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Simulation Based Temperature Profiling of Human Eye due to the Exposure of LED Light

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Abstract

The use of LED luminaries is increasing day by day and the traditional sources of light are being replaced by this semiconductor technology. In this study, the interactions of Red, Green and Blue LED light with human-eye are considered to model the temperature profile due to the attenuation in the ocular media. The simulation has been done using COMSOL Multiphysics 5.3. The results of the study show that Blue LED light causes temperature rise more than the other two colours of light. At the tip of the corneal surface, blue LED light causes the temperature to rise by 0.91^0C whereas the rise of temperature for green and red LED are 0.85^0C and 0.46^0C respectively. However, the temperature at the posterior layers of the eye, sclera, choroid and retina undergoes little thermal effects due to LED light owing to the fact that the heat-flux due blood flow is dominant in that region.

Keywords: Human eye, Temperature, Homogenous Region, LED Light, Numerical Method

I. Introduction

The use of Light Emitting Diode (LED) has grown up very fast with the increase of the use of different electronic gadgets like laptop, smart-phone, personal-computer etc. Now-a-days, the use of smart devices has reached a point that people spend most of the time viewing the electronic displays. LED is used as the backlighting unit to produce different colors in different types of electronic displays[1]. In addition, indoor and outdoor luminaries based on the LED technology have seen a rapid progress in the past decade due to its high energy efficiency than the traditional light sources of incandescent and fluorescent lamps[2,3].

The power spectrum of LED light is pseudo monochromatic making it different than the conventional light sources being used throughout the past century[3].Visible light passes through the ocular-media of cornea, aqueous humor, pupil, lens and vitreous humor to reach retina and creates the sense of vision[4]. While passing through the ocular media, light interacts with different ocular tissues which results in reflection, refraction, absorption and scattering of light depending on the wavelength of light and the properties of the respective eye-tissue[5]. As the spectrum of LED has a distinct characteristic, the interactions of LED light with the intra-ocular media are also different[5].

As a vastly growing technology, the interactions of LED light with eye have earned the interest of different researchers throughout the world. A research-work has been carried out on the effects of LED light on the ocular surface of mouse[6]. Characterizing the possible hazards of commercially available LED lamps by analyzing the effects on the eyes of rabbits and monkeys have been presented[2]. Studies have presented the assessment of risks of blue light emitted by the LED lamps[7,8]. The effect of the LED displays on the suppression of melanin has been studied[9]. A study has portrayed the phenomenon of melatonin suppression due to different types of electronic lamps including LED and the results show the LED screen to be responsible to disorder the sleep cycle[10]. The hazardous effects of blue LED light from the electronic devices have been assessed and the results show the LED screen with the blue light filter to be better for longer screen-times[11].

Temperature profiling of human eye, based on computer simulation and numerical methods has become an area of interest among the researchers[12,13]. Changes in the temperature profile of eye due to the external effects like electromagnetic radiations, infrared ray, sunlight, etc. have been studied in the previous studies[14,15,16,17]. A study has shown the analysis of wearing glasses on the alteration of human eye temperature at different weather conditions[18]. The alterations of ocular temperature with age have been analyzed in[19,20]. The effects of radio frequency radiations have been modeled and the results reveal the rise of ocular temperature due to the external thermal effects[17]. The effects due to working in the exposure of infrared ray have been studied and the results portray the detrimental effects of the prolonged exposure of infrared radiation[21,22].

After reviewing the research-articles present in the literature, it is observed that the thermal effects on human eye due to the exposure of LED light are yet to be carried out. A study shows that eye-temperature profile can be used as an indicator of healthy and diseased eyes[22]. It can also be helpful to predict or analyze the chances of thermal damage due to different types of radiation[23]. In this paper, the changes of ocular temperature due to LED light have been analyzed using numerical analysis. The temperature profiles of the human eye, including and excluding the effects of LED have been developed in this study. The exposure of LED has been modeled for three colors of LED light: red, green, and blue. The simulation has been carried out in the COMSOL Multiphysics using a 3D model of the human eye, developed in the Solid Works.

