Effects of the environment on thermo physiological responses via 3D human eye model with porous media heat transfer theory under inconstant solar irradiation

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Abstract
The human eye is one of the most sensitive parts of our entire body. The lens is an important component of the eye, and it also plays an important role in vision. A lens has a normal temperature below 38.5°C. Thermal effects with solar irradiation result in the temperature of the lens to increase to more than 38.5°C and may significantly influence the thermal physiologic response which, in turn, will cause the deterioration of the lens. Therefore, investigation to get knowledge and guidelines to avoid thermal effects from the environment with solar irradiation, will help prevent the eyes from deterioration. However, the study of invasion, within the human body is impracticable. The study of environmental effects on thermo physiological responses within the human eye, from numerical analysis, is another alternative that is gaining attention worldwide. The purpose of this research is to learn about thermal physiologic response on human eyes exposed to solar irradiation, using the three-dimensional (3D) model by finite element method (FEM) via a computer program. This study uses the heat transfer equation and the Navier-Stroke equation to describe heat transfer phenomena in porous mediums and fluid flow phenomena within the 3D human eye model, based on considering the natural convection heat transfer of aqueous humor and vitreous humor, under inconstant solar irradiation. The effects of the environmental parameters such as ambient temperature and air convection heat transfer coefficient are investigated. The results show that the case study which makes the best cooling mechanism is the effect of ambient temperature with ambient temperature at 25°C and effect of air convection heat transfer coefficient at 40 W/m²·K that the eye can absorb maximum solar irradiance at 575 W/m² at the lens reaches 38.5°C and the worst cooling mechanism is the effect of ambient temperature with ambient temperature at 35°C that the eye can absorb maximum solar irradiance at 360 W/m² at the lens reaches 38.5°C. The results from this study provide the essential aspects for a fundamental understanding of thermal physiologic response within human eye subjected to solar irradiation.

Keywords: Human eye, Porous media, Finite element method, Environmental effects
1. Introduction

The human eye is an important organ used for seeing. An important part of the eye, sensitive to heat, is the lens. The lens is a medium, that controls light going to the retina, and then the sensory system generates the image [1]. Lenses deteriorate faster as heat increases their temperature. The International Commission on Non-Ionizing Radiation Protection (ICNIRP) Guidelines specified the lens’s normal temperature should be below 38.5°C [2]. The three types of solar radiation are ultraviolet (UV), visible light and infrared (A and B) [3]. ICNIRP Guidelines indicated that the iris absorbs visible light and infrared-A region which are the main part of solar radiation [3-4]. Iris heat generation is performed on the lens which results in a higher lens temperature [5-6]. However, the invasive study of human bodies to measure some parameters such as the lens’s temperature, it is limited. Therefore, to gain insight into the heat transfer phenomena and thermo physiological responses in the human body, especially within the human eye subject to solar irradiation, investigations are carried out via numerical simulation. Furthermore, numerical simulation under various conditions can be utilized to determine and identify essential parameters, as well as providing guidance for different applications.

