KATHMANDU UNIVERSITY JOURNAL OF SCIENCE, ENGINEERING AND TECHNOLOGY
VOL. 9, No. II, December, 2013, pp 47-58.

TRANSIENT THERMAL MODEL OF AIRFLOW EFFECTS IN HUMAN EYE TEMPERATURE

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Received 27 November, 2013; Revised 27 December, 2013

ABSTRACT

High air speed makes thinner the thermal boundary layer between cornea and environment. This accelerates evaporation of water and convective heat transfer. Both factors drop corneal temperature. Most of the literatures of thermal modeling in human eye air forced convection effects is not considered. Based on different climatic conditions of Nepal and their impact on two-wheeler rider's eye, one dimensional variational finite element model is developed to investigate the forced convection effects of airflow in eye temperature distribution. The bio-heat transfer process is simulated in transient state cases. The results show that, high air speed decreases corneal temperature rapidly in cold climate but there is no significant decrease found in hot climate. The corneal temperature starts to plateau from approximately same time at same air speed and in different ambient temperature.

Keywords: Bio-heat transfer; Airflow; Eyelid; FEM.

1. INTRODUCTION

Temperature is of vital importance for all biological bodies. If temperature drops below normal level, several body components do not work properly. The continuous drop in temperature may lead to death. Human eye is assumed the most sensitive organ in human body even for weak thermal interactions because; there is a lack of sufficient blood flow and lack of protecting layer (such as skin)[1]. Several environmental factors may drop human eye temperature such as cold temperature, high-speed airflow etc. Common eye injuries from cold temperature exposure are eye pain, loss of vision, severe sensitivity to light etc. In rare cases, the cornea may freeze, which can lead to blurred vision, excess tearing and pain.

The dry eye condition affects millions of people, interfering with their daily living and normal activities. Certain environmental conditions such as high or low temperatures and wind flow are known factors to cause dry eye[2]. In cold climate temperature of cornea drops obviously. In addition, if high speed air blows the cornea, its temperature drops well below normal level. As temperature decreases and wind speed increases, the eye can feel much colder than the standard temperature reads. While the temperature does not change, an increased wind speed can make eye feel colder and causes greater risk of injuries.

The use of two wheelers in developing countries has been increasing rapidly. While driving, two wheeler riders wears helmet with visor. Visor prevents driver’s eye from dust, smoke, foreign body and hot/cold wind flow. In several cases, the driver used to open their visor. Some of the cases are: a) when the environmental temperature is very low than normal, the water vapor due to respiration covers hole area of visor's inner part causes poor vision, b)when raining, the rain water drops hits the visor surface continuously causes blurred vision and c) at night, the refraction of light into the visor by anti-vehicles light or street lights causes poor vision. In the above cases, the airflow caused by riders speed directly interacts with riders' cornea causes forced convection heat transfer.

Energy transfer between the surface and fluid (gas or liquid) due to temperature difference by external or internal high velocity flow is termed as forced convection. While the term forced convection can be used to refer to any fluid, it is most commonly associated with forced air-cooling. Because of the usually high air speeds associated with forced convection, significant amounts of heat can be transported quickly and effectively. The amount of heat transported by air through forced convection is proportional to the flow speed. Generally, the faster the flow, the thinner the boundary layer and hence higher the heat transportation rate.

Lagendijk[3] used a finite difference method to calculate the temperature distribution in human and rabbit eyes during hyperthermia treatment. The heat transport from the sclera to the surrounding anatomy is described by convection heat transfer coefficient of blood flow in retina and choroid. Scott[4], Ng and Ooi[5] utilized finite element method to obtain the temperature profile based on heat conduction using convection heat transfer coefficient in sclera given by Lagendijk. Flyckt, Roaymakers and Lagendijk[6] studied the convection effect of choroidal blood flow in sclera by using three methods: Lagendijk model, bio-heat model and discrete vasculature model. Shafai and vafai[7] proposed the porous media model along with natural convection in aqueous humor to analyze the eye thermal characteristics during exposure to thermal disturbances. Most of these past models used only natural convection in temperature distribution between cornea and environment. Some models [1, 4, 5, 8] performed sensitivity analysis by varying the values of convection heat transfer coefficient between cornea and environment. Some authors [3, 6] studied the convection effects of blood flow in posterior eye. However, most of them neglected the effects of forced convection due to air velocity in corneal surface, although it is significant.

