CST0003

Comparison of thermal degradation area on a small automotive lamp by using ray tracing method and Monte Carlo radiation model

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Abstract. With increasing demands for more light efficiency and longer lifetime, all automotive lamps must be physically tested to evaluate both illumination and thermal quality. However, due to an excessive heat from a more powerful light source and modern complex design plastic lamps, a severe thermal degradation can be occurred on thermoplastic parts of those automotive lamps. Hence, this paper proposes an application of ray tracing method to examine the beam quality and predict the thermal degradation area on a small automotive lamp in the early design stage. First, by applying ray tracing method, both illuminance and lux distribution on a small automotive lamp were calculated in order to examine its beam quality. Next, the energy concentration on lux distribution was presented to predict the possible thermal degradation area on lamp components and then compared with thermal distribution results obtained from finite element Monte Carlo radiation analysis. Finally, the thermal degradation area forecasted from lux concentration were validated with temperature measurement of a lamp prototype. In this study, the ray tracing simulation results show that the lux concentration regions are prone to the thermal failure area on the lamp. Consequently, this method can be used as a speculative tool not only to precedent assess the illumination and thermal quality of lamps, but also reduce the cost and time-to-market for automotive lamp manufacturing as well.

1. Introduction

In modern automotive lamp design, beam quality, durability, lightweight and cost reduction are major challenges for increasing competitiveness in vehicle lighting market. To fulfill those demands, both shape and features of lighting systems are more complex and dissimilar thermoplastic materials are then used to reduce cost and weight of the lamp. For the modern automotive lamps, the high temperature of a high flux bulb may cause the thermal deformation on both housing and covered lens, due to the low permissible temperature of thermoplastic materials, which this can result in a severe beam shift problem or thermal degradation. Therefore, the beam quality and thermal behavior of those lamps must be carefully considered and tested to evaluate their illumination and thermal quality during its operation. In order to predict the beam quality and thermal defect of small automotive lamps, a ray tracing and finite element method are introduced in this paper for a license plate lamp's illumination design and thermal analysis. By using these two numerical methods, engineers can develop an automotive lighting design guideline without the costly fabrication and testing of multiple physical prototypes. In this study, the illumination of a license plate lamp was investigated by using ray tracing method to examine the energy hot spots in a lux distribution and besides, use to predict the probable thermal degradation area on the thermoplastic lamp's components in the early design stage. First, by applying ray tracing method, both illuminance and lux distribution on a license plate lamp were calculated in order to examine its beam quality. Next, the energy concentration on lux distribution was presented to predict the possible thermal degradation area on plastic lens and then compared with thermal distribution results obtained from finite element Monte Carlo radiation analysis. Finally, the thermal degradation area, forecasted from lux concentration, were validated with temperature measurement of a license plate lamp prototype. Consequently, this method can be used as a speculative tool not only to pre-assess the illumination and thermal quality of lamps, but also reduce the cost and time-to-market for automotive lamp manufacturing as well.

2. Theory

2.1 *Ray tracing method*

In ray tracing method, light is considered as an electromagnetic wave traveling through space. A light ray is defined as a line normal to the direction of wave propagation [4]. A light ray or ray obeys the laws of geometrical optics and can be transmitted, reflected, and refracted through an optical system following the Snell's law [5] as described below,

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \quad (1)$$

where n_1 and n_2 are the refractive indices of medium 1 and 2, respectively, θ_1 is the incident angle of light ray with respect to the normal, and θ_2 is the refracted angle.

After, the ray paths from light bulb to detector are determined, the flux or energy per unit time of each ray will be calculated. Flux is the time rate change of energy and can be defined by [6]

$$\phi = \frac{dQ}{dt} \quad (2)$$

where Q is the radiant energy of light.

Ray tracing for an automotive lamp analysis is based on a calculation of flux for each ray following the determined ray paths. When the light passes through an object, some of all flux will be absorbed. The flux of transmitted light can be calculated by [5],

$$\phi = \phi_0 e^{-\alpha x} \quad (3)$$

where ϕ is the intensity of transmitted light, ϕ_0 is the intensity of light entering the material, α is the absorption coefficient of material, and x is the thickness of the object.