Previously, many researchers have studied heat transfer phenomenons in the eye. In 1982 Lagendijk J. J. W. [7] set an invasive experiment to measure the thermal properties of rabbit eyes. Some thermal properties were used in the rabbits’ eye model to analyze heat transfer using the finite-difference method (FDM). The results showed that the temperature of rabbit eyes, between the experimental and the numerical results, were similar in each component. Scott, J. A. [8] studied temperature distribution on the two-dimensional (2D) of human eye model based on the bio-heat transfer equation and solved the governing equations with boundary conditions by the finite element method (FEM). The human eye model was constructed consisting of four homogeneous domains, and thermal properties of the human eye component from previous research was used. The effects of the ambient temperature and the body-core temperature on the temperature distribution within the human eye was considered. After that, the human eye model was developed by Ng, E. Y. K. and Ooi, E. H. in 2006 [9]. The three-dimensional (3D) symmetry of human eye model with six components were presented. The bio-heat transfer equation to study the temperature distribution of human eye model were solved using FEM via computer simulation. Ooi, E. H. and Ng, E. Y. K. in 2008 [10] improved their human eye model from the previous human eye model. The flow phenomenon of aqueous humor (AH), which remains behind the cornea, with buoyancy force due to the temperature difference of AH (Boussinesq approximation) was considered. The lens deterioration from high ambient temperature was investigated by Sharon N. et al. [11]. The computational fluid dynamics (CFD) was used to solve the problem and to determine the temperature in the eye lens when exposed to environmental temperature fluctuations. It was found that the damage appeared earlier in the 6 h exposure and proceed from the lens anterior suture to its center. Optical damage was recovered in lenses exposed 1 h to 39.5°C, but the damage remained in the lens epithelial cells. Heat transfer in porous media was used in the human eye model to represent the actual eye because the actual eye components consisted of 2 phases in each component i.e., tissue and blood phases. Wessapan T. and Rattanadecho P. [12] applied the porous media heat transfer theory with modified Pennes bio-heat transfer to describe the temperature distribution on the 2D human eye model which iris and sclera were treated as the porous medium domains. The temperature distribution under the electromagnetic field at 900 MHz with the influences of ambient temperature were studied. The porous media heat transfer theory with local thermal equilibrium (LTE) model was widely used for investigating temperature changes in various tissues during thermal ablation [13-14]. There are many treatment methods for eye such as laser treatment using numerical simulation was useful for investigating the thermal effect and thermal damage with the appropriate power, time and processing position [15]. Garcia O. P. et al. [16] investigated the effects of vitreous humor (VH) flow phenomenon under the heating by laser-induced on the 2D human eye model with various size tumors at the retina under the various power of the laser. Although there have been studies on heat transfer phenomenon in human eye model based on LTE assumption, very few works have studied thermo physiological responses via 3D human eye model under inconstant solar irradiation with porous media heat transfer theory. Furthermore, the human eye models from the literature review are mentioned before, there are
still differences from the actual human eye because of the complexity of the model. The model that is representative of the real human eye will contribute to a greater clarity concerning attributes more closely to actual behavior of heat transfer phenomenon in human eye subjected to solar irradiation.

In this study, improves the 3D human eye model base on porous media heat transfer theory by considering the natural convection heat transfer from aqueous humor and vitreous humor to represent the actual human eye. The heating load of this research focuses on inconstant solar irradiation with increasing function depend on the time is absorbed by iris only then convert to the heat generation. The effects of the environment such as the effect of ambient temperature and the effect of air convection heat transfer coefficient are considered. This research purpose to investigate the intensity of solar irradiance that makes the lens’s temperature reach the maximum normal temperature of the lens (38.5 °C). The analysis from this study serves as essential fundament for the understanding of thermal physiologic response within human eye exposed to the solar irradiation.

2. Methodology
This section is divided into 3 sections to explain the details of this research which consist of the modeling and materials, the governing equation and boundary condition and the numerical method.

2.1 Modeling and materials
This research constructs the 3D human eye model with the dimension of human eye elements as following the human eye model from the literature reviews. The human eye model has 25 mm diameter, cornea thickness 0.5 mm and 7.7 mm radius, anterior chamber length 3.4 mm, iris thickness 0.5 mm, ciliary body thickness 2 mm, lens thickness 4.2 mm and height 9.6 mm, pupil radius 2.5 mm, sclera thickness 0.99 mm, choroid thickness 0.2 mm and retina thickness 0.25 mm [17] as shown in Figure 1. The essential thermal properties for simulation as shown in Table 1. The heat load, which is an increased function of solar irradiation used in the analysis, as shown in Figure 2. The solar irradiance was measured during a clear sky day in Bangkok, Thailand [18]. This research considers only 2 regions of the electromagnetic wave in solar irradiation, there are visible light region and near-infrared or infrared-A region.

