CONCEPTUAL DEVELOPMENT OF AUTOMOTIVE FORWARD LIGHTING SYSTEM USING WHITE LIGHT EMITTING DIODES

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ABSTRACT

This paper focuses on redesigning the headlamp subsystem functional architecture. The design involves meeting three major functional requirements:

1. Achieving the lumen requirements according to Economic Commission for Europe (ECE) 324 regulations
2. Meeting the illumination pattern
3. Maintaining the Light Emitting Diode's (LED) junction temperature at 90°C

White LEDs are considered in the design to satisfy the functional requirements due to their high lumen efficacy, compact size, and long life. These benefits, when compared to existing headlight systems benchmarked, present enough potential to warrant further conceptual virtual prototyping. The prototyping focused on solutions that allowed control of sizing and numbering of LEDs, illumination pattern limits, and temperature to achieve the multiple functions in a dynamic headlight system. A primary challenge in this design is to maintain the LED's junction temperature within a recommended operational range. A conceptual design is presented with metal foam meta-material which act as both a heat exchanger to maintain the LED's junction temperature and a structural member. The metal foam design also exploits the environmental conditions of the vehicle operation to meet the desired functionality. An analytical thermal model is used to predict the LED's junction temperature, thus allowing for optimization of the metal foam constituent properties. A finite element model is developed to view the thermal affects of an LED on adjacent LEDs. The results of the finite element model are used in conjunction with an optical analysis to determine any LED arrangement pattern restrictions and limitations. The number of LEDs required is derived from the lumen requirements set by ECE directive while including lumen deficiencies. Finally, the results of the individual model are integrated to meet the functional requirements of the headlamp subsystem.

PROJECT GENESIS

This project entails the redesign of a headlamp subsystem to incorporate the use of Light Emitting Diodes (LEDs) in place of existing High Intensity Discharge (HID) and halogen light sources. The motivation of the design originates from the numerous advantages and benefits for use of LED light sources.

USES OF LEDS IN VEHICLES – In the rear signal lamp sector, companies has successfully been using LEDs as light sources for more than ten years now, in high-mounted stop lamps, for example, or for tail light, stop light and direction indicator functions in combination rear lamps, such as in the case of the Volkswagen Golf Plus [1]. White LEDs have already been used for signal functions like positioning or daytime running lights [2]. The development of the first full LED headlamp appeared in the Auto R8, seen in Figure 1. For the first time, all light functions of a serial headlamp are being realized in LED technology, these are low and high beam, daytime running light, turn indicator and position light [2].
MOTIVATION – The motivation for using LED headlamps are their many advantages over existing headlight systems. LEDs, as a light source, generate completely new possibilities for headlamp shapes and arrangements [1]. Due to their high reliability, long operating life, fast response time and efficiency, LEDs are finding increasing use in automotive applications [4].

ADVANTAGES OF USING LEDS – There exist many advantages for using LEDs as a light source for vehicle headlamps. There are major benefits in terms of energy efficiency. For instance, in traffic lights, a red traffic signal head that contains 196 LEDs draws 10W versus its incandescent counterpart that draws 150W, estimating a potential energy savings ranging from 82% to 93% [5]. LEDs are projected to produce a much longer service life than their counterparts. A LED can maintain an operating life of 100,000 hours [6]. For this reason LEDs are ideal for hard-to-reach areas [5]. Other benefits of LEDs include [5]:

- No UV Emissions
- Durable and rugged

HEADLIGHT SPECIFIC ADVANTAGES – Alongside the many advantages offered by LEDs, there exists many advantages unique to their use within headlamp systems. Figure 2 provides a tabulated list of LED advantages within the headlight market to justify their use as headlight alternatives.

Due to LEDs ability to easily change luminosity, transitioning from lit to unlit, they allow use in situations where light is needed for a short period of time or shifts and oscillations in luminosity are required. This modularity within an array of LEDs could substitute subsystems such as those which control dynamic motion (cornering and auto leveling). This removes the complexity of incorporating a dynamic system that requires use of a motor.

In terms of efficacy, the lumen output per Watt of power entering the system, LEDs have a significant advantage over alternative lighting systems. An LED is able to provide 160% the efficacy of an HID system. This reduces the energy constraint on the vehicle. This does not include energy savings from removing unneeded mechanical systems.