At the detector, the irradiance or radiant incident (E) of the ray can be calculated by [6],

$$E = \frac{d\phi}{dA} \quad (4)$$

where A is the area of the detector surface.

2.2 *Monte Carlo radiation model*

For thermal radiation analysis, there are two main kinds of radiative approximation methods, which are ray tracing and differential method. The difference between those two models are the directions in which the radiation transfer equation (1) are solved

$$\frac{d}{ds} I(\underline{r}, \underline{s}) = k_a (I_b(\underline{r}) - I(\underline{r}, \underline{s})) \quad (5)$$

Where I is intensity, I_b is the blackbody intensity, $\underline{r}$ is position vector, $\underline{s}$ is unit vector in direction of a ray, and k_a is absorption coefficient. In this paper, the Monte Carlo radiation model was employed for thermal radiation analysis from a wire filament within incandescent light bulb.

In contrast to the previous ray tracing method, aligning with the volume element of the fluid flow, the Monte Carlo radiation model considers the radiation field as a photon gas and assumes that the intensity is proportional to the differential angular flux of photons. If k_a is the probability that a photon is absorbed per unit range. Then, the mean intensity, I is proportional to the travelling distance of a photon in each volume element at $\underline{\ }$r in unit time. A photon is selected from a photon source and tracked through the system until its weight falls below the minimum point. By tracing a typical bundle of photons in each volume element, each time the photon refracts, reflects, transmits, absorbs or scatters at the surface. The mean total radiant intensity can be calculated.

2.3 *Heat transfer*

In this paper, the covered lens and housing of license plate lamp was modeled as solid parts that transport energy by conduction. At the inner surface of the covered lens, heat is convected to the enclosed air within the housing and at the outer surface of the lens, heat is naturally convected to the ambient air. Hence, the heat transfer equation for conduction and convection would be presented in the calculation.

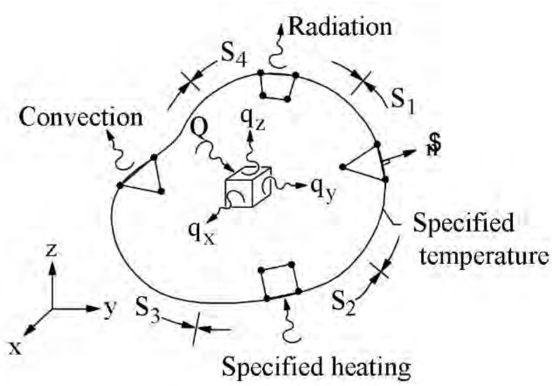


Figure 1. General heat transfer in 3-Dimension [1]

Governing heat transfer equation [1]

$$-\left(\frac{\partial q_x}{\partial x}+\frac{\partial q_y}{\partial y}+\frac{\partial q_z}{\partial z}\right)+Q=\rho c_p\frac{\partial T}{\partial t} \tag{6}$$

where q_x , q_y and q_z are the heat flow rate in x, y and z axis, respectively, Q is an internal heat generation, ρ is the mass density, c_p is the specific heat, and T is the constant temperature, not changing by time t ($\frac{\partial T}{\partial t}=0$)

The essential ingredients of forced convection heat transfer analysis were given by Newton's Law of Cooling,

$$\dot{Q} = hA(T_w - T_\infty) = hA\cdot\Delta T \tag{7}$$

The rate of heat $\dot{Q}$ transferred to the surrounding fluid is proportional to the object's exposed area A, and the difference between the object temperature T_w and the fluid free-stream temperature T_∞. The constant of proportionality h is termed the convection heat-transfer coefficient.

By applying the method of weighted residuals (MWR) with Bubnov-Galerkin technique and the boundary conditions, the finite element equations could be represented in the following form [1],

$$[C]\{\dot{T}\} + [[K_c] + [K_h] + [K_r]]T = \{Q_c\} + \{Q_Q\} + \{Q_q\} + \{Q_h\} + \{Q_r\} \quad (8)$$

3. Numerical Analysis

In order to forecast the thermal defect of a small automotive lamp in the initial design stage, this paper investigated a thermal degradation area on a license plate lamp by using ray tracing method to identify the hot spot area on thermoplastic covered lens and then comparing to the thermal distribution results obtained from finite element Monte Carlo radiation model. First, with ray tracing analysis, the lux distribution on plastic lens of a license plate lamp is determined under operating condition. Then, the hot spots in lux distribution on the lamp components were compared to another thermal simulation results obtained by a finite element analysis using Monte Carlo radiation model with an identical boundary conditions. Finally, a comparison of possible thermal deformation area from the ray tracing analysis was validated with temperature testing results on a license plate lamp prototype measured by using thermocouples and IR thermal camera.