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II. Methods & Materials

This work focuses on determining the effects of LED light exposure on ocular tissue. The effect is quantified by measuring the increase of ocular temperature due to light exposure of different wavelengths. The simulation of ocular tissue is done using Finite Element Method. The simulation platform is integrated with two different types of physics, namely Optical physics to generate light source and Bioheat transfer physics to calculate the heating effect due to exposed light. The work flow can be illustrated using the flow diagram in Figure 1.

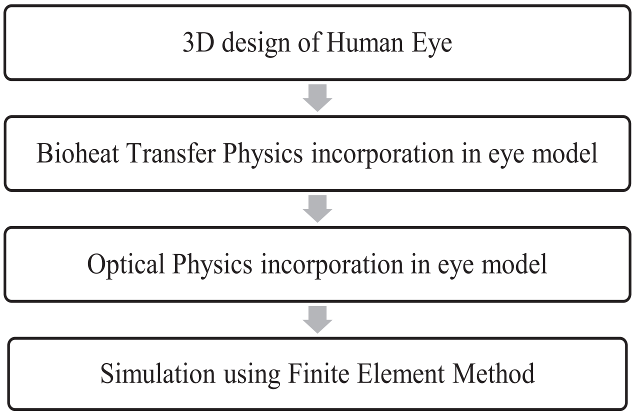

Fig. 1. Work Flow of the study

(a) 3D Design of Human-Eye

Human eye is a very complex biological structure with different types of tissues. In the literature, the research-works on schematic eye are also based on the assumptions of some homogenous regions[24]. Using SolidWorks, a 3D geometric model of the human eye is created in this study. The cornea, aqueous fluid, lens, iris, ciliary body, vitreous humor, retina, choroid, and sclera are among the nine homogeneous areas in the geometric model. Fig.2 shows a 2D image of the geometric-model of the human eye. The eye-model has a pupillary axis of 24 mm and a vertical axis of 22.5 mm in diameter.The thicknesses of different eye-tissues are taken from the literature[5,25]. A 3D view of the developed geometric model is shown in Fig. 3.

(b) Governing Equations of the Temperature Distribution

The temperature-profile of human-eye without any external effects is produced considering only the biological phenomena within the eye. The temperature profile is generated by solving the Penne's bioheat transfer equation shown in (1)[5].

$$\rho c\left(\frac{\partial T}{\partial t}\right)=\nabla\left(k\nabla T\right)+\omega\rho_b c_b\left(T-T_b\right)+Q \qquad (1)$$

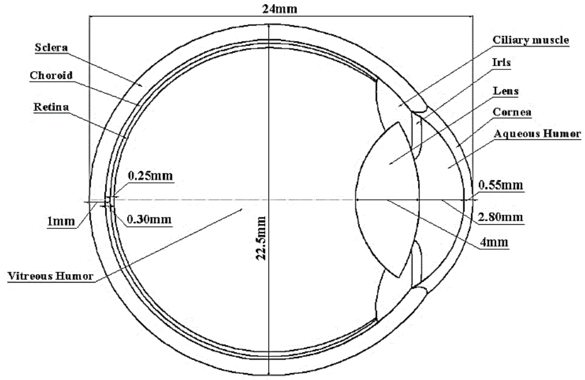

Fig. 2. 2D View of the Developed Human-Eye Model including the Dimensions.