In outdoor conditions, the wind accelerates the drop in temperature of the ocular surface below normal level. Most often, eye injuries caused by cold exposure occur in individuals who try to force their eyes open in high wind or cold weather such as in the case of two-wheeler rider. Thus, it is worth investigating the temperature changes in the eye and its effects with appropriate forced convection coefficient. In this study, the effect of wind flow in temperature distribution specially the temperature drop in two-wheeler rider's eye surface is modeled using appropriate physical and physiological values. One dimensional finite element method is used as a tool to simulate transient temperature distribution on eye cornea.

2. MODEL FORMULATION

2.1 Eye geometry and properties

A schematic diagram of the eye when eyelid is opened is displayed in figure 1. For modeling purpose, the opened eye is divided into six regions: cornea, aqueous humor, lens, vitreous humor, retina, and sclera with thickness $l_{1'}, l_{2'} - l_{1'}, l_{3'} - l_{2'}, l_{4'} - l_{3'}, l_{5'} - l_{4'}$ and $l_{6'} - l_{5'}$ respectively. Each region is assumed to be perfectly bonded and homogeneous. The diameter of the eye along pupillary axis is about 25.10mm[5]. $T_{0'}, T_{1'}, T_{2'}, T_{3'}, T_{4'}$ and $T_{5'}$ are the nodal temperatures and $T_{6'} = T_c$ is the body core temperature. The parameter values for different parts of eye are presented in table I.

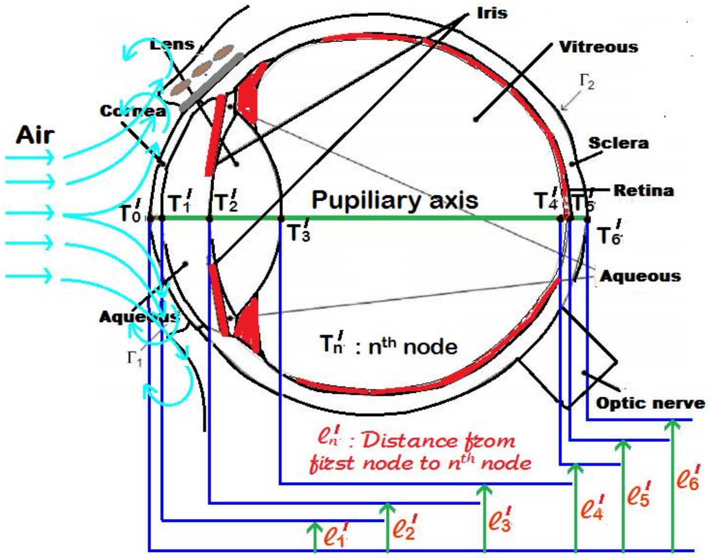

Figure 1: Finite element sketch of human eye

Table 1: Thermal properties of human eye tissues

Tissue	Thermal Conductivity K ($Wm^{-1o}C^{-1}$)	Blood Perfusion ω (s^{-1})	Metabolic Rate Q_m (Wm^{-3})	Density ρ (kgm^{-3})	Specific heat C ($J\ kg^{-1°}C^{-1}$)
Cornea	0.58 [5]	0 [6]	0 [10]	1050[5]	4178[5]
Aqueous humor	0.58 [5]	0[6]	0 [10]	996[5]	3997[5]
Lens	0.400 [5]	0 [6]	0 [10]	1050[5]	3000[5]
Vitreous humor	0.603[5]	0 [6]	0 [10]	1000[5]	4178[5]
Retina	0.565[9]	0.0222[6]	22000[10]	1050[9]	3680[9]
Sclera	1.0042[5]	0[9]	0[9]	1100[5]	3180[5]