3.1 *License plate lamp model*

First of all, a CAD model of a license plate lamp was built for our study. This lamp model consists of an automotive light bulb, a thermoplastic lens, and a plastic housing as shown in Figure 2. In this model, an incandescent bulb, 12V 5 watts W5W, generates both visible light and radiative heat loss from a tungsten filament. The optical plastic lens has light transmission at 88% with 1.2 g/cm^3 density, 0.2 W/m/K for thermal conductivity and a permissible temperature at 125 ℃. The plastic housing has density at 1.45 g/cm^3, thermal conductivity at 0.32 W/m/K and a permissible temperature at 207 ℃.

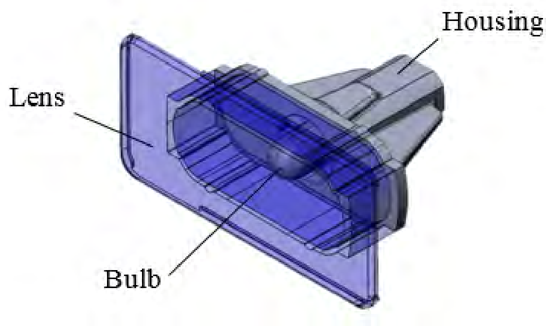


Figure 2. License plate lamp CAD model

3.2 *Hot spot analysis by ray tracing method*

In order to calculate the hot spot or high lux concentration area, the CAD model of the license plate lamp was imported to a physics-based light simulation software named “SPEOS”, then its optical properties such as reflectance and transmittance are applied. After that, the ray tracing method was executed to determine the ray paths, beam pattern, and illuminance of the license plate lamp. The ray path and illuminance results were used as a guideline to indicate the hot spot area with high lux concentration on the plastic covered lens. This hot spot area would answer where the thermal defects could occur on this license plate lamp. With ray tracing method, all irradiated rays, generated by the tungsten filament of W5W incandescent bulb, are traced from the filament through glass bulb before transmit pass the covered lens as shown in Figure 3. Then, an energy in W/m^2 for each ray that incidents on the surfaces of plastic lens was used to calculate a lux distribution on each surface of covered lens in Lux unit as shown in Figure 4. According to operating condition of this license plate lamp, the output luminous flux at 50 lm for 5 watts input is applied for the tungsten filament in ray tracing model. The glass bulb has index of refraction at 1.52 and the absorption coefficient of plastic lens is 0.056 mm^{-1}, while the housing material property is set to opaque.

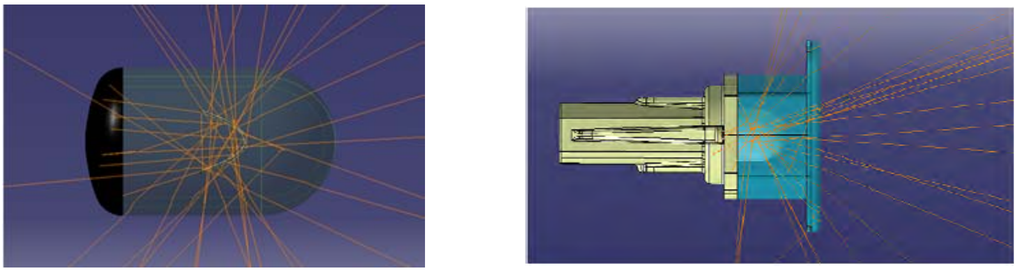


Figure 3. Ray tracing analysis for license plate lamp

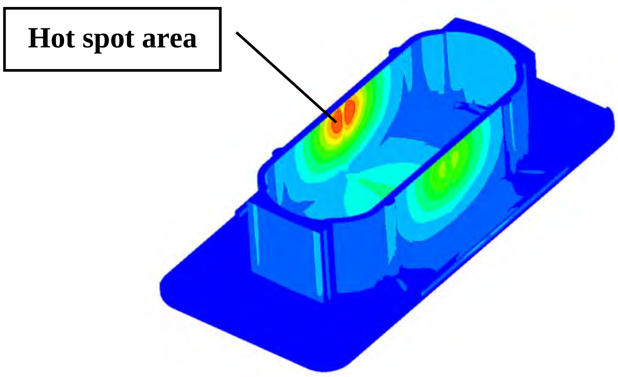


Figure 4. Lux distribution and hot spot on the covered lens of license plate lamp