![Figure 1. The 3D human eye model in (a) front view and (b) side view](image)
Figure 2. The time-dependent functions of solar irradiance

Table 1. Thermal properties in each element [17]

| Human eye model’s element | Density $\rho$ (kg/m$^3$) | Thermal conductivity $k$ (W/m·K) | Specific heat capacity $c_p$ (J/kg·K) |
|---------------------------|---------------------------|----------------------------------|-------------------------------------|
| Cornea (a)                | 1050                      | 0.58                             | 4178                                |
| Aqueous humor (b)         | 996                       | 0.58                             | 3997                                |
| Iris (c)                  | 1100                      | 1.0042                           | 3180                                |
| Posterior chamber (d)     | 996                       | 0.58                             | 3997                                |
| Ciliary body (e)          | 1040                      | 0.498                            | 3430                                |
| Lens (f)                  | 1050                      | 0.4                              | 3000                                |
| Sclera (g)                | 1100                      | 1.0042                           | 3180                                |
| Choroid (h)               | 1060                      | 0.53                             | 3840                                |
| Retina (k)                | 1039                      | 0.565                            | 3680                                |
| Vitreous humor (l)        | 1000                      | 0.603                            | 4178                                |

2.2 Governing equation and boundary condition

An analysis of heat transfer and fluid flow within the 3D human eye model subjected to the solar irradiation will be illustrated. The governing equations as well as initial and boundary conditions are solved numerically using the FEM to determine the temperature distribution and the velocity profile of the 3D human eye model. Heat transfer analysis of the human eye model has the assumptions to simplify the problem as follows: 1. There is no phase change in each domain. 2. Thermal properties in each domain are constant. 3. Porous mediums analyze with the local thermal equilibrium between tissue and blood. 4. There is no chemical reaction in each domain. 5. The thermoregulation mechanism is neglected. The heat transfer equation which implements to the porous medium domains (c, h) based on the modified Pennes bio-heat transfer as given in equation (1), the homogeneous solid domains (a, d, e, f, g, k) based on the classical conduction heat transfer equation as given in Equation (2) and the homogeneous fluid domains (b, l) based on convection heat transfer equation as given in Equation (3).

\[(1-\phi)\rho c_p, i \frac{\partial T_i}{\partial t} = \nabla \cdot (\nabla T_i) + \rho_{bl} c_{p, bl} \phi_{bl} (T_{bl} - T_i) + Q_{ext, j} + Q_{ext} = \alpha I(t)\]  

where $T$ is the temperature (°C), $\rho$ is the density (kg/m$^3$), $c_p$ is the specific heat capacity (J/kg·K), $k$ is the thermal conductivity (W/m·K), $\phi = 0.85$ is the porosity [19], $\rho_{bl} = 1060$ kg/m$^3$ is the density of blood [17], $\phi_{bl} = 0.022$ l/s is the blood perfusion rate [20], $c_{p, bl} = 3594$ J/kg·K is the specific heat capacity of blood [17], $T_{bl} = 37°C$ is the blood temperature [12], $Q_{ext}$ is the external heat source generates by solar irradiation (W/m$^3$), $\alpha = 2250$ 1/m is the average absorption coefficient at the wavelength between 400 nm to 1400 nm [21] and $I(t)$ is the solar irradiance (W/m$^2$). When $i$ and $j$ denote the domains, which use Equation (1), thus $i$ is the iris and choroid and $j$ is only the iris.
\[ \rho c_{p,i} \frac{\partial T_i}{\partial t} = \nabla \cdot (k_i \nabla T_i) \]  
(2)

when \( i \) denote the domains, which use Equation (2), thus \( i \) is the cornea, posterior chamber, ciliary body, lens, retina and sclera.

\[ \rho c_{p,i} \frac{\partial T_i}{\partial t} = \nabla \cdot (k_i \nabla T_i) - \rho_i c_{p,i}u_i \cdot \nabla T_i \]  
(3)

where \( u \) is the velocity of a fluid (m/s). When \( i \) denote the domains, which use Equation (3), thus \( i \) is the AH and VH.