The operating life of an LED is unmatched, capable of maintaining operation for 100K hours. Incandescent lights, the closest perform, achieve a life span a third of LEDs. With a mileage of 300,000 kilometers in 15 years, the typical service life is 3000 to 7000 hours according to different OEMs [4]. Standard bulbs have lifetimes of approximately bout 300 hours [4].

<table>
<thead>
<tr>
<th>Advantage</th>
<th>Comment</th>
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| Design flexibility, modularity, and re-use of LEDs for different applications | • Unique night time identification, offers lit and unlit differentiation  
• Rears of cars already have innovative arrangement of LEDs | [7] |
| Reduces front-end overhang | • Depth of LED headlamp could reduce  
• Tighter turning circle, improved response to sharp bumps, better cornering | [8],[9] |
| Increased efficacy (lm/W) | LED  
Incandescent  
Fluorescent  
HID | Up to 115  
15  
60  
72 | [9], [10]  
[11], [12] |
| Long lifetime (Hrs of operation) | LED  
Incandescent  
Fluorescent  
HID | Up to 100K  
30000  
2000  
3000 | [6], [13] |
| High lumen maintenance | 10% > HID | [6] |
| Comfort to human eye | Color temperature of 6000 K, Compare 4100 K - Xenon | [14] |
| Cool light | No heat transfer by radiation | [15] |

Figure 2: Lighting Comparison
**CONCEPTUAL DESIGN**

The initial phase of design requires defining the system boundaries and the specifications the system must meet. These requirements came in part due to the regulation standards the LEDs are imposed to achieve, operational constraints provided by LED manufacturer, environmental constraints the system must take into consideration, constraints imposed by other subsystems within the vehicle, and client imposed constraints.

**DESIGN OBJECTIVE** – The objective of this project is to develop a concept that explores the use of LEDs as a light source for headlights. This requires developing a LED headlight concept that replaces the existing system in terms of functionality and meets the dynamic capabilities of standard headlight systems. This concept will require supporting evidence to demonstrate the LEDs ability to operate within the prescribed conditions.

**CONCEPT EQUIPMENT** – The LEDs used to realize the concept are the Cree XLamp 7090 XR-E LEDs, shown in Figure 3 [16]. The Cree XLamp 7090 XR-E LEDs were an appropriate selection as they were considered an efficient LED at the time of design conceptualization and technical specifications were provided by the manufacturer.

![Image of Cree XLamp 7090 XR-E LED](image)

**Figure 3: Cree XLamp7090XR-E [16]**

**REQUIREMENTS** – The design of the LED headlight requires the consideration of many constraints. Each requirement was accounted for throughout the design process to ensure an suitable concept was developed. It is important to note that while constraints were imposed by the project client, these constraints are proprietary and cannot be disclosed.

Governmental – To ensure an appropriate and permissible system is designed, ECE (Economic Commission for Europe) regulations were referred to. ECE is an organization which adopted a uniform technical prescription for wheeled vehicles, equipment and parts which can be fitted and/or be used on wheeled vehicles and the conditions for reciprocal recognition of approvals granted on the basis of these prescriptions [17]. The ECE make use of a light intensity screen in which LEDs must meet prescribed illumination targets within different locations on the screen (ECE 324 / Rev 2/Oct’06 cl.6.3 [18]).

According to ECE requirements, the light source and the light intensity screen on which the light is illuminated are 25 meters apart. The screen, seen in Figure 4, is 4.5 meters long and 4.5 meters wide. The LED array considered during development was only concerned with high beam conditions. This was due to the additional lumen requirements needed to meet high beam conditions. The high beam requirements set forth by ECE do not impose any requirements on the vertical axis of the screen. The intersection point of the center line of the screen is referred to as H-V point. The screen is positioned so the longitudinal axis of the headlamp intersects with the H-V point. At the H-V point, a headlamp is allowed to have a maximum of 196 lux (measurement of light intensity per area). The requirements also enforce a minimum of 16 and 6 lux at distance of 1.125m and 2.25m from the HV point respectively.

![Image of ECE High Beam Conditions Regulation Board](image)

**Figure 4: ECE High Beam Conditions Regulation Board [18]**
Environmental – There are constraints put forth by the operational environment of the LED. This environment within the vehicle place energy, thermal, and dynamic constraints that must be considered to ensure proper functioning of the system. These requirements exist to ensure the system is able to operate as designed despite the external factors within a vehicle affect its operation.