3.3 *Thermal analysis by finite element Monte Carlo radiation model*

For thermal analysis, the Monte Carlo radiation model in ANSYS CFX module was employed for thermal distribution simulation. The thermal distribution on a license plate lamp is determined under operating condition at ambient temperature 25 °C. The governing equations like conservation of mass, momentum and energy were solved along with Monte Carlo radiation models. The grey medium is assumed for radiative approximation and the simulation was conducted at steady state condition. The fluid inside and outside the lamp is assumed to be incompressible ideal gas where the Boussinesq equation is applied. An electric power at 5 watts is dissipated inside the bulb's filament as a heat loss. This excessive heat is transferred from the filament by radiation and natural convection to glass bulb. Some of the radiation transmitted through the glass bulb can be reflected and absorbed. The bulb, lens, and housing of the license plate lamp is made from the same materials as defined previously. Besides, the optical lens of the lamp was modelled as solids that transport energy by conduction. At the inner surface of the lens, heat is convected to the enclosed air within the housing and at the outer surface of the lens, heat was naturally convected to the ambient air. By using Monte Carlo radiation model, the finite element heat transfer analysis has been initiated from the wire filament surface through an outer lens' surface. Figure 5 below shows the finite element Monte Carlo radiation model with 2,516,843 nodes and 13,764,234 elements for thermal analysis.

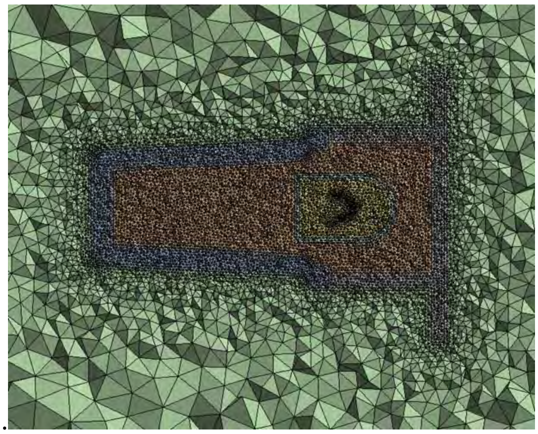


Figure 5. Finite element Monte Carlo radiation model for thermal analysis

4. Thermal Measurement

In order to validate the location of possible thermal degradation area forecasted by ray tracing analysis, the hot spot area simulation results are confirmed with the thermal measurements of a license plate lamp prototype by using thermocouples and IR thermal camera. The thermal testing was carried out on a license plate lamp prototype in the weathering test chamber as shown in Figure 6. The temperature of the lens surface and housing body are directly collected by PT-100 RTDs and transferred to a data logger.

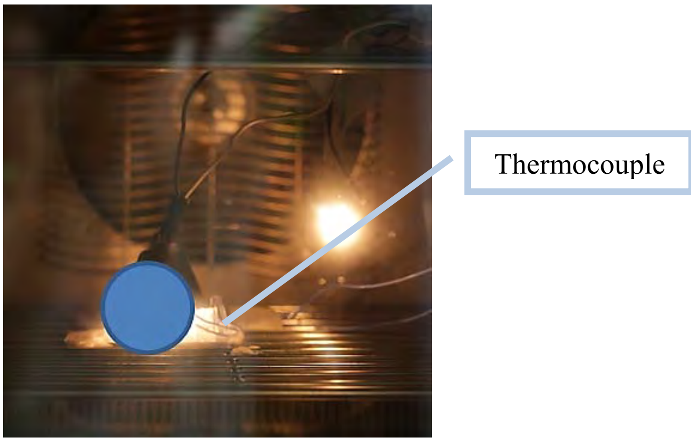


Figure 6. Thermal measurement of a license plate lamp prototype in weathering chamber

From Figure 6, the RTDs are inserted into the material body of lens and housing, where the position of thermocouples are selected referred to the simulation results. The ambient temperature in the chamber was keep constant from initial to steady state. After steady state had reached, thermal images on the lens and housing surface were instantaneously captured by FLIR TG165 thermal camera. With the accuracy of 1.5%, the emissivity and temperature range of 0-360 °C of the camera were set. Then, both high temperature position and value, obtained from thermocouples and thermal camera are compared with the ray tracing mapping and Monte Carlo analytical results for correctness evaluation.