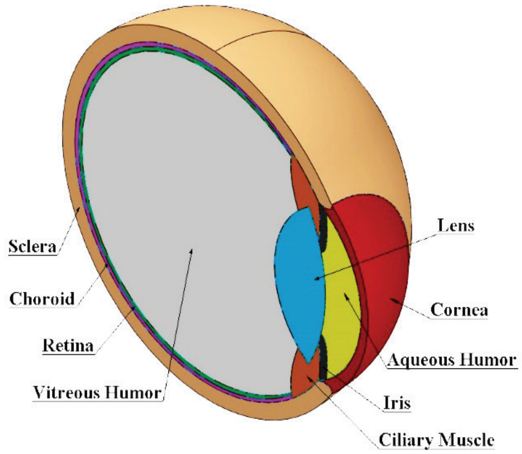

Fig. 3. 3D View of the Developed Human-Eye.

In this equation, ρ is Density (kgm^{-3}),c is Specific heat (J $kg^{-1}K^{-1}$), ω is the blood perfusion rate (1/s), k is the thermal conductivity of local tissue ($Wm^{-1}K^{-1}$), Q is heat generation (Wm^{-3}) due to metabolism or from external sources, T is temperature (K), and tis time (s). The partial derivative of the temperature with respect to time, $\rho c\left(\frac{\partial T}{\partial t}\right)$ represents the variations of temperature with the progress of time in the ocular tissues. Blood is denoted by the subscript b. The gradient of temperature in the developed human eye model is represented using the term $\nabla\left(k\nabla T\right)$. The next term on the right-hand side of equation (1), $\omega\rho_b c_b\left(T-T_b\right)$ models the effects due to blood flow. The last term on the right-hand side of equation (1) represents the internal and external heat sources by the term Q.The value of ω is typically small, for which the contribution in temperature rise due to blood flow becomes quite negligible when compared to temperature rise due to external sources. Hence, in this study, the term related to the blood flow, $\omega\rho_b c_b\left(T-T_b\right)$ has been neglected to simulate the heat transfer in the eye[24].The thermal properties for the heat transfer simulation are shown in Table 1.

Table 1. Thermal Properties of the Homogenous Ocular Regions[5].

Ocular Region	Thermal Conductivity k $(Wm^{-1}K^{-1})$	Specific Heat c $(JKg^{-1}K^{-1})$	Density ρ (Kgm^{-3})
Cornea	0.58	4178	1050
Aqueous Humor	0.58	3997	996
Lens	0.4	3000	1050
Iris	1.0042	3180	1100
Vitreous	0.603	4178	1000
Sclera	1.0042	3180	1100
Retina	0.565	3680	1039
Choroid	0.530	3840	1040
Ciliary	0.498	3340	1040

(c) Boundary Conditions of the Heat Transfer Simulation

Blood flow creates the heat generation at sclera. The generated heat spreads throughout ocular media due to convection. The phenomena can be modelled using (2)[18].

$$k\frac{\partial T}{\partial n} = h_b\left(T - T_b\right) \tag{2}$$

The normal direction to the surface boundary is *n*, the convection coefficient between the blood and the eye is h_b, the blood temperature is T_b, and the thermal conductivity is *k*. Heat is lost at the cornea owing to three different types of heat transfer pathways. At the corneal surface, the heat loss occurs due to convection, radiation and tear evaporation. The phenomena are represented using (3)[26].

$$k\frac{\partial T}{\partial n} = h_{amb}\left(T - T_{amb}\right) + \sigma\epsilon\left(T^4 - T_{amb}^4\right) + E \tag{3}$$

In this equation, the term in the left-hand side represents the heat flow in the normal direction to the corneal surface. The convection of heat between cornea and the surrounding air is modelled by the first term of the right-hand side. h_{amb} is the convection coefficient and $T_{amb}$is the ambient temperature. The second term represent the radiative heat transfer between the corneal surface and the surrounding air where σ is the Stefan–Boltzmann constant and ϵ is the emissivity of the cornea. The third term, E, represents the phenomenon of tear evaporation. The values of these parameters are given in Table 2.

Table 2. Parameters at the Boundary[27].