The primary constraints on the LEDs performance are the effect of temperature on the photometric efficiency. The requirements primarily focus on the upper limit temperatures the LEDs are exposed to. The environment the LEDs are exposed to is illustrated in Figure 5. The LEDs selected to realize the concept have a maximum junction temperature of 90°C. While the LEDs are capable of operating at higher temperatures, there is a decrease in efficiency. The temperature of the ambient air is 50°C. This reflects the upper limit the design is approaching to ensure appropriate operation of the LEDs. The engine bay temperature is considered to be 105°C. However, the design assumes the LEDS will be insulated from the engine bay temperature through use of an interior headlamp shield.

Figure 5: LED Environment

The LEDs must operate under the following required conditions:
- Engine bay temperature: 105°C
- Environment temperature: -40 to 50°C
- Output 2000 lumens per headlamp

Operational – The LEDs used during the concept development phase imposed constraints to ensure operation within an efficient range. These constraints were provided by the manufacturer of the LEDs.

As seen in Figure 6, the Cree XLamp 7090 XR-E LEDs are capable of operating at currents up to 1000mA. 350mA is considered operation at normal output to avoid overload on the LED. However, the LEDs are well suited for increased current if thermal issues can be mitigated. For the concept, the LEDs were assumed to operate at 700mA. At 700mA, the photometric output of LEDs is approximately 170 lumens.

Figure 6: Intensity of LED with respect to Current [16]

It is important to note the intensity of 170 lumens (at 700mA) is performed a junction temperature of 25°C. However, the environmental constraints require operation at lower (-40°C) and higher (50°C) temperatures. As a result, it is important to view how temperature changes affect the photometric output. Figure 7 displays the junction temperature and its effect on the photometric output. As noted, at 25°C, the photometric output is 100%. At a junction temperature of 90°C, a 170 lumen white LED output is degraded to approximately 160 lumens. This information aids in determining the efficiency drop that will be encountered with temperature rise. This information will be used in addressing thermal issues and determining the number of LEDs required.

Figure 7: Photometric Output vs. Junction Temperature [16]

The LEDs will not operate on 100% efficiency in terms of power input to output. Approximately 90% of the power supplied to the LED is converted to heat, while the remaining 10% is used in providing light. In the case of the design, this translates to 3.35 Watts of the original inputted energy (3.5 Watts) transferring into thermal energy. For conservative measurements, an assumption that 100% of the input is converted to thermal energy, meaning the LED outputs 3.5 Watts of thermal energy.
PROTOTYPE DESIGN

The thermal inefficiency of LEDs causes an increase of thermal energy within the system. This results in a rise of temperature which, in turn, reduces the optical efficiency. For an LED system to function as designed in the defined environment, a means of dissipating the heat must be incorporated within the system. A metal foam concept is proposed to be used as a medium of dissipating energy to prevent temperature rise and maintain photometric efficiency.

CONCEPT SELECTED – In the proposed concept, shown in Figure 9, LEDs are directly mounted over a metallic foam plate. This allows the heat generated by the LEDs to be transmitted through the metallic foam. Since the metal foams are highly porous in nature, it is possible to direct the flow of air through the foam. This design allows for the dissipation of heat generated by the LEDs through convection. Furthermore, when the vehicle is in motion the same system acts as a forced convection unit which can significantly improve the thermal energy removal rate due to its high surface area to volume ratio.

ADVANTAGES OF METAL FOAM – In the proposed concept shown in Figure 8, LEDs are directly mounted over a metallic foam plate. This allows the heat generated by the LEDs to be transmitted into the metallic foam. Since the metal foams are highly porous in nature, it is possible to direct the flow of air through the foam. This setup allows for removal of heat generated by the LEDs through convection. Furthermore, when the vehicle is in motion the system acts as a forced convection unit which can significantly improve the heat removal rate.

ANALYSIS

The analysis of the concept was divided into two major categories. A thermal analysis is performed to view the conductive and convective ability of the system. This is done to ensure the system is capable of dissipating the required thermal energy to maintain an appropriate junction temperature. An optical analysis is performed to view if adjacent LEDs have an effect on one another. This localized affect is determined so the mechanics of the thermal dissipation is identified and a methodology for arranging LEDs to meet other requirements is found.

THERMAL ANALYSIS – Due to the complex morphological structure of metal foam and the lack of mathematical models to evaluate their thermal capabilities, it is difficult to accurately measure the thermal conductivity and convection of the metal foams. Many of the calculations are solved through use of empirical data developed through similar studies.