5. Analysis results and thermal measurement validation

After ray tracing method and Monte Carlo radiation model were applied for a license plate lamp analysis. The hot spot area and thermal distribution on the plastic lens were calculated under the operating condition as mentioned earlier. Then, a comparison between numerical results and thermal measurement is presented in this section.

5.1 *Ray tracing analysis results*

With ray tracing method, the illuminance on the outer surface of plastic lens was calculated by tracing rays from a tungsten filament through a glass bulb and transmits to the outer surface of plastic lens. In Figure 7, the lux distribution on the outer surface of the W5W glass bulb shows that the maximum illuminance (hot spot area) locates at the middle area of the glass bulb at 227,900 lux, while the illuminance value continually decreases until reach the minimum value at the top and base area of the glass bulb surface.

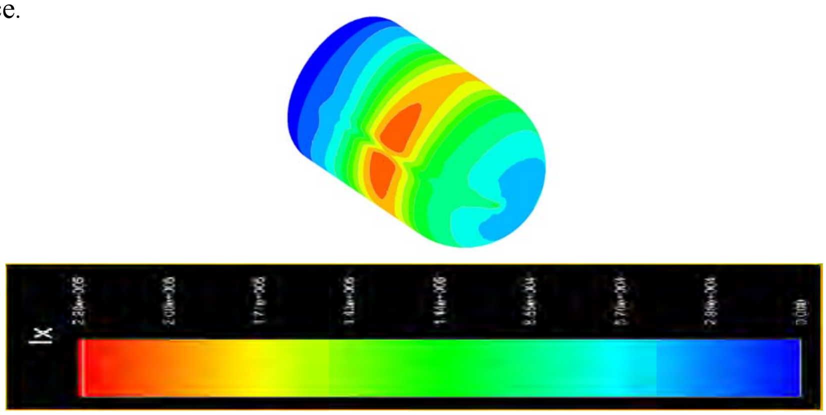


Figure 7. Lux distribution on a surface of W5W glass bulb within license plate lamp

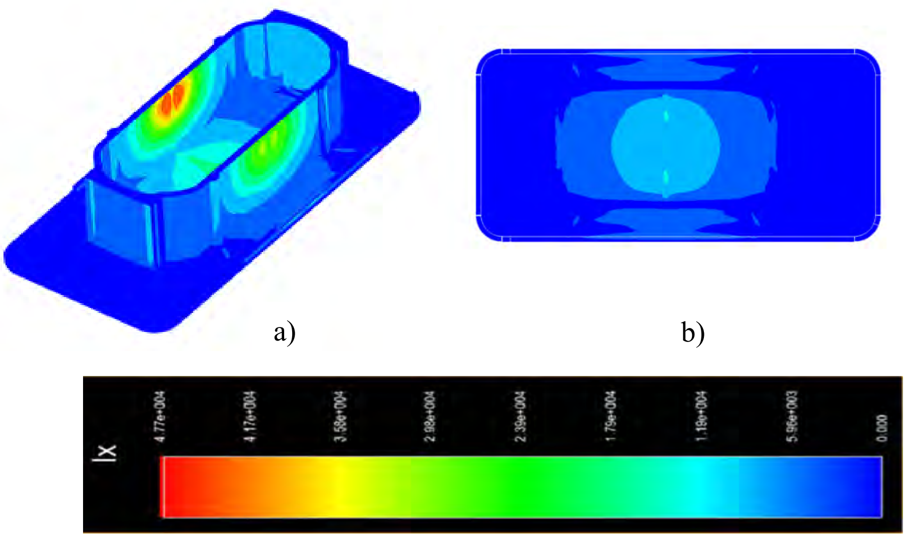


Figure 8 Lux distribution on the plastic lens of license plate lamp.
a) 3D surface of covered lens b) bottom surface of covered lens

According to the lux distribution results in Figure 8, the maximum illuminance (hot spot) is 47,600 lux located near the upper edge at the middle of inner surface on the front side of plastic covered lens as shown in Figure 8a, while the maximum illuminance on the bottom surface of lens is lesser, approximately 12,200 lux as shown by Figure 8b.