Fluid flow analysis of the human eye model has the assumptions to simplify the problem as follows:

1. AH and VH are incompressible Newtonian fluid with laminar flow.
2. The buoyancy force of fluid is defined by the Boussinesq approximation when the states that the density of fluid changes slightly with temperature but negligibly with pressure. The Navier-stokes equations include 2 equations, the continuity equation and the momentum equation as in Equation (4) and Equation (5).

\[ \nabla \cdot u_i = 0 \]  
(4)

\[ \rho_i \frac{\partial u_i}{\partial t} + \rho_i u_i \nabla \cdot u_i = -\nabla p_i + \nabla \left[ \mu (\nabla u_i + (\nabla u_i)^T) \right] + \rho_i \beta_i (T_i - T_{ref}) \]  
(5)

where \( p \) is the pressure (N/m\(^2\)), \( \mu = 0.00074 \) and 0.7 N·s/m\(^2\) is the viscosity of AH and VH [10,22], \( g = 9.81 \) m/s\(^2\) is the gravitational acceleration, \( \beta = 0.000337 \) 1/K is the volume thermal expansion coefficient of AH and VH [10] and \( T_{ref} = 37°C \) is the reference temperature [12]. When \( i \) denote the domains which use these equations, thus \( i \) is the AH and VH.

The boundary conditions of the human eye model are applied to each region as shown in Figure 3. Heat transfer boundary conditions include 4 equations. There is the convection boundary condition by air, radiative boundary condition and evaporation boundary condition as given in equation (6) is applied to boundary 1 (B1) as shown in Figure 3. The convection boundary condition which represents the convection heat transfer coefficient between sclera and fat as given in equation (7) is applied to boundary 2 (B2) as shown in Figure 3. The symmetric boundary condition as given in equation (8) is applied to boundary 3 (B3) as shown in Figure 3. and the continuity boundary condition as given in equation (9) is applied to contact surface between domains.

\[ -\n \cdot (k\nabla T) = h_s (T - T_{amb}) + \varepsilon \sigma (T^4 - T_{amb}^4) + E \text{ at B1} \]  
(6)

where \( E = 40 \) W/m\(^2\) is the heat loss due to tear evaporation [17], \( \varepsilon = 0.975 \) is the emissivity [12], \( \sigma = 5.67 \times 10^{-8} \) W/m\(^2\)·K\(^4\) is the Stefan-Boltzmann constant, \( h_s \) is the ambient convection heat transfer coefficient (W/m\(^2\)·K) and \( T_{amb} \) is the ambient temperature (°C).

\[ -\n \cdot (k\nabla T) = h_f (T - T_f) \text{ at B2} \]  
(7)

where \( h_f = 20 \) W/m\(^2\)·K is the convection heat transfer coefficient of fat [17].

\[ -\n \cdot (k\nabla T) = 0 \text{ at B3} \]  
(8)

\[ -\n_{dst} \cdot (k_{dst} \nabla T_{dst}) = \n_{src} \cdot (k_{src} \nabla T_{src}), T_{dst} = T_{src} \]  
(9)

where subscript \( dst \) and \( src \) denote destination and source pair of the contact surface.