The LEDs will require an input of 3.5 Watts to operate. As noted previously, 90% of the LED input energy is transferred into thermal energy. This thermal analysis, being a conservative analysis, will assume all 100% of the energy inputted will transform into thermal energy. While this is not possible, it is taken as a safe measurement. This thermal energy outputted by the recent research shows that forced convection has a very significant effect on the overall ability of the metal form to dissipate heat form the foam [20]. Metal foam is proposed as a concept for use as a heat exchanger to take advantage of its ability to dissipate high amounts of thermal energy due to its high surface area to volume ratio.
LEDs will cause an increase in temperature of the metal foam. Using the ambient temperature flow of 50°C air, the metal foam must maintain a temperature of 90°C or less on the LED face of the metal foam structure. This is seen in Figure 11. It is assumed in this analysis the LED and metal foam are insulated from the engine compartment through use of a headlamp interior shield.

Thermal Conductivity – The heat transfer due to conduction is given through Equation 1. The thermal power is divided by time to transfer it in terms of energy.

\[ Q = \frac{KA(T_m - T_a)}{t} \quad (1) \]

Where:
- \( Q \) = heat transferred (Joules)
- \( t \) = time (sec)
- \( K \) = thermal conductivity (W/mK)
- \( A \) = area, \((m^2)\)
- \( T_m \) = Temperature at the base of LED (K)
- \( T_a \) = Ambient air temperature (K)

Metal foam is of unique form due to its hybrid volume of solid and gas (material and air). As a result, the conductivity is a combination of the conductivity of the material and the fluid which will reside within the material. There is a correlation made between the conductivity of the fluid and material to develop an effective thermal conductivity. To find the effective thermal conductivity coefficient, Equation 2 is used [20].

\[ k_e = \frac{\sqrt{2}}{2(R_a + R_b + R_c + R_d)} \quad (2) \]

Where:
- \( k_e \) = Effective thermal conductivity coefficient (W/mK)
- \( R_a, R_b, R_c, R_d \) = Fluid and Solid Relationship

The fluid and solid relationships \((R_a, R_b, R_c, R_d)\) are solved using Equations 3, 4, 5 and 6.

\[ R_a = \frac{4\lambda}{(2e^2 + \pi \lambda (1-e))k_s + (4-2e^2-\pi \lambda (1-e))k_f} \quad (3) \]

\[ R_b = \frac{(e-2\lambda)^2}{(e-2\lambda)e^2k_s + (2-4\lambda-e-2\lambda)e^2k_f} \quad (4) \]

\[ R_c = \frac{(\sqrt{2}-2e)^2}{2\pi \lambda(1-2e\sqrt{2})k_s + 2(\sqrt{2}-2e-\pi \lambda^2(1-2e\sqrt{2}))k_f} \quad (5) \]

\[ R_d = \frac{2e}{e^2k_s + (4-e^2)k_f} \quad (6) \]

Where:
- \( k_s \) = Thermal conductivity of solid (W/mK)
- \( k_f \) = Thermal conductivity of fluid (W/mK)
- \( e \) = porosity
- \( \varepsilon \) = .339

Lambda \((\lambda)\), a constant, is found using equation 7.

\[ \lambda = \sqrt{2} \left( \frac{\varepsilon}{\pi} \right) e^2 - 2 \varepsilon \]

\[ \frac{3-4e\sqrt{2}-e}{\pi} \quad (7) \]

Using the equations above, and inserting the appropriate values:

\[ Q/t = 3.5 \text{ (W)} \]
\[ A = 0.000063 \text{ m}^2 \text{ (LED footprint is 7mm by 9mm)} \]
\[ T_m = 363 \text{ K} \]
\[ T_a = 323 \text{ K} \]
\[ k_s = 401 \text{ (W/mK) for copper } \]
\[ 237 \text{ (W/mK) for aluminum} \]
\[ k_f = .025 \text{ (W/mK) } \]
\[ \varepsilon = .9 \text{ (90% porosity)} \]

Using the information, the effective thermal conductivity coefficient is found to be approximately 11.1 W/mK for copper and 6.6 W/mK for aluminum.

