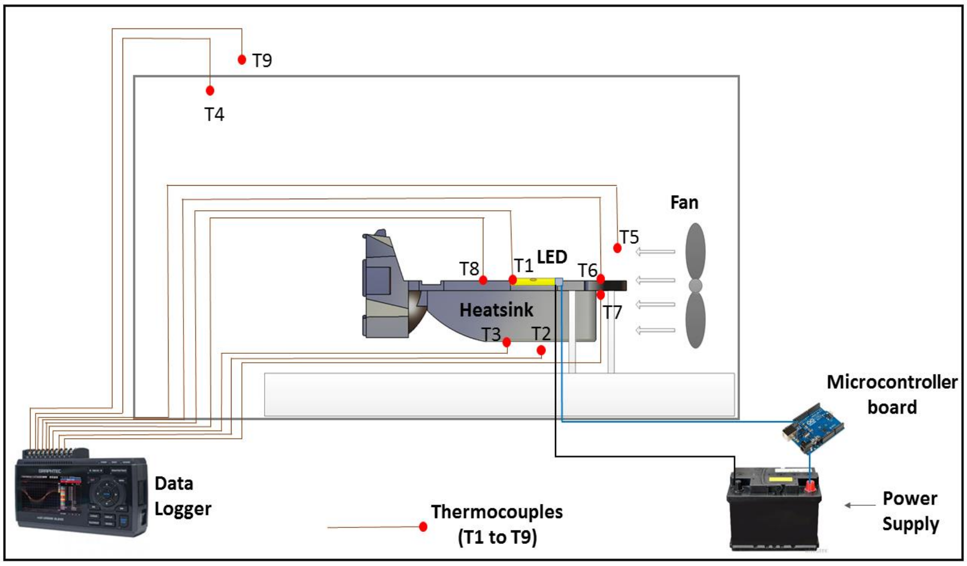

Figure 1. Schematic of Experimental Setup

As discussed, heat generated during LED operation is first effectively dissipated by heatsink by means of conduction and further by forced convection using a fan. For dissipating heat effectively a fan is placed behind the heat sink for an active air cooling of the heatsink.

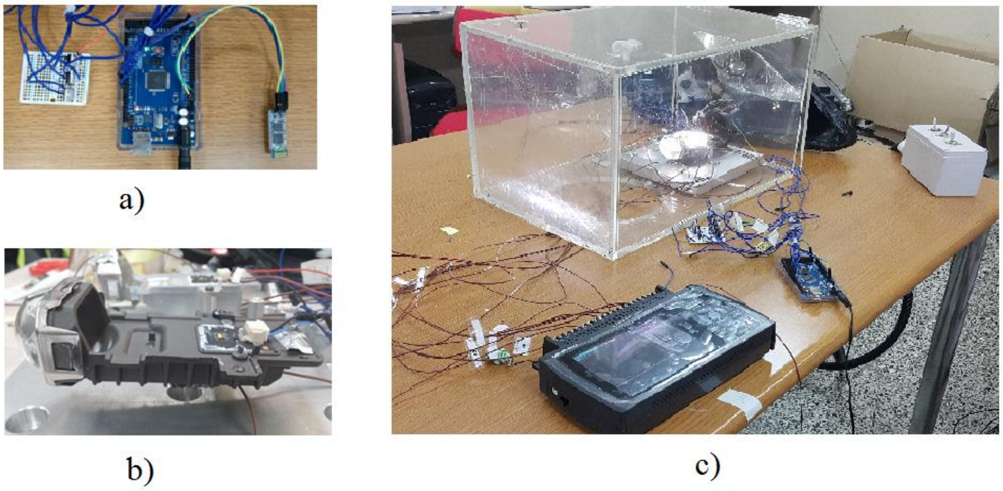

Figure 2. a) Microcontroller board b) LED with heat sink c) Experimental Setup

The air flows over the heat sink, where it takes away the heat and forced away from the heatsink and lens, making way for low temperature air. This thermal management protects LED from overheating as well as supports defogging of outer lens in cold conditions. This is achieved by moving hot air over the lens which gets heated up. To control and vary the input power and fan output, a microcontroller board (Arduino MEGA 2560) has been used. Figure 2 shows the arrangement for microcontroller board.