2.2 Governing equation and boundary conditions

The governing differential equation representing the bio-heat transfer in the human eye can be written by the well known Pennes equation addressing the effect of blood perfusion and metabolism [11] is given by:

$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \omega\rho_b c_b (T_b - T) + Q_m + Q \qquad (1)$$

where, ρ_b = blood density (kgm^{-3}), c_b = blood specific heat ($J\ kg^{-1°}C^{-1}$), k = tissue thermal conductivity ($Wm^{-1}\ °C^{-1}$), ω = volumetric blood perfusion rate per unit volume (s^{-1}), T_b = blood temperature (°C), T = tissue temperature (°C), Q_m = heat generation due to metabolism (Wm^{-3}) and Q = heat generation due to external heat source(Wm^{-3}).

Boundary and initial conditions for the system can be defined as follows:

1. On the outer surface of the sclera, the heat flows run into the eye with the complicated network of ophthalmic vessels which are located inside the choroidal layer acting as a

heating source to the sclera. This heat exchange between the eye and the surrounding is modeled using the following convection boundary condition:

$$\Gamma_2 :\ -k_s \frac{\partial T}{\partial \eta} = h_b(T - T_b) \quad (2)$$

where η is the normal direction to the surface boundary, k_s is the thermal conductivity of sclera, h_b is the heat transfer coefficient between blood and eye ($Wm^{-2}\ {}^{\circ}C^{-1}$), and T_b is blood temperature (°C).

2. Since the cornea is exposed to the environment, the heat loss caused via convection, radiation, and evaporation. This loss is modeled using the following boundary condition :

$$\Gamma_1 :\ -k_c \frac{\partial T}{\partial \eta} = h_a(T - T_a) + \sigma\varepsilon(T^4 - T_a^4) + E \quad (3)$$

where h_a represents heat transfer coefficient between environment and cornea($Wm^{-2\,o}C^{-1}$), T_a is the ambient temperature (^{o}C), σ is the Stefan Boltzmann constant ($5.67 \times 10^{-8} Wm^{-2\,o}C^{-4}$).

3. The inner body core temperature T_c is assumed 37°C. Therefore, the initial condition is

$$T_c = 37\ {}^{\circ}C \quad (4)$$

The nonlinear radiation term in the boundary condition (3) is treated by using simple iterative procedure as follows: $-k_c \frac{\partial T_1}{\partial \eta} = [h_a + \sigma\varepsilon(T_1 + T_a)(T_1^2 + T_a^2)](T_1 - T_a) + E$ (5)

$$-k_c \frac{\partial T_1^m}{\partial \eta} = h_{cr}(T_1^m - T_a) + E \quad (6)$$

$$h_{cr} = h_a + \sigma\varepsilon(T_1^{m-1} + T_a)((T_1^{m-1})^2 + T_a^2) \quad (7)$$

where T_1^m are temperature sequences for m = 1, 2, 3, … and T_1^0 represents an initial guess of temperature.

The iteration is completed when the convergent condition is satisfied:

$$\|T_1^m - T_1^{m-1}\| < \delta \quad (7)$$

where δ is iteration tolerance.

