The Effects of Inhaled Heat Transport Dynamics in Human Trachea

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Abstract

The purpose of this work is to study the effects of inhaled heat transport dynamics in human trachea. The result might help us better understanding the development of burn taking place in the human trachea exposed to various fire situations. To minimize lung injury when exposed to a fire or natural disaster, the time for first degree burns to occur is also theoretically predicted. Further, we studied the effect of heat of air region and tissue region, burning evaluation of inhalation of hot air in the human trachea under various fire situations.

1 INTRODUCTION

A study of the heat transfer mechanism of the human respiratory tract helps assess any heat, smoke and fire related injury affecting the human respiratory tract. The design of respiratory systems used by people working in extreme environments, like fire fighters exposed to forest fire, chemical and biological exposure or hazardous material exposure can be better improved by comprehensive study of the thermal profile. This can help in better occupational health and safety in the case of fire fighters and emergency responders. These emergency responders are exposed to extreme temperatures and do have protection equipments like a respirator for oxygen supply, but still the inhaled air is heated because of the extreme temperature in the surrounding atmosphere.

C. P. Yu and C. K. Diu (1983) have presented the total and regional deposition of inhaled aerosols in humans. C. Kleinstreuer and Z. Zhang (2008) have studied the airflow and particle transport in the human respiratory system. Raju et al., (2014) have discussed the radiation absorption effect on MHD free convection heat and mass transfer flow of viscoelastic fluid through porous medium bounded by an oscillating plate in slip flow regime with constant section. J.S. Guy and M.D. Peck (1999) have studied the smoke inhalation injury: pulmonary implications. J. Liu and C. Wang (1997) have discussed the bioheat transfer.

The airway can be idealized as a long, right circular cylinder. The tissue temperatures are considered as continuous functions of axial (z) and radial (r) positions and time (t), while the air temperatures are only the continuous functions of axial position (z) and time (t), based on the well known Pennes bioheat transfer equation.
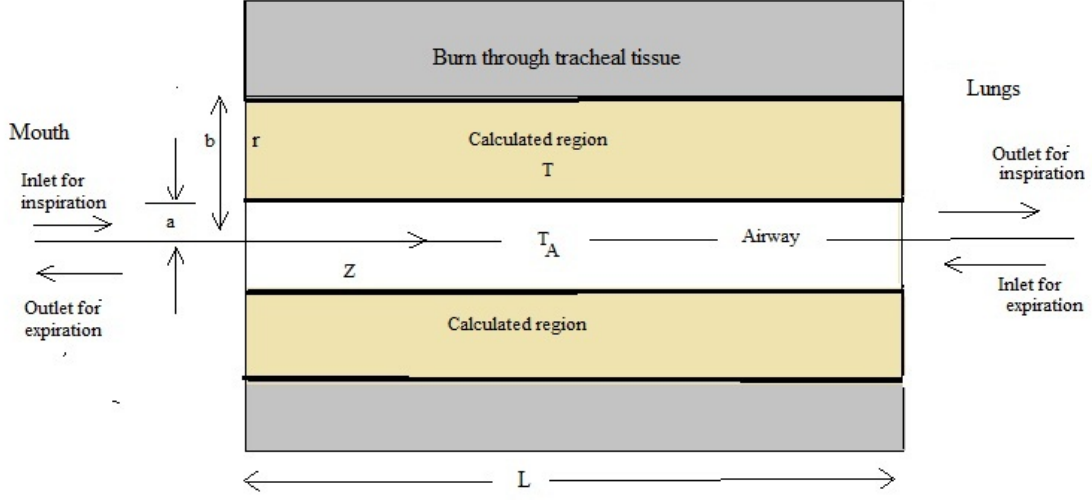
Figure 1: Schematic model for the respiratory tract(idealized trachea)

For the tissue area, the resulting equation is as follows:

$$\frac{1}{\alpha}\frac{\partial T_t}{\partial t} = \frac{\partial^2 T_t}{\partial r^2} + \frac{1}{r}\frac{\partial T_t}{\partial r} + \left[\frac{W_b C_b (T_a - T)}{K}\right] + \frac{\partial^2 T}{\partial z^2} \tag{1}$$

where $\alpha = \frac{K}{\rho C}$ is the diffusivity of tissue, ρ, C, K are, respectively, the density, specific heat and thermal conductivity of the tissue; C_b denote specific heat of blood; W_b the blood perfusion; T_a the supplying arterial blood temperature which is treated as a constant, and T the tissue temperature, and Q_m the metabolic heat generation rate.