A glass container has been chosen so as to minimize the outside air movement effect on the heat dissipation rate of heat sink. Table 1 shows the specifications of heat sink and microcontroller. Also, Table 2 shows the test conditions used in this study. Table 3 shows the accuracy of the test instruments.

Table 1. Specifications of the Heat Sink and Microcontroller

Items		Specifications
Heat sink	Material of the heat sink	Aluminum
	Length of the heat sink (mm)	120
	No. of straight long fins	5
	No. of cross small fins	16
Microcontroller board	Name	Arduino MEGA 2560
	Operating voltage (V)	5
	DC current per I/O pin (mA)	20
	Digital I/O pins	54

The input current was set to 0.5A and the voltage was varied from 5.3 V to 11.5 V. The output of cooling fan behind the heat sink for LED cooling system was set to 4030 m^3/min, 5750 m^3/min, 5910 m^3/min, and 8650 m^3/min respectively. The ambient temperature was set to 16 ºC, 21 ºC, 22 ºC and 27 ºC respectively.

Table 2. Test Conditions

Items	Specifications
Outdoor temperature (ºC)	16,21,22,27
Input current (A)	0.5
Voltage (V)	5.3, 7.25, 8.5, 10.7, 11.5
Fan output (m^3/min)	4030, 5750, 5910, 8650
Time (sec)	1800, 3600

Table 3. Instrument Accuracy

Instrument Name	Measured property	Accuracy of the instrument
DT-830B multi-meter	Voltage	±0.5% 5D
	Current	±2.0% 5D
GRAPHTEC midi LOGGER GL820	Temperature	±0.1% of reading + 0.5ºC

3. Results and Discussion

The amount of energy consumed for vehicle accessories like headlamp are considerable and can affect the vehicle range for electric vehicles. To develop a system with minimized energy consumption and longevity of LED operating lifecycle, it is imperative to analyze the effects of various parameters on cooling performance. The current experimental study investigates the cooling performance characteristics of an air cooled heat sink when various parameters are varied.

Figure 3 shows the variation of temperature at LED junction point under the influence of forced and natural convection. For forced convection analysis the fan output is varied from 4030 m^3/min to 5910 m^3/min, while input power is kept constant at 5.75 W for the time period of 3600 seconds. The temperature distribution at LED junction for natural convection suggests that the heat dissipation is not sufficient for a long life cycle of LED. Hence an active air cooling has been suggested. The junction temperature drops significantly when an active air cooling is used. In addition, it is important to observe the effects of different fan outputs. Although the fan output is increased from 4030 m^3/min to 5910 m^3/min, the temperature drop at the junction point was found to be 0.8 ºC only after 3600 seconds. This suggests that increase in fan output alone is not sufficient to develop advanced cooling system and modified heatsink model can be a good option. Although recent investigations for LED chip cooling systems using active liquid cooling can provide enhanced cooling performance, this makes system cumbersome and needs more sophisticated leakage proof system.

Figure 4 shows the variation of illuminance as input power and distance are varied. The input power is varied from 2.5 W to 5.75 W using a microcontroller board (Arduino MEGA 2560). The test is conducted for 1800 seconds with constant fan output of 5750 m^3/min. The illuminance of LED increased as the input power consumption is increased and the junction temperature also increased due to enhancement in heat generation.

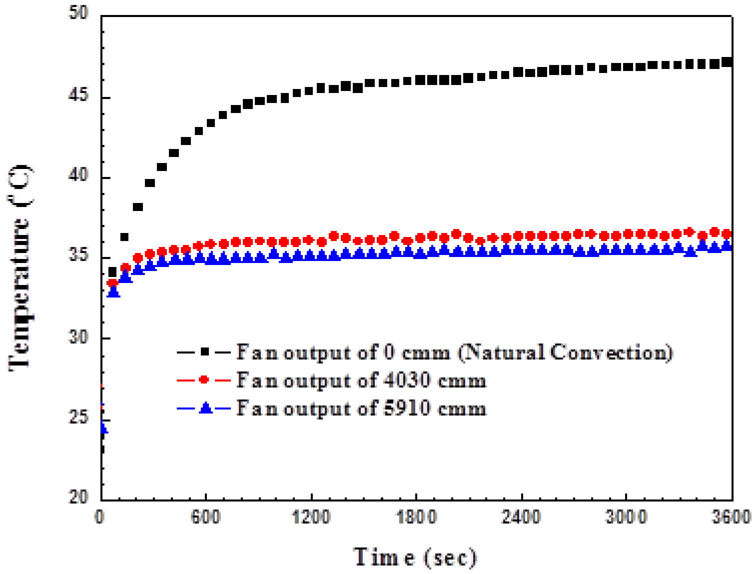

Figure 3. Junction Temperature Distribution for Different Fan Output at Constant Input Power of 5.75 W