2.3 Forced Convection

Forced convection heat transfer from cornea results from an airstream perturbing the insulating boundary layer of air clinging to the surface. The fundamental non-dimensional quantities describing forced convection are Nusselt number(*Nu*), Prandtl number(*Pr*) and Reynolds number(*Re*). These three dimensionless groups are related together with the following equation[12]

$$Nu = C\, Re^n\ Pr^m \quad (8)$$

where *C, m* and *n* are constants to be determined from experimental data. The three quantities *Nu, Re* and *Pr* further expressed as follows

$$Nu = \frac{h_a d}{k_f} \quad (9)$$

$$Pr = \frac{v_f}{\alpha} \quad (10)$$

$$Re = \frac{u\, d}{v_f} \quad (11)$$

where h_a is convective heat transfer coefficient ($Wm^{-2}\,{}^{\circ}C^{-1}$), k_f is the thermal conductivity of the air ($W\,m^{-1}\,{}^{\circ}C^{-1}$), d is the diameter of cornea (m), u is ambient air speed (ms^{-1}), v_f is kinematic viscosity (m^2s^{-1}) and α is thermal diffusivity ($\mathrm{m^2s^{-1}}$).

The correlations of the experimental data of Hilpert for gases indicated that average heat transfer coefficient is calculated with the following equation

$$Nu = C\,Re^n\;Pr^{\frac{1}{3}} \tag{12}$$

where the constants C and n are tabulated in table 2[13].

Table 2. Constants C and n for use with Equation(12)

Re	C	n
0.4-4	0.989	0.330
4-40	0.911	0.385
40-4000	0.683	0.466
4000-40000	0.193	0.618
40000-400000	0.0266	0.805

Properties for use with equation (12) are evaluated at the film temperature as indicated by the subscript f. The film temperature T_f, defined as the arithmetic mean between the eye surface (cornea or eyelid skin) and ambient air temperature

$$T_f = \frac{T_s + T_a}{2} \tag{13}$$

where T_s is the eye surface temperature and T_a air temperature. The parameter values k_f, v_f and Pr_f based on film temperature T_f for air are tabulated in table 3. We assume that all these parameter values are linearly dependent with film temperature T_f. The calculated convective heat transfer coefficient h_a from equation (12) is substituted in boundary condition (3).

Table 3. Properties of air[13]

T_f	v_f	k_f	Pr
27	15.69×10^{-6}	0.02624	0.708
77	20.76×10^{-6}	0.03003	0.697

2.4 Numerical method

The partial differential equation (1) together with boundary conditions (2) and (3) in one dimensional variational form is:

$$\mathrm{I} = \frac{1}{2}\int_{\mathrm{L}} \left[\mathrm{K}\left(\frac{\mathrm{dT}}{\mathrm{dx}}\right)^2 + \omega\rho_{\mathrm{b}}\mathrm{c_b}(\mathrm{T_b} - \mathrm{T})^2 - 2\mathrm{Q_m}\mathrm{T} + \rho\mathrm{c}\frac{\partial \mathrm{T}^2}{\partial \mathrm{t}}\right]\mathrm{dx} + \frac{1}{2}\mathrm{h_b}(\mathrm{T} - \mathrm{T_b})^2 + \frac{1}{2}\mathrm{h_{cr}}(\mathrm{T} - \mathrm{T_a})^2 + \mathrm{ET} \tag{14}$$

To optimize I, we differentiate I partially with respect to $\mathrm{T_i}$ and equating to zero as follows

$$\frac{\partial \mathrm{I}}{\partial \mathrm{T_i}} = 0 \tag{15}$$

Equation (15) is the system of linear equations which can be written in matrix form as

$$[C]\{\dot{T}\} + [K]\{T\} = \{R\} \tag{16}$$

where $\{\dot{T}\} = \left\{\frac{\partial T_i}{\partial t}\right\}$, $\{T\} = \{T_i\}$ and $\{R\} = \{R_i\}$ are 6×1 vectors and [C] and [K] are 6×6 matrices.

Crank-Nicolson method is applied to solve the system (16) with respect to time using the following relation

$$\left(\frac{1}{\Delta t}[C] + \frac{1}{2}[K]\right)\{T\}_{n+1} = \left(\frac{1}{\Delta t}[C] - \frac{1}{2}[K]\right)\{T\}_n + \{R\} \tag{17}$$

where Δt is time interval.