Parameter	Value
Blood convection coefficient, h_b	65 $Wm^{-2}K^{-1}$
Blood temperature, T_b	37^0C (310 K)
Ambient convection coefficient, h_{amb}	10 $Wm^{-2}K^{-1}$
Ambient temperature, T_{amb}	25^0C (298 K)
Stefan–Boltzmann constant, σ	5.67 x10^8 $Wm^{-2}K^{-4}$
Emissivity of cornea, ϵ	0.975
Tear evaporation rate, *E*	40 Wm^{-2}

(d) Modelling the Effects of LED Light in the Simulation

Light enters the human-eye through the cornea. Then, it goes through aqueous humor, lens and vitreous humor to reach the retina to create the sense of vision. As light travels through the ocular media, the attenuated rays deposit its energy in the ocular tissue. The deposited energy is absorbed by the eye-tissue and causes the temperature to rise[28]. In this study, the Ray Optics Module and the Bioheat Transfer Module of COMSOL Multiphysics 5.3a are coupled to simulate the heat transfer phenomena of the ocular media due to LED radiation[29].

In the COMSOL Multiphysics Ray Optics Module, the attenuation of rays occurs through a medium with complex refractive index $\alpha - i\beta$, where α is the real part of the refractive index and β is the imaginary part[29]. The real part, α, is responsible for the refraction at the surface of different mediums. The imaginary part, β is responsible for the attenuation within the ocular tissue. The attenuation of the intensity and power of a ray travelling through the ocular media is governed using (4)[29].

$$I = I_o \exp\left(-\frac{2k_o\beta L}{\alpha} cos\alpha\right) \tag{4}$$

In this equation, *I* is the attenuated intensity for an initial intensity of I_o. *L* is the optical path length and $k_o$is the wavenumber in free space. The energy lost due to the attenuation is used to calculate the heat generated in the ocular media.

In many applications of LEDs, like white LED lamps, displays of the smart devices etc. Red, Green, and Blue (RGB) LEDs are used to produce different colors[30]. As RGB LED is the fundamental component in different applications, in this study the interactions of RGB LED light with human-eye is considered to bring out the temperature-profile of the human eye. The properties of the RGB LED light are taken from a study conducted on mouse ocular surface due to the overexposure of LED light where the irradiances of the RGB LED are measured using spectroradiometer[6]. The properties of the RGB LED light are shown in Table 3.

Table 3. Intensity of LED Light in the Simulation[6].

Colour of LED Light	Wavelength (nm)	Intensity (mW/cm^2)
Red (R)	630±8	48.8
Green (G)	525±2	59.5
Blue (B)	410±10	29.2

In the simulation, LED light entering the eye is parallel to the optical axis as illustrated in the ray trajectory of Fig. 4. The rays entering through the cornea in Fig. 4 are parallel and they coincide at the posterior focal point on the retina. The black lines in this figure represent the rays of light.

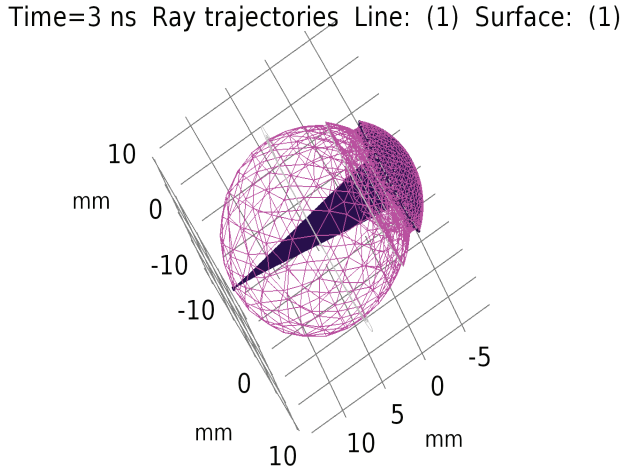

Fig. 4. Simulated Ray Trajectory through the Developed Human Eye Model.