5.2 *Finite element Monte Carlo radiation analysis results*

For Monte Carlo radiation model, the 5 watt dissipated heat was applied directly on the tungsten filament of bulb, the radiative and convective heat on the glass bulb was calculated by solving energy transfer equation, then the heat is transferred to the fluid within the lamp, housing, and lens by radiation, convection, and conduction. As a result, the maximum temperature on W5W glass bulb is approximately 311 °C situated at the middle area of the glass bulb surface as shown in Figure 9.

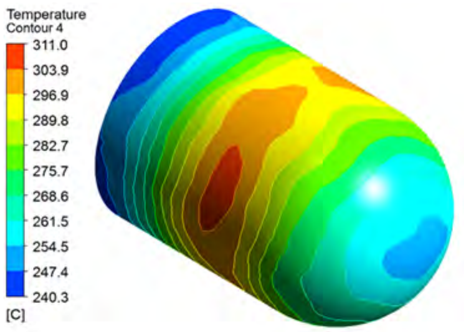
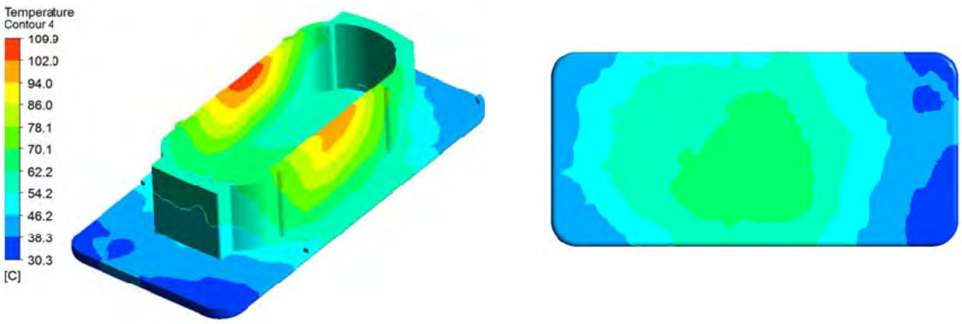


Figure 9. Thermal distribution on a surface of W5W glass bulb within license plate lamp



a) b)

Figure 10. Temperature distribution on license plate lamp using Monte Carlo radiation model
a) 3D surface of covered lens b) bottom surface of covered lens

According to Figure 10, the maximum temperature on the plastic covered lens is 106.8 °C located near upper edge at the middle of front surface as shown in Figure 10a, which quite agree well with hot spot area in ray tracing analysis. While the hot temperature on the bottom surface of lens is approximately 91.2 °C as shown by Figure 10b.

5.3 *Simulation validation with thermal measurement*

For this section, the analysis results carried out by the ray tracing method and finite element Monte Carlo model was compared with thermal measuring by using thermocouple and IR thermal camera as shown in Figure 11.

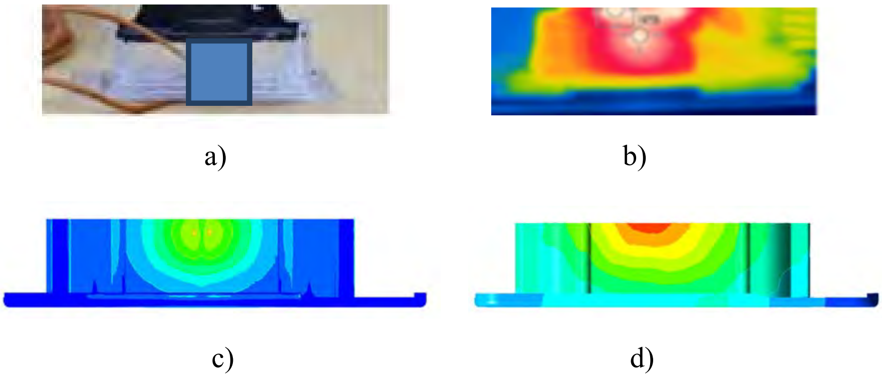


Figure 11. Comparison between a) thermocouple measuring b) IR thermal camera result c) ray tracing result and d) finite element Monte Carlo radiation result