The temperature increases from outer surface of the eye towards core, when ambient temperature is less than 37°C and vice versa. Hence, we consider the temperature increases/decreases in linear order towards eye core with regard to thickness. For initial nodal temperatures $\{T\}_0$ at time $t = 0$, we assume the following initial condition

$$T(x = l_i, t = 0) = T(0,0) + r l_i \tag{18}$$

where i ranges from $1,2,3,\ldots,6$, $T(0,0) = 20^{\circ}C$ and $r =$ constant to be determined. The equation (17) is repeatedly solved to get the required nodal temperatures.

4. RESULTS

Nepal has varied climate zones based on elevations ranging from less than 100 meters to over 8000 meters. The climate variation ranging from the subtropical Terai to the alpine himalayan ranges. The Terai, the hottest part of the country, summer temperature may rise as high as 40°C and winter may fall up to 5°C. In the Middle Hills, summer temperature may rise to 32°C and winter may fall to sub zero. The great majority of Nepal’s population occupies these two climate zones. In summer hot air flows from Terai(south) to Himalayas(north) and in winter cold air flows from Himalayas to hills, valleys and Terai.

Hence, to incorporate all those varied climatic conditions and their effects on temperature distribution, the numerical calculations are carried out at different atmospheric air temperatures 0, 10, 20, 30 and 35°C. Based on many previous studies [1, 4, 5, 8] 20-25°C is assumed as normal air temperature and the temperatures below and above this range are cold and hot. We supposed that the effects of airflow in resting cornea is equivalent to the effects of still air in moving cornea. Based on this assumption the riders speed in still air is assumed as airflow speed. Hence, to simulate air flow effects, the numerical calculations are carried out at air speeds 0, 20, 40 and 60 km/hr. The two-wheeler rider's speed in valleys and hills is assumed 20 km/hr as low 40 km/hr as normal and 60 km/hr as high. The normal speed 40 km/hr is the mean speed which the two-wheeler companies marked as most economy and efficient speed.

Figures 2, 3, 4, 5 and 6 shows transient temperature distribution of cornea for 1 hour at ambient temperatures 0, 10, 20, 30 and 35°C with various air speeds respectively.