(e) Optical Properties of Ocular Tissues for the Simulation

To simulate the phenomena of the light travelling through the ocular media, the refractive index and the absorption coefficient needs to be defined. The refractive index is needed to simulate the light trajectory at the refracting surfaces within the eye. The absorption coefficient of a particular ocular tissue is needed to calculate the imaginary part of the complex refractive index, β to simulate the phenomena of the absorption of light using the Ray Optics Module of COMSOL Multiphysics.Though refractive index, α is dependent on wavelength, it is assumed to be constant throughout the spectrum of visible light for different ocular tissues. The refractive index of the refracting media of the eye are given in Table 4.

Table 4. Refractive Index of the Ocular Tissues[31].

Parts of the Eye	Refractive Index, ***α***
Cornea	1.377
Aqueous Humor	1.337
Lens	1.420
Vitreous Humor	1.336

The absorption coefficient, μ_a data is not readily available in the literature. It is derived from the value of the transmittance using (5)[5].

$$\mu_a = -\frac{1}{d}\ln\left(\frac{T_r}{100}\right) \tag{5}$$

$$\beta = \frac{\mu_a \lambda}{4\pi} \tag{6}$$

In this equation, T_r is the percentage transmission of the ocular tissue and d is the thickness of the corresponding tissue. The thickness, d of the ocular tissues is shown in Table 5. The values of the transmittance and the absorption coefficient of ocular tissues used in the simulation are shown in Fig.5 and Fig.6 respectively. The values of transmittance are taken from a study[32]. Absorption coefficients are derived using equation (5). Equation (6) relates the absorption coefficient, μ_a and the wavelength, λ of light with the imaginary part of the complex refractive index, β. The imaginary part of the refractive index, β is calculated from the absorption coefficient using (6)[33].In this study, cornea, aqueous humor, lens and vitreous humor are considered transparent and their interactions with light are considered to develop the temperature-profile. The remaining ocular tissues are considered to be opaque for simplification and lack of available literature data.

Table 5. Thickness of the Ocular Tissues to Determine the Absorption Coefficient.

Eye Tissue	Cornea	Lens	Aqueous Humor	Vitreous Humor
Thickness,d (mm)	0.55	4	3	15.1

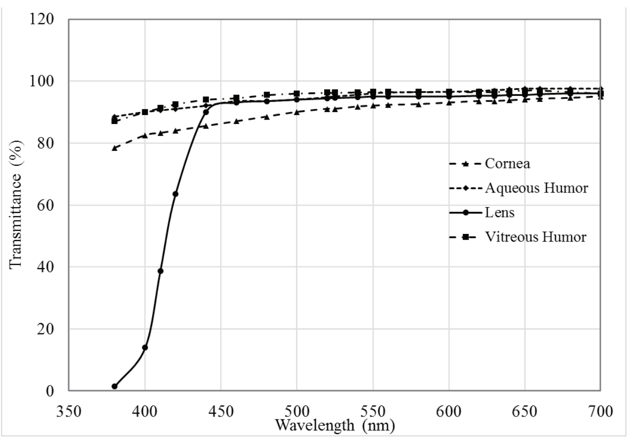

Fig. 5. Percentage Transmittance of the Ocular Tissues (redrawn)[5].

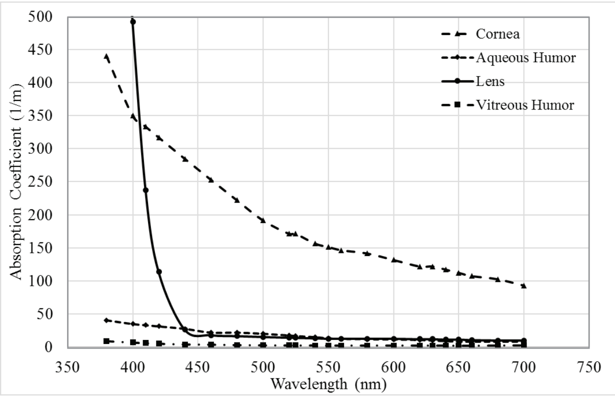

Fig. 6. Absorption Coefficients of the Ocular Tissues.