As shown in Figure 11b, 11c and 11d, the thermal image of the covered lens obtained from IR thermal camera and simulation results from ray tracing method and Monte Carlo radiation analysis can be comparable. Figure 11 shows that the high temperature area on plastic covered lens of license plate lamp is quite agree well between a thermal image from IR camera, hot spot area and maximum temperature area. Therefore, the hot spot obtained from ray tracing analysis could be used as a guideline for predicting the possible thermal degradation area on the plastic lens of license plate lamp in the initial illumination design stage.

Table 1 shows the comparison results of temperature of the license plate lamp obtained by thermocouples, IR thermal camera, and Monte Carlo method on the matching locations as shown in Figure 12.

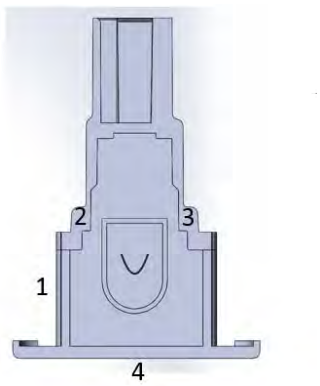


Figure 14. Temperature measuring position on license plate lamp prototype

Table 1. Temperature on license plate lamp obtained by thermocouples, IR thermal camera, and numerical calculation in degree Celsius

Position No.	Thermocouple (°C)	IR Camera (°C)	Monte Carlo (°C)
1	102	107.5	106.8
2	93.6	87.4	95.9
3	90.7	-	90.15
4	90.7	88.4	91.2

From Table 1, the magnitude of temperature obtained from thermocouples and IR camera are close to the numerical analysis by Monte Carlo method. According to the Table, the measuring temperature results and numerical analysis show the same tendency that the maximum temperature locates at position No.1 near the middle of upper edge of front covered lens' surface, which imply that the thermal degradation of this license plate lamp can occur at the front side of lens during thermal testing due to low permissible temperature (125 ℃) of this plastic lens material which this is quite agree well with the hot spot area determined by ray tracing method.

6. Discussion

In this study, although the ray tracing simulation results and finite element thermal analysis support that the hot spot area could be used to predict the possible thermal failure area on small automotive lamp, however there is no clues about how many lux concentration can possibly melt or still harmless to thermoplastic automotive lamp. Therefore, it would be beneficial to benchmark the intensity of lux concentration that melts the thermoplastic components with the physical temperature testing for plastic materials in automotive lamp manufacturing. As shown in Figure 15, another remark is that the temperature distribution on the lens surface obtained from finite element method differs to the almost symmetric lux distribution of ray tracing method due to asymmetrical geometry of covered lens and the domination of conduction, especially in a small-size lamp, where the inside cavity is very small and the heat source is very adjacent to the covered lens.

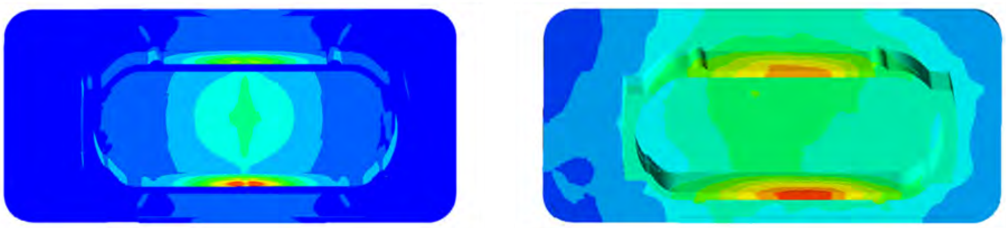


Figure 15. Comparison between hot spot area by ray tracing and FE thermal distribution on the covered lens