Thermal Convection – To measure the heat transfer due to forced and natural convection, Equation 12 is used.

\[ Q = hA(T_m - T_a) \quad (8) \]

Where:
- \( h \) = Convective heat transfer coefficient (W/m²K)

To solve Equation 8, the surface area must be computed. This is a relatively difficult task for metal foam due to their complex structure. However, empirical data is provided to build a relationship between the surface area and volume. Metal foams with porosity greater than .85 can use a relationship in which a surface area density is used [20]. Since a porosity of .9 (90% porous) is used, to maximize surface area while maintaining structural integrity, this relationship is valid for use within the analysis. This relationship, seen in Equation 9, calculates the surface area density caused by the pores in a given volume. This relationship is dependent on the porosity and pore diameter.
\[
\tilde{a} = \frac{3a_d f (1 - e^{-\frac{1-e}{0.04}})}{(59d_p)^2}
\]  

(9)

Where:
- \(\tilde{a}\) = surface area density (1/m)
- \(d_i\) = diameter of pores (m)
- \(\varepsilon\) = .9 (90% porosity)
- \(d_p\) = pore size (m)

Equation 9 requires finding the diameter of the pores (\(d_i\)) and pore size (\(d_p\)). These are not the same value as pore overlap (between open pores) affects the size of each pore. The pore size is controlled by the manufacturer of the metal foams. Pore size is measured by the number of pores per inch (ppi). The current manufacturer of interest, Porvair PLC, provides this information [21]. Porvair PLC offers 10 and 80 ppi copper metal foams. The metal foam used for the calculations will use an 80ppi pore structure due to their high surface area to volume ratio. Using the pore size, the diameter of the pores can be found using a porosity and pore size relationship. This relationship, seen in Equation 10, is used to find the diameter of the pores. This equation can be solved in terms of the pore diameter to find its value.

\[
d_i = 1.18 \sqrt{\frac{(1-\varepsilon)}{3\pi}} \left(\frac{1}{1-e^{-\frac{1-e}{0.04}}}\right)
\]  

(10)

Using the pores per inch and pore diameter, the surface area density can be solved. To find the heat transfer due to thermal convection, the heat transfer coefficient must be found. As noted previously, the convective heat transfer coefficient will be found for natural and forced convection.

**Forced Convection** – To measure the heat transfer through forced convection, the convective heat transfer coefficient requires calculating. There exists a relationship between the heat transfer coefficient and the Nusselt number. This is seen in Equation 11.

\[
h = \frac{Nu \ k_f}{L}
\]  

(11)

Where:
- \(Nu\) = Nusselt Number
- \(L\) = Characteristic Length (m)

From Equation 15, the conductivity of the fluid (\(k_i\)) is known. The characteristic length requires a calculating through Equation 16.

\[
L = \left(1 - e^{-\frac{1-e}{0.04}}\right) df
\]  

(12)

To find the heat transfer coefficient in Equation 11, the Nusselt number (\(Nu\)) is needed. Equation 13 is used to find the Nusselt number.

\[
\begin{align*}
\text{For natural convection:} & \quad \text{Nu} = .76Re_d^{4/3} Pr^{37} \text{ for } (10^3 \leq Re_d \leq 4 \times 10^4) \\
\text{For forced convection:} & \quad \text{Nu} = .52Re_d^{5/3} Pr^{37} \text{ for } (4 \times 10^1 \leq Re_d \leq 10^3) \\
& \quad \text{Nu} = .26Re_d^{5/3} Pr^{37} \text{ for } (10^3 \leq Re_d \leq 2 \times 10^5)
\end{align*}
\]  

(13)

Where:
- \(Re_d\) = Reynolds number
- \(Pr\) = Prandtl number

The Nusselt number is depending on Reynolds number and Prandtl number. The Prandtl number, being a constant, is found to be .708. To find the Reynolds number, Equation 14 is used.

\[
Re_d = \frac{u d}{v}
\]  

(14)

Where:
- \(u\) = air flow velocity (m/s)
- \(d\) = characteristic length (m)
- \(v\) = kinematic fluid viscosity (Pa s)

To find Reynolds number, the air flow velocity is required. This will depend on the speed of the vehicle or headwind the system encounters. This value will remain a variable. The kinematic fluid viscosity of air is approximately 20.43 x 10^{-5} Pa s at 90°C. With this information, Reynolds number can be found through air velocity. The Reynolds number is then used to find the Nusselt number, which in turn is used to find the heat transfer coefficient. Effectively, the velocity of the air entering the metal foam can be used to find the heat transfer coefficient.