(f) Numerical Methods

The analytical solution of Penne's bio-heat transfer equation is confined to a few basic geometries with a high degree of symmetry, but we may tackle issues with complicated geometry, such as the human eye, using the Finite Element Method. COMSOL Multiphysics uses the Finite Element Method to solve Penne's bioheat transport equation (FEM). The 3D geometry imported to the COMSOL Multiphysics has nine domains. Each homogenous regions of the developed 3D human-eye represents each domain. The 3D geometry of human-eye is symmetrical along the pupillary axis. So, the half-section of a complete 3D human-eye is designed and used for the simulation to be efficient in terms of the memory and the time of computation. The simulation is conducted for 10000s in the COMSOL Multiphysics software. The developed computer aided design of the human eye has 9 domains, 35 boundaries, 65 edges, 40 vertices.Tetrahedral mesh elements are used to build the mesh for FEM simulation with 345340 domain elements,61023 boundary elements, 2046 edge elements.The developed computer aided design of the human eye has been imported in the COMSOL Multiphysics 5.3 for simulation and the meshedeye-modelis shown in Fig. 7.

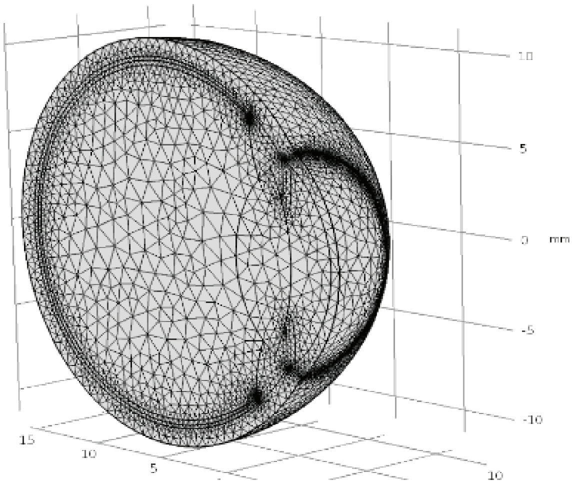

Fig. 7. The 3D Human-Eye after Meshing using Tetrahedral Elements.

III. Results and Discussion

To observe the time-dependent behavior of the eye-temperature, the developed 3D temperature profiles are evaluated at,

- Tip of the anterior surface of cornea
- Tip of the anterior surface of lens
- Tip of the posterior surface of lens

These points are selected as the LED exposure causes the temperature to rise in the cornea, aqueous humor and lens region more than that of in the other parts of the eye.In Fig. 8 to Fig. 10, the temperature profiles at the mentioned points of eye are shown. The temperature curve without the LED effect is marked using solid line and labelled as normal conditions. In all the cases, it is observed that the blue LED causes the temperature to rise more than the other two colors of light. The temperature rises from the initial condition of the simulation to the steady state temperature in each of the cases. At steady state condition, blue LED light causes the temperature to rise by 0.91^0C at the tip of the corneal surface whereas the rise of temperature for green and red LED are 0.85^0C and 0.46^0C respectively, as shown in Fig. 10. The time varying temperature profiles at the other two points of eye also show a similar rise of temperature with blue LED causing the maximum rise of temperature.