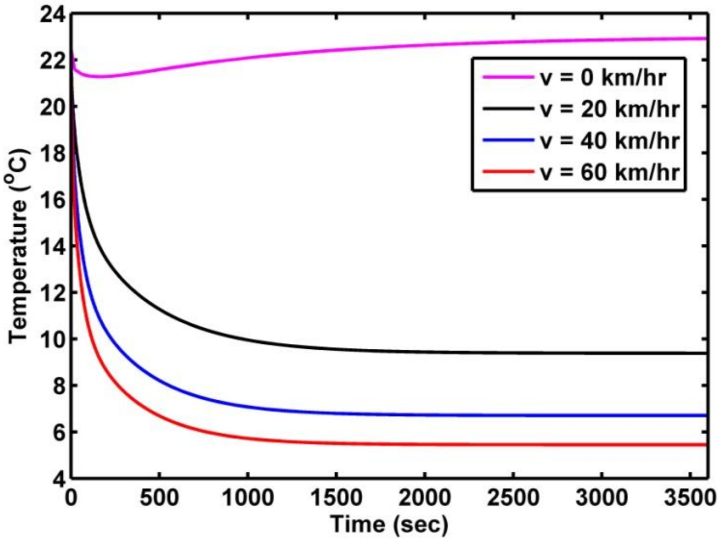

Fig. 2 Temperature variation at $T_a = 0$°C

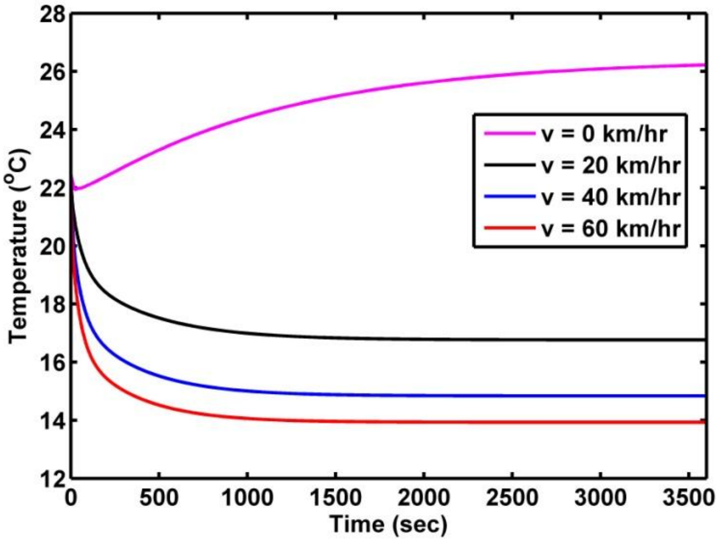

Fig. 3 Temperature variation at $T_a = 10$°C

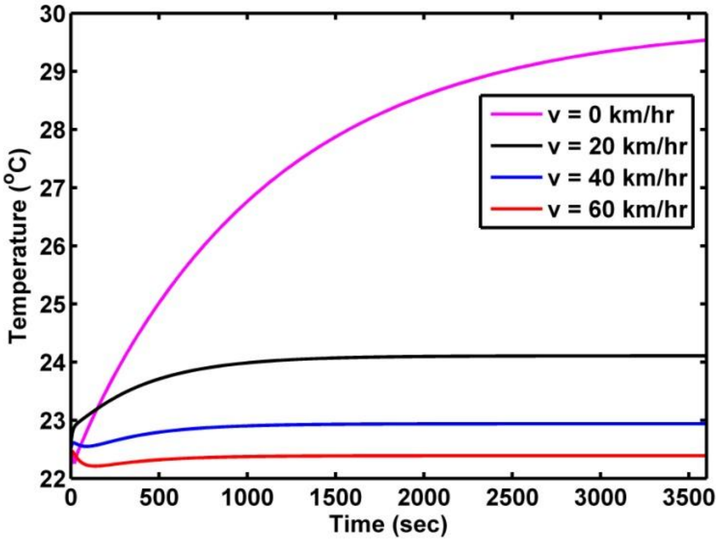

Fig. 4 Temperature variation at $T_a = 20$°C

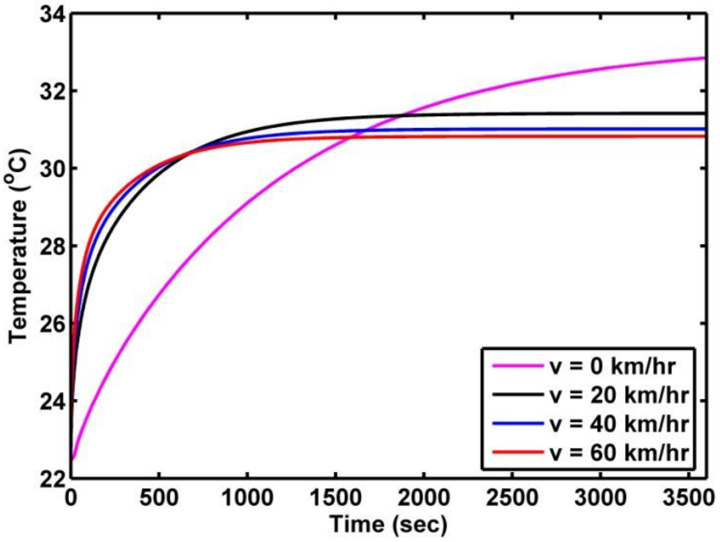

Fig. 5 Temperature variation at $T_a = 30$°C

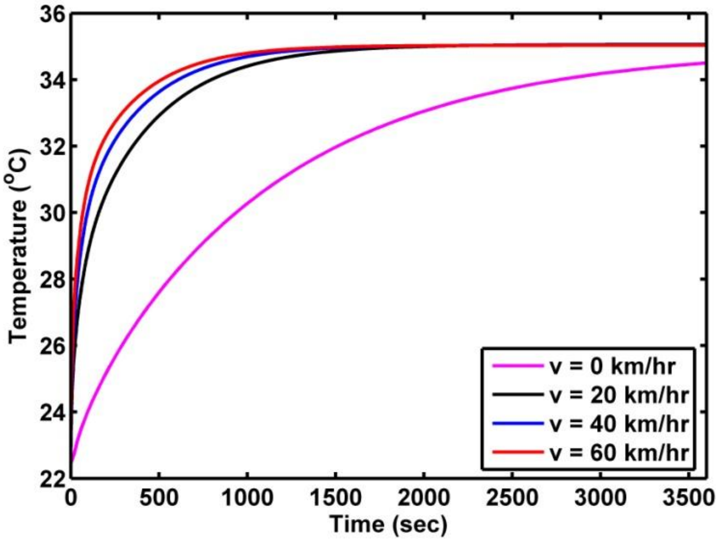

Fig. 6 Temperature variation at $T_a = 35$°C

The cornea directly interacts with ambient temperature and airflow. Therefore, the maximum temperature decrease occurs in cornea than other parts of eye tissues. The temperature values obtained at cornea at different ambient temperatures and air speeds are tabulated in table IV.

Table 4. Corneal temperatures in opened eye

Ambient Temperatures (°C)	Air speeds			
	0 km/hr	20 km/hr	40 km/hr	60 km/hr
0	22.91	9.36	6.69	5.43
10	26.23	16.75	14.82	13.92
20	29.54	24.10	22.93	22.38
30	32.85	31.41	31.01	30.82
35	34.50	35.06	35.04	35.03

Significant decrease in corneal temperature is found at high air speed and cold temperature. Although the temperature drops at high atmospheric temperatures, no significant temperature variations are observed at various air speeds. In still air, steady state corneal temperature is observed in around 41 minutes. When air speed increases from 20 km/hr to 60 km/hr, the corneal temperature approaches steady state in around 16 minutes.

5. DISCUSSION

The results show that increase in ambient temperature increases eye tissue temperature. Rapid decrease in corneal temperature is observed at low atmospheric temperatures and higher airflow rates. At low atmospheric temperature, high amount of heat is lost from cornea to environment due to convection and radiation but heating mechanism for cornea is only conduction from body core.