7. Conclusion

In this paper, the predictive methodology for thermal degradation area of a small automotive lamp was investigated. With ray tracing analysis, both illuminance and possible thermal degradation area of a license plate lamp can be evaluate in the illumination design stage by considering energy hot spots in lux distribution. This information can facilitate automotive lamp engineers in thermal quality assessment and gives them useful information in the early design stage. Besides, the CFD heat transfer model for filament bulb, housing, and lens was built to predict the thermal behaviour due to radiation from the bulb's filament within the lamp by using Monte Carlo radiation model. According to the results, ray tracing analysis shows that the maximum lux concentration (hot spot) at 47,600 lux on the front side of covered lens, while the bottom surface of covered lens show a lesser illuminace at 12,200 lux, which these results are congruent with finite element heat transfer analysis and thermal measurement by thermocouples and thermal IR image. From the thermal analysis, the maximum temperature at 106.8℃ locates near the upper edge of covered lens' front surface, whereas the bottom lens' surface shows lower temperature at 91.2°C. As a result, the thermal degradation area of the thermoplastic lens can be predicted by ray tracing method and validated with the thermal measuring obtained from prototype testing. In this study, the ray tracing simulation results show that the lux concentration regions are prone to the thermal failure area on the lamp. Although the time consuming Monte Carlo method can give an accurate thermal analysis results for a license plate lamp, but the three-day faster ray tracing analysis can also give a similar tendency of thermal problem area on the license plate lamp as well. In consequence, the thermal degradation area gained from both ray tracing method and Monte Carlo method can be used as a guideline for redesign, if required, or a material selection of the lamp in the early design process.

References

[1] Dechaumphai, P. 2004 *Finite Element Method in Engineering*, Third Ed., Chulalongkorn University Press, Bangkok, Thailand.

[2] Kays, W.M., and Crawford M.E. 1993 *Convective Heat and Mass Transfer*, Third Ed., McGraw-Hill, Inc., Singapore

[3] Siegel, R., and Howell, J.R., *Thermal Radiation Heat Transfer*, Second Ed., Hemisphere Publishing Corporation. USA., 1981, 31.

[4] Walther, A. 1995 *The Ray and Wave Theory of Lenses*, First Ed., Cambridge University Press, Cambridge, UK, 283-285.

[5] Hecht, E. 2002 *Optics*, Fourth Ed., Addison Wesley, San Francisco, USA, 87-103, 128.

[6] Murdoch, J.B.1985 *Illumination Engineering – From Edison's Lamp to the Laser*, First Ed., Macmillan Publishing Company, New York, USA, 27-35.

[7] H.P Bensler, A. de Risi, C. Freek, Heath D and Montefrancesco. E, *Investigation of thermal and fluid characteristics in Automotive headlights*, SAE Technical paper, 2005-24-069.

[8] Costa Edinilson alves and Santos Luis dos 2006 *Wall temperatures and Air flow prediction in automotive headlights utilizing the CFD methodology*, SAE technical paper 2006-01-2646

[9] Sato Harumi, Takaki Nakamura, Minoru Inoue, Yoshiichi Ozeki and Tsunehiro saito. 2011 *Thermal fluid analysis by a mesh free simulation- part 1 Analysis of the thermal fluid field in a headlamp based on the real 3D-CAD model*, SAE Technical paper, 2011-28-0135.

[10] Tankala Triloka, Sudhakar R.Marur and Jim Wilson. 2006 *Rapid thermal predictions for headlamp reflectors*, SAE Technical paper, 2006-01-1189.

[11] Shiozawa Touichirou, Masatoshi Yoneyama, Kiochi Sakakibara, Shuichi goto, Norihisa Tsuda, Tetsuo saga and Toshio kobayashi. 2001 *Analysis of natural convection inside an Automotive headlamp by using CFD and temperature prediction of the parts by SHT method*, SAE Technical paper, 2001-01-0860.

[12] Manoj Kumar S, N. Suresh Kumar, and R. Thundil, *Automotive headlamp using CFD*, IJIRAE paper, ISSN: 2349-2163

[13] Christian Mielke, Stepan Senin, Andreas Wenzel, and Carsten Horn. 2011 *Simulation of the temperature distribution in automotive headlamps*, NAFEMS International Journal of CFD case studies, volume 9

[14] ANSYS CFX 2012 version 12.1, user manual, www.ansys.com/products/icemcfd.asp Contact Information