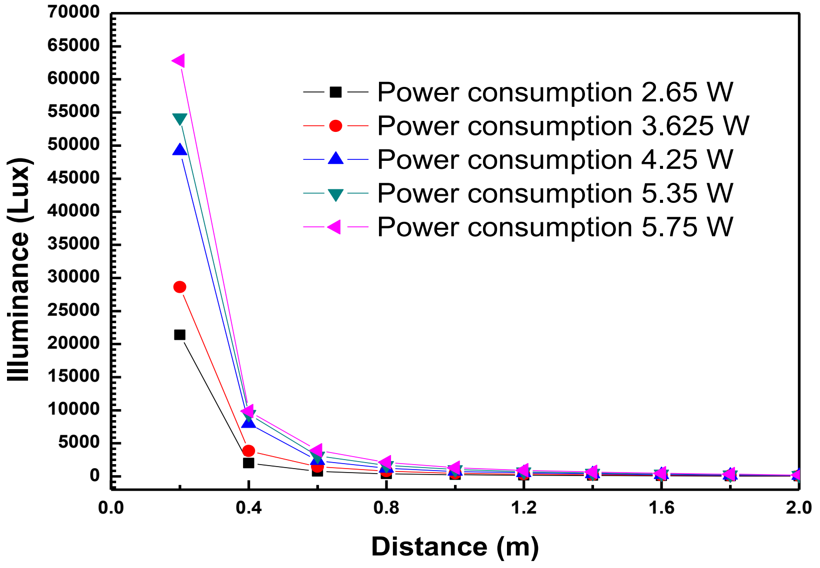

Figure 4. Variation of Illuminance with Respect to Change of Input Power and Distance

Figure 5 shows the temperature distribution at different locations for forced convection with fan output of 5910 m^3/min. The relative positions of all the thermocouple positions have been indicated in Figure 1 which the schematic of experimental setup. It is found that the temperature of heat sink fin surface is relatively lower than LED junction and nearby locations indicating the heat sink suitability for this cooling application.

For different variety of electronic devices, thermal resistance concept helps to select the proper heat sink. Table 3 shows the thermal resistance variation with different power input. The thermal resistance increases with increase in power input, as increased amount of heat needs to be dissipated through same surface area.

Table 3. Thermal Resistances with Respect to Input Power

Power input (W)	Thermal resistance after 1800 sec (°C/W)
2.65	0.188
3.625	0.303
4.25	0.352
5.35	0.392
5.75	0.5

Figure 6 shows the variation of junction temperature of LED headlamp with change in ambient temperature. The junction temperature is increased as the ambient temperature is varied to 16 °C, 21 °C and 26 °C respectively. The variation in junction temperature is found to be linear with variation in ambient temperature.