In still air, there is a thick thermal boundary layer at the surface of cornea. The increase in air speed plays a role of catalyst in heat transfer, which makes thinner the boundary layer and decreases the diffusion distance. This phenomenon increases heat transfer between ambient air and cornea. Thus, high-speed air accelerates convectional heat transfer. The heat loss rate due to air forced convection is higher than heat gain due to conduction from body core. Hence, high amount of heat energy is convected from cornea to environment results rapid corneal temperature drop.

In cold temperatures and in still air the difference in temperature between air molecules and corneal surface is very high (22.91°C at 0°C ambient temperature). This obviously increases heat transfer. In hot climate the difference is very small(0.5°C at 35°C ambient temperature). Although heat transfer increases with increase in air speed, corneal temperature is not significantly affected by air speeds in hot climatic conditions due to this small temperature difference.

The meibomian lipid layer solidifies below 19°C, quasi solid in the range between 20°C and 30°C and completely clear liquid in the range between 30°C and 45°C. Thus if the corneal temperature drops below 30°C (a distinctive possibility in cold weather, especially in combination with wind), the chances are that meibum in the glands will become thicker than usual, which, in turn, would impede its normal delivery to the ocular surface[14]. Also tear film lipid layer will solidify, thus losing its functionality. These events may limit the protective effect of the tear film by adversely affecting the structure, stability and dynamics of the lipid layer.