**Natural Convection** – To measure the heat transfer through free convection, the natural heat transfer coefficient must be calculated. This is done through using Equation 11. The natural convective heat transfer coefficient requires a different calculation for the Nusselt number than that of forced convection. Equation 15 is used to find the Nusselt number in the case of natural convection.

\[
Nu = \left\{ 
\begin{array}{ll}
0.825 + 0.387 \times \frac{1}{Ra^\frac{1}{6}} & \text{for } 9 \times 10^5 \leq Ra \leq 9 \times 10^7 \\
1 + (\frac{0.493}{Pr})^{\frac{1.65}{27}} & \text{for } 9 \times 10^5 \leq Ra \leq 9 \times 10^7
\end{array}
\right.
\]  

(15)

Where:
- \(Ra\) = Rayleigh Number

As seen from Equation 15, Rayleigh number is needed to find the Nusselt number. The Rayleigh number is calculated through Equation 16.

\[
Ra = G_r \ast Pr
\]  

(16)

Where:
- \(G_r\) = \(g \ast \beta \ast (T_m - T_w) \ast \frac{L^3}{v^2}\)

Where:
\[ \beta = T f^{-1} = \frac{2}{T_m + T_\infty} \]

\[ T_m = 90^\circ C = 363 K \]

\[ T_\infty = 50^\circ C = 323 K \]

\[ L = \text{Characteristic Length (mm)} \]

Using the above equations, the appropriate values can be inputted to find the Nusselt number. The characteristic length (L) is a design variable based on material porosity and pores per inch, as seen in Equation 12. A correlation exists between the natural convection and the characteristic length. This is shown in Figure 12.

Figure 12: Natural Convective Heat Transfer vs. Characteristic Length

Other design variables that affect the heat transfer rate of the metal foam are volume, pores per inch, and air velocity. The correlations between the heat transfer rate and the mentioned design variables are investigated.

Figure 13 illustrates the heat transfer rate with varying pores per inch and volume. It can be observed for a fixed volume, as the pores per inch increases the heat transfer rate increases accordingly.

Figure 13: Forced Convective Heat Transfer vs. Pores per inch (ppi) vs. Volume

Figure 14 displays the effect of vehicle speed (air velocity) and volume on the heat transfer rate of the metal foam heat exchanger. When air velocity is generated, the metal foam heat exchanger transforms into a forced convection unit due to the constant supply of air. There is a significant increase in the heat removal rate with the increase in the vehicle speed.

Figure 14: Convective Heat Transfer vs. Vehicle speed vs. Volume

When the vehicle is at rest, the metal foam heat exchanger undergoes heat transfer by means of natural convection. The increase in heat transfer rate due to natural convection with the change in volume is significant as observed from Figure 15. For a volume of \(3 \times 10^{-5} m^3\), the heat transfer rate is approximately 5 Watts, a rate well above the heat generated by an LED (3.5 Watts). This validates the system, given the appropriate volume, porosity and pores per inch, is able to dissipate the required thermal energy under natural convection.

Figure 15: Convective Heat Transfer (reduced scale) vs. Vehicle speed vs. Volume
OPTICAL ANALYSIS – The use of LEDs in the automotive headlamp application imposes a challenge of maintaining a junction temperature below 90°C. The use of an array of LEDs led to an investigation viewing the relative heating effect of one LED to an adjacent LED. Coupled with the thermal analysis, this would provide a methodology for arranging the LEDs. This section entails the optical analysis performed identify the following requirements:

1. The number of LEDs required
2. The minimum gap required between the LEDs
3. Appropriate array pattern

The Cree XLamp 7090 XR-E LEDs are considered for the analysis. The calculation for number of LEDs to meet lumen requirement was calculated by first finding the inefficiencies within the system so they may be accounted for. This is done through Equation 17.

\[ \eta_{total} = \eta_o \eta_t \eta_e \eta_a \]  

Where:
\[ \eta_{total} = \text{Total System Efficiency} \]
\[ \eta_o = \text{Optical Efficiency} = 61\% \]
\[ \eta_t = \text{Thermal Efficiency} = 96\% \]
\[ \eta_e = \text{Electrical Efficiency} = 85\% \]
\[ \eta_a = \text{Average Light Intensity} = 96.5\% \]

The total system efficiency is found to be 47.5%. Using this figure, the number of LEDs required can be calculated. For high beam requirement, the total lumen output must be 2000 lumens. The total number of LEDs required is found through equation 18.

\[ \text{Total LEDs Required} = \frac{2000 \text{ Lumens}}{\text{LED}} \times \eta_{total} \]  

Knowing each LED outputs 170 lumens and taking into consideration the total efficiency of the system, the number of LEDs required is found to be approximately 25 LEDs.