Fluid flow boundary conditions include 2 equations. There is no-slip boundary condition as equation (10) is applied to boundary 4 (B4) and symmetric boundary condition as Equation (11) is applied to boundary 5 (B5) as shown in Figure 3.

\[ u = 0 \text{ at B4} \]  
(10)

\[ u \cdot n = 0 \text{ at B5} \]  
(11)
2.3 Numerical method

The system of governing equations to predict the temperature distribution and the velocity profile of the 3D human eye model is in the form of nonlinear partial differential equation. The governing equations are solved numerically using the FEM via the commercial program COMSOL Multiphysics. This program accommodates all steps for FEM such as meshing, computational process and post-processing. The human eye model provides mesh independent analysis for the minimum number of the elements which the result slightly changes as shown in Figure 4. This convergence test leads to the 3D human eye model is meshed by 195,000 linear tetrahedral elements as shown in Figure 5. It is reasonable to assume that, at this element number, the accuracy of the simulation results is independent of the number of elements. The numerical model presented is verified by Lagendijk’s experiment results in 1982 which specimen is the rabbit eye and installed the thermometer in the rabbit eye with 3 positions along the pupillary axis. In the validation, the parameters are used with the same Lagendijk’s experiment such as ambient temperature is 23°C, convection heat transfer coefficient of air is 20 W/m²K and body core temperature 38.8 °C (rabbit body). The comparison between temperature distribution obtained from this numerical study and obtained by Lagendijk’s experiment as shown in Figure 6. The figure indicates that the slight temperature difference between Lagendijk’s experiment and present study at 3 positions. The estimated error in 3 positions is 0.85 %, 0.99 % and 0.26 % that the average error is 0.7 %. These estimate errors are satisfied for investigating the environmental effects of thermo physiological responses on the 3D human eye model.

![Figure 3. The boundary conditions of (a) heat transfer analysis and (b) fluid flow analysis](image)

![Figure 4. Mesh independent of the human eye model](image)
3. Results and discussion

The results of environmental effects are investigated in this section and provide the intensity of solar irradiance that the lens’s temperature reaches 38.5°C in any case study while exposed to inconstant solar irradiation.

3.1 Effect of ambient temperature

In this research, the effect of ambient temperature includes 25°C, 30°C and 35°C based on the other parameter is constant (the air convection heat transfer coefficient at 20 W/m²·K) in each case. The temperature distribution and velocity profile on the symmetry plane of the 3D human eye model at various time exposed to inconstant solar irradiation as shown in Figures 7 and Figures 8, respectively. From the Figures 7 and Figures 8 show the ambient temperature affects directly to cooling mechanism because the different temperatures between air and anterior ocular make the buoyancy force of Boussinesq approximate at AH which flows with higher velocity when the different temperature is higher and convection heat transfer between cornea and ambient is higher too. The flow direction of the cold fluid and hot fluid is downward and upward respectively. Thus, the lowest ambient temperature makes the anterior ocular’s temperature lower when compared to the results of other ambient temperatures at the same time in Figure 7. In Figure 8 displays the velocity profile of VH is stationary even if the different temperatures between anterior ocular and VH are high due to the viscosity of VH is high. The lens’s maximum temperature along the time that appears at the top lens near the iris as shown in Figure 9. The ambient temperature is the significance of the cooling mechanism while the eye exposed to inconstant solar irradiation. Figure 9 shows the effect of ambient temperature on the maximum temperature in various exposure time. In Figure 9 shows, the ambient temperature at 25°C that makes the lens’s maximum temperature reach 38.5°C at 90 min and solar irradiance equal to 575 W/m², at 30°C that makes the lens’s maximum temperature reach 38.5°C at 48 min and solar irradiance equal to 460 W/m² and at 35°C that makes the lens’s maximum temperature reach 38.5°C at 18 min with solar irradiance equal to 360 W/m² which the solar irradiation corresponds to Figure 2.

Figure 5. The human eye model with meshed (a) isometric view and (b) side view

Figure 6. The comparison of temperature results between present study and Lagendijk’s experiment
Figure 7. Temperature distribution on symmetry plane of human eye model with ambient temperature at (a) 25°C, (b) 30°C and (c) 35°C.

Figure 8. Velocity profile on symmetry plane of aqueous humor and vitreous humor with ambient temperature (a) 25°C, (b) 30°C and (c) 35°C.
Figure 9. Maximum temperature of the lens along the time with the effect of ambient temperature.