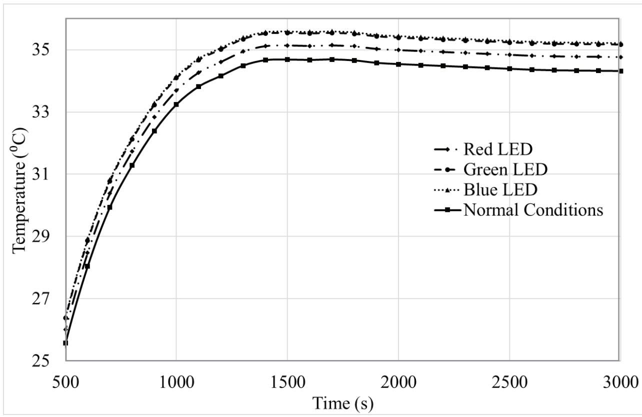

Fig. 8. Temperature vs Time at the Surface of Cornea.

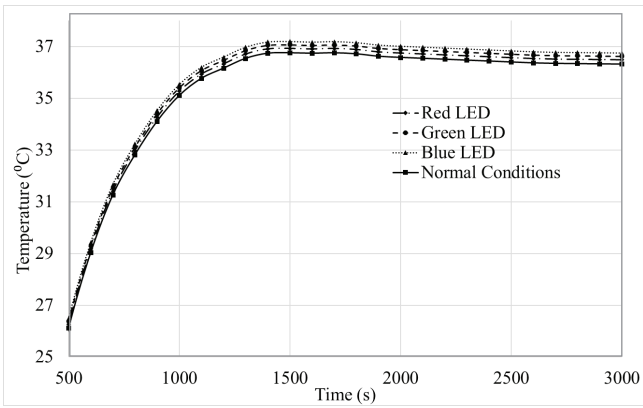

Fig. 9. Temperature vs Time at the Anterior Surface of Lens.

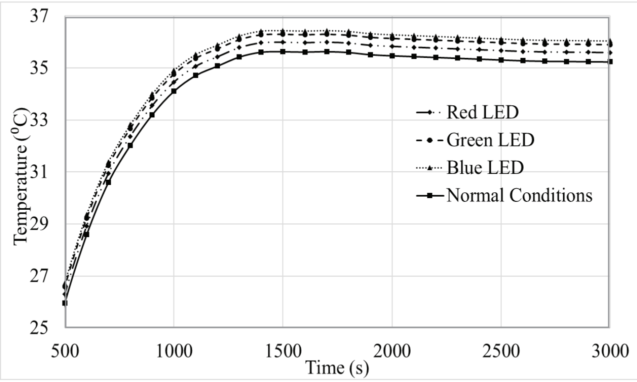

Fig. 10. Temperature vs Time at the Posterior Surface of Lens.

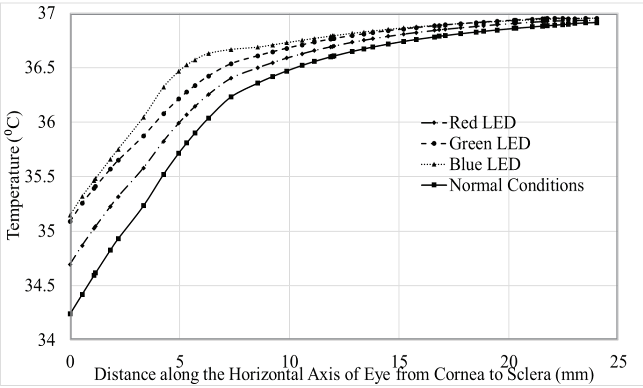

Fig. 11. Temperature-Rise vs Distance along the horizontal axis from Cornea to Sclera.

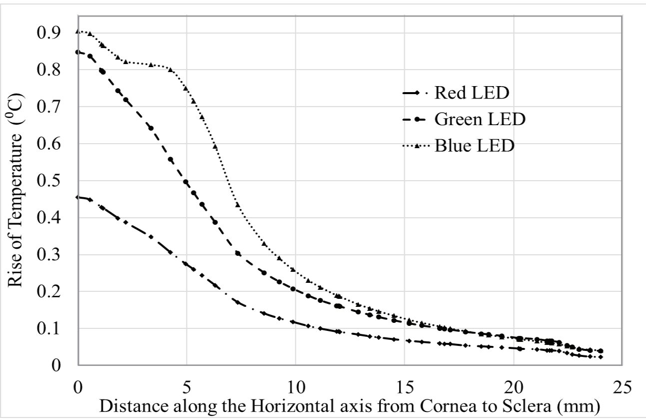

Fig. 12. Temperature vs Distance along the Horizontal Axis of the Human-Eye Model from Cornea to Sclera.