The light intensity distribution, as specified by the manufacturer, is seen in Figure 16. The light has a relative intensity of approx 96.5% over a spread of 5 degrees per side.

The edge of the screen subtends at an angle of 10.2 degrees with the source. A single LED is able to illuminate the entire ECE light intensity screen. This suggests that a unit displacement of the LED at the source can shift the entire beam by same magnitude. The LEDs are positioned in a manner where the distance between farthest LED is not more than half the size of screen. This is to ensure light from all the LEDs merge to at least the center of the screen where maximum intensity is needed. A 2-D sketch, seen in Figure 17, of the aforesaid scenario is created to find the intensity overlap. It was inferred from the 2-D sketch the H-V point of the board would have substantial overlaps of the light rays thereby meeting the lumen requirements. The sketch is constructed by assuming a series of LEDs on the H-V axis and one row on either side of the H-V axis with 5mm space. The dark regions show the overlap of the 96.5% intensity boundaries. These bright regions can be eliminated with the use of a standard reflector. Reflectors can however be used to shape the beam to meet ECE requirement.
FEA MODEL – A Finite Element Analysis (FEA) is also included to determine the thermal interaction between LEDs and the gaps (distance between LEDs) that would be needed to minimize this interaction. Thermal analysis was conducted using Abaqus analysis software. The substrate was modeled with aluminum material. The junction temperature was limited at 90°C. A transient heat transfer analysis was run for 60 seconds to determine the heat rise and for possible thermal interactions between LED. It was inferred from the FEA report there is no thermal interaction between LEDs. This analysis is shown in Figure 18. Conduction is the only mode by which heat is transferred in the current setup. Heat quickly flows through the aluminum block, as it offers the least thermal resistance. There is a possibility of heat conduction between LEDs, provided the aluminum block and LEDs reach a common temperature. This case is impossible as LEDs generate heat constantly, maintaining a positive temperature gradient with the aluminum block. Hence it was concluded the gap between LEDs can be of the designer's choice to suite aesthetic and packaging requirements.

FUTURE DEVELOPMENT

FUTURE RECOMMENDATIONS – The number of LEDs will increase if the lights for dynamic bending and auto leveling are also considered. However, higher lumen LEDs are continuously being launched [22]. This would substantially reduce the number of LEDs used and hence the packaging space. OSRAM is a manufacturer which has announced their tentative launch schedule of high lumen LEDs [23]. The launch of these products would revolutionize the headlamp design of automobiles.

POTENTIAL USES – The use of metal foams can expand into many other facets of vehicle subsystems which require the dissipation of thermal energy. A unique advantage of metal foams is their ability to maintain structural integrity. This is dependent on the porosity and pores per inch of the metal foam. This allows for integration of vehicle subsystems that require both structural support and heat exchanger.

CONCLUSION

The analysis performed revealed the characteristics of this concept. The thermal analysis is able to demonstrate that orientations of pores per inch, porosity and volume can be developed to appropriately dissipate thermal energy maintain the junction temperature. The FEA illustrated the negligible effect adjacent LEDs have on one another, hence simplifying the thermal situation into a 2D problem. An optical analysis is performed to reveal the LEDs can be placed in any pattern regardless of gap size, with a suitable reflector, within the given headlamp design space to meet the lumen ECE lumen requirements. This analysis did not take into consideration the additional LEDs required to account for dynamic bending and auto leveling.

This concept and analysis provide the client with details suggesting this concept is feasible and the design variables that can be adjusted to meet client constraints. External to this concept, the use of metal foams as a structural members and heat exchanger allows for potential use within other subsystems within a vehicle.

This analysis did not investigate LEDs effect on glare and peripheral vision. This requires further research and experimental tests to comprehend its effect on the mesopic vision of human eye [23].

REFERENCES


16. C. L. Light, "Cree XLamp XR-E LED Data Sheet."


18. U. Nations, "ECE Regulation 324 Rev.2/Add.110.


22. (2006, January) LEDs are getting brighter.