3.2 Effect of air convection heat transfer coefficient
The effect of air convection heat transfer coefficient includes 10 W/m²·K, 20 W/m²·K and 40 W/m²·K based on the other parameter is constant (the ambient temperature at 30°C) in each case. The temperature distribution and velocity profile on the symmetry plane of the 3D human eye model at various time exposed to inconstant solar irradiation as shown in Figure 10 and Figure 11, respectively. These figures show the air convection heat transfer coefficients directly affect the cooling mechanism on anterior ocular when air convection heat transfer coefficient is high that represents the velocity of ambient air is faster (windy) than the lower air convection heat transfer coefficient (lightly windy). The velocity profile of VH is also high when air convection heat transfer coefficients are higher which makes the high-temperature differential between the cornea and AH. Thus, the velocity of AH is high from the buoyancy force with high-temperature differences. The flow direction of the cold fluid and hot fluid is downward and upward respectively. In the part of VH, the velocity profile in each case are the same results as the effect of ambient temperature, the VH is stationary. The lens’s maximum temperature time that appears at the top lens near the iris as shown in Figure 12. In Figure 12 shows, the air convection heat transfer coefficients at 10 W/m²·K that makes the lens’s maximum temperature reach 38.5°C at 30 min with solar irradiance equal to 400 W/m², the air convection heat transfer coefficients at 20 W/m²·K that makes the lens’s maximum temperature reach 38.5°C at 48 min with solar irradiance equal to 460 W/m² and the air convection heat transfer coefficients at 40 W/m²·K that makes the lens’s maximum temperature reach 38.5°C at 90 min with solar irradiance equal to 575 W/m² which the solar irradiation corresponds to Figure 2.

4. Conclusion
The environmental effects on the thermo physiological via the 3D human eye model under inconstant solar irradiation are investigated. The heat transfer model is developed based on porous media heat transfer by considering the natural convection of AH and VH. The main findings of this study are:

1. Both the effect of ambient temperatures and the effect of air convection heat transfer coefficients, are significant to the cooling mechanism of the human eye model, when the human eye model is exposed to inconstant solar irradiation.

2. The best and worst cases for the cooling mechanism of the human eye model, in the effect of ambient temperatures, are the ambient temperatures of 25°C and 35°C that can absorb the solar irradiance at 575 W/m² and 360 W/m², respectively when the lens’s maximum temperature reaches 38.5°C.

3. The best and worst cases for the cooling mechanism of the human eye model in the effect of air convection heat transfer coefficients of 40 W/m²·K and 10 W/m²·K that absorbs the solar irradiance at 575 W/m² and 400 W/m², respectively when the lens’s maximum temperature reaches 38.5°C.
4. To reduce the computational times and computational resources, due to the results of the velocity profile of VH, are slightly changed based on the condition in this study. This research recommends treating only the AH as a fluid and VH can treat as a solid because the velocity of VH is stationary from the result. However, the VH is considered to be fluid when the VH’s viscosity is low as AH (Eye floaters: the VH gel becomes liquid phase) that the flow of VH has occurred.

In further studies, the human eye model will be developed for representing the actual human eye by considering some mechanisms of the eye such as the eye-blinking effect, which is an important mechanism of the human eye, that may affect temperature distribution on the human eye model.

**Figure 10.** Temperature distribution on symmetry plane of human eye model with air convection heat transfer coefficient (a) 10 W/m²·K (b) 20 W/m²·K and (c) 40 W/m²·K

**Figure 11.** Velocity profile on symmetry plane of aqueous humor and vitreous humor with air convection heat transfer coefficient (a) 10 W/m²·K (b) 20 W/m²·K and (c) 40 W/m²·K
Figure 12. Maximum temperature of the lens along the time with the effect of air convection heat transfer coefficient

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