The developed temperature-profiles of human eye shows 34.2^{0}C at the corneal surface. The mean temperature in the literature is found to be 34.65^{0}C[24]. This discrepancy is due to the fact that boundary conditions and different control parameters like ambient temperature, blood temperature, convection coefficient etc. are not equal in different studies[24]. The differences in the geometrical modelling of eye in different studies are also responsible. The comparison of the temperature rise along the horizontal axis of eye from cornea to sclera is shown in Fig. 11. The black solid line in Fig. 12 represents the eye-temperature without the LED effect.

In Fig. 11 and Fig. 12, the distance of 0 mm represents the surface of the cornea whereas the outer surface of sclera is at the distance of 24 mm. These figures show that blue LED light is responsible for the maximum temperature rise in the eye. The maximum rise of temperature due to blue LED is 0.91^{0}C at the surface of cornea. This phenomenon can be supported by the fact that blue light has lower wavelength and higher frequency compared to red and green light. So, the blue light has higher energy according to the formula, $E=h\nu$, where h is the Plank's constant and ν is the frequency of light.

As the simulation of COMSOL Multiphysics considers the attenuation of rays in the absorbing media to build the temperature profile, the higher energy of blue LED deposits more energy in the ocular media compared to the other two colors of LED light. The Red LED light causes the temperature to rise by 0.46^{0}C at the surface of cornea making it lowest among the three colors of LED. There is negligible rise of temperature at the posterior part of the human-eye model where ocular layers of retina, choroid and sclera are situated. This phenomenon can be explained by the fact that there is blood flow in this region of the eye. Heat transfer due to blood-flow is dominant in this part of the eye. As a result, the temperature-profile in this region is also close to the blood temperature.

IV. Conclusions

The purpose of this study was to develop the temperature profile of human eye due to the exposure of LED light. The study was conducted to bring out the effects of Red, Green and Blue (RGB) LED light on the heat transfer phenomena of human-eye. As the rays of light goes through the ocular media, the energy of light is absorbed by the intra-ocular tissues. The absorbed energy results in heat that propagates throughout the ocular media. The boundary conditions at sclera and cornea define the heating and cooling mechanisms of eye respectively.

To summarize, the results of this study, the following points can be made,

- The temperature-profile of the unexposed human-eye gives 34.2^{0}C at the surface of the cornea which resembles the data found in the literature.
- The temperature profile of the human-eye under the influences of LED light shows a rise in the temperature in the ocular media due to the absorption of the energy of light.
- The Blue LED light causes the temperature to rise more than the other two colours of LED with a maximum of 0.91^{0}C at the surface of the cornea. The temperature rise due to red light is 0.46^{0}C at the corneal surface being lowest among the three colours of LED.
- The values of temperature at sclera, choroid and retina undergo negligible rise due to the dominant effects of blood flow in these tissues.

There are scopes to improve the results of this study to make it more relevant to the practical situations. The iris is an absorbing media which was neglected due to the lack of directly available data in the literature. Research will be continued to overcome this limitation. Neglecting the energy absorbed by the layers of retina, choroid and sclera has a minor effect on the temperature profile as discussed earlier.

The research-work was conducted using the parameters of a healthy eye. The results of this study reflect the temperature-profile of a healthy person. Studies are being conducted to find the relations between the temperature of healthy and diseased eye. The result presented in the study will be helpful to diagnose eye having disturbances in the temperature-profile.

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