In our case, in still air, corneal temperature is found 22.91°C at ambient temperature 0°C. At ambient air temperature 0°C the corneal surface temperature drops to 5.43°C at 60 km/hr air speed. This may solidify the meibomian lipid layer that may cause blurred vision. In addition, high air speed affects the distribution of tear film and lipid layer which protects the corneal epithelium against the evaporation of aqueous tears[15]. High air velocity causes greater evaporation of water from the pre-corneal tear film. Exposure of tear film to high air velocity caused significant decrease in lipid layer stability, tear stability and tear meniscus[16]. If the lipid layer destroyed(a distinctive possibility in high air speed), the evaporation from the tear film increases approximately 4 times greater than with the lipid layer[17]. This higher rate of evaporation reduces corneal temperature rapidly.

In hot climate corneal temperature exceeds normal level but doesn't exceed physiological temperature level(37°C) of our body, which induces minor changes to the corneal surface. In our case, corneal temperature is found to be 34.50°C at ambient temperature 35°C. The steady state temperature is achieved earlier in higher air speeds. The corneal temperature reaches in steady state very fast at air speed 60 km/hr (approximately 9 minutes) than in still air (approximately 33 minutes). In cold temperatures, the steady state temperature drops very well and plateau of corneal temperature is achieved faster in higher air speeds. In hot climatic conditions the steady state temperature of cornea does not drop significantly but plateau of corneal temperature is achieved faster as in cold climatic conditions.

The flow speed equally affects the thermal boundary layer(reducing the thickness) either in hot or cold conditions. This may increase heat transfer approximately in same manner in hot and cold climatic conditions. In our case, the value of heat transfer coefficient at air speed 60 km/hr is found as 122.80 $Wm^{-2}°C^{-1}$ and 119.30 $Wm^{-2}°C^{-1}$ at ambient temperatures 0°C and 35°C respectively. Hence, the plateau of corneal temperature starts from nearly same time at same air speed and at same ambient temperature. In this model the steady state corneal temperature is found to be 32.17°C at normal ambient temperature 25°C and in still air. Ng and Ooi [5] summarizes the experimental results of corneal temperatures, which vary from 32°C to 36.6°C. Hence, our steady state results are in a good agreement with many past experimental results.

Gurung and Saxena [18] studied the effects of wind flow in human skin temperature. They found a drop in human skin temperature of 7.45°C at 0°C atmospheric temperature and at 4m/s wind speed. Freeman and Fatt [19] studied the effects of air velocity on human cornea temperature experimentally using thermistor probe and Thermometer Bridge. They observed 13°C temperature drop at 4m/s air speed and at 0°C ambient temperature. In our case, the corneal surface temperature is obtained to be 9.36°C at 5m/s air speed and at 0°C ambient temperature. This shows our model results are in good agreement with past experimental results.

6. CONCLUSION

In this study, transient temperature distribution of human eye is computed using one dimensional finite element method using crank-Nicholson scheme. The study focused on the change in temperature of cornea in hot and cold climatic conditions and at different air speeds. The different climatic conditions of Nepal and their effects on two-wheeler rider's eye are investigated. The results show that decrease in ambient temperature decreases eye temperature rapidly in cold climatic conditions but no significant drop occurs in hot climates. Corneal temperature plateaus very fast in high air speeds than in still air in all climatic conditions. Thus, high air speed in cold ambient temperature is hazardous for ocular surface. In this situation, thermal feedback mechanism would require to increase local temperature.

One of the important limitations of this study is the exclusion of thermal effects of eyelid and blinking in temperature distribution. Results by Koh et al.[16] shows that blink frequency increases significantly by 59% during air flow exposure in eye. Another limitation is the exclusion of tear flow dynamics in temperature distribution. Mapstone[20] indicates that a rapid increase in corneal temperature (i.e. in a matter of seconds) can result only from tearing since other factors need some time to act.

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