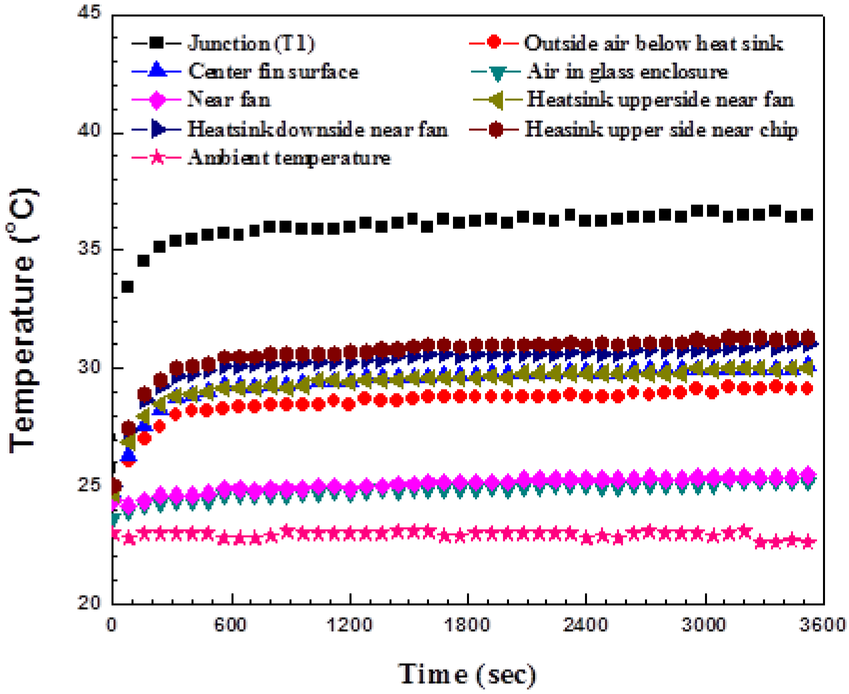

Figure 5. Temperature Distribution at Different Locations with Input Power 5.75 W and Fan Output 5910 M^3/Min

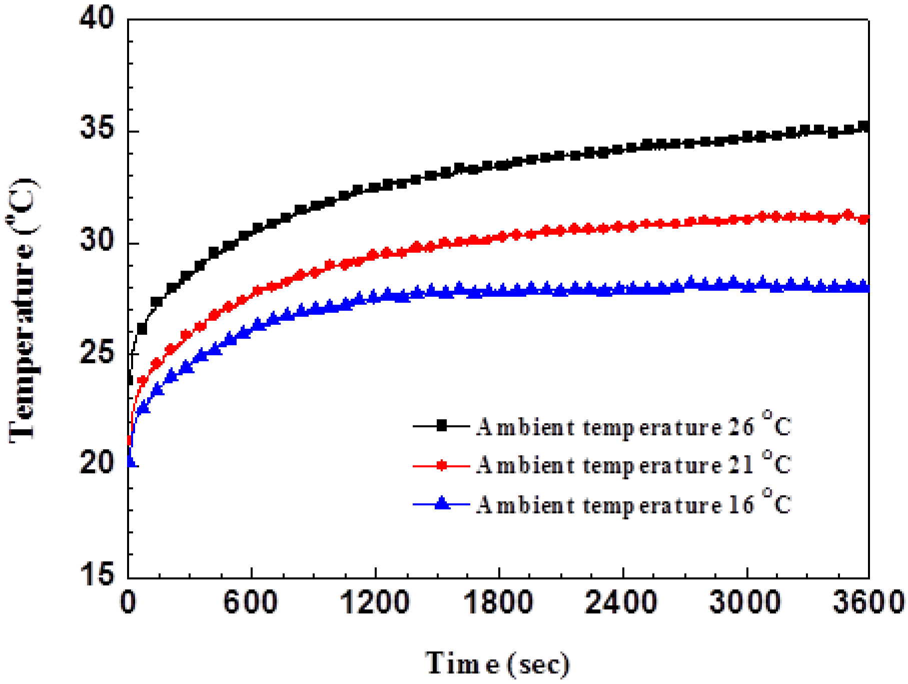

Figure 6. Junction Temperature Variation with Ambient Temperature

4. Conclusions

LEDs are considered promising option in vehicle headlamp for front side illumination in place of xenon and halogen headlamp systems. The large amount of heat is generated during LED operation with very small surface area to dissipate, demanding an advanced cooling system to dissipate large heat flux. In this investigation, an active air cooled heat sink model has been studied for enhancement of the heat transfer under various operating conditions. Various parameters have been studied for their effects on the cooling performance characteristics of the heat sink. Natural convection seems insufficient and forced convection needs to be used to transfer heat effectively. With more power consumption the heat dissipation rate per unit area increases and indicates to develop advanced cooling system to dissipate more heat. Although forced convection can dissipate heat more rapidly, temperature decrement of only 0.7 °C was seen when fan output was increased almost 1.5 times. The junction temperature of the LED increased as the ambient temperature is increased. The illuminance variation experiment with respect to power input and distance was conducted. The maximum thermal resistance was observed for the input power of 5.75W.

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< Research Interests>

Heat and mass transfer, New & renewable energy conversion system, Thermal management system for electric cars