During a real thermal process, the boundary condition (BC) at the tract skin surface is often time-dependent. At this mucous-air interface (r=a), the generalized composed of two parts, i.e., convection and evaporation. At the entrance of the nasal cavity (z=0), the continuity of the perpendicular heat flux has been imposed as a convective boundary condition.

Boundary Conditions are

- $K\frac{\partial T}{\partial r} = h_f(T - T_A) + \frac{H_m(P_{sk}^* - QP_a^*)}{1000}$, at r=a interface

- $\frac{\partial T}{\partial r} = 0$, at r=b, symmetry

- $K\frac{\partial T}{\partial z} = h_f'(T - T_f)$ at $z = 0$

- $\frac{\partial T}{\partial z} = 0$, at $z = L$

- Initial condition: $T = T_0$ at t=0

where T_0 is steady-state temperature field, which is assumed as the uniform value T_a, T_f the surrounding hot air temperature, h_f' the apparent heat convection coefficient between

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the tissue and the surrounding air and h_f the heat convection coefficient between the mcousal surface and the following air stream, φ the relative humidity of surrounding air, H the latent heat of water vapour, m is water penetrative coefficient in mucosal surface, p_a^* the saturated vapour pressure at surrounding air temperature and p_{sk}^* is the saturated vapour pressure at tissue temperature.

Using dimensionless quantities

$$\chi_T = \frac{T - T_f}{T_a - T_f}; \quad \zeta = \frac{z}{L}; \quad \xi = \frac{r}{r_w}; \quad \tau = 2\pi f t$$

The boundary conditions are,

(i) $\frac{\partial \chi_T}{\partial \tau} = \frac{r_w h_f}{K} \chi_T + h_f \chi_A \frac{r_w}{K} + 2 h_f T_f \frac{r_w}{K} \frac{T_a - T_f}{T_a - T} + \frac{C_7 r_w}{K(T_a - T_f)}$ at $\xi = 1$

(ii) $\frac{\partial \chi_T}{\partial \xi} = 0$ at $\xi = 0.95$

(iii) $\frac{\partial \chi_T}{\partial \zeta} = \frac{L}{K} h_f' \chi_T$ at $\zeta = 0$

(iv) $\frac{\partial \chi_T}{\partial \zeta} = 0$ at $\zeta = 1$

(v) $\chi_T = 1$ at $\tau = 0$

Using the dimensionless quantities in the equations (1), we get,

$$\frac{1}{\alpha}(T_a - T_f) 2\pi f \frac{\partial \chi_T}{\partial \tau} = \frac{1}{r} \frac{(T_a - T_f) \partial \chi_T}{r_w \partial \xi} + \frac{(T_a - T_f)}{r_w^2} \frac{\partial^2 \chi_T}{\partial \xi^2}$$
$$+ C_1 - C_2 \chi_T + \left(\frac{W_b C_b}{K}\right) T_f + \frac{1}{L^2} \frac{\partial^2 \chi_T}{\partial \zeta^2}$$

$$\frac{1}{\alpha} \frac{\partial \chi_T}{\partial \tau} = \frac{1}{(T_a - T_f) 2\pi f} \left[\frac{1}{r_w \xi} \frac{T_a - T_f}{r_w} \frac{\partial \chi_T}{\partial \xi} + \frac{T_a - T_f}{r_w^2} \frac{\partial^2 \chi_T}{\partial \xi^2} \right]$$
$$+ \frac{1}{(T_a - T_f) 2\pi f} \left[C_1 - C_2 \chi_T + \left(\frac{W_b C_b}{K}\right) T_f + \frac{1}{L^2} \frac{\partial^2 \chi_T}{\partial \zeta^2} \right]$$

$$\frac{1}{\alpha} \frac{\partial \chi_T}{\partial \tau} = \frac{1}{r_w^2 2\pi f} \left[\frac{1}{\xi} \frac{\partial \chi_T}{\partial \xi} + \frac{\partial^2 \chi_T}{\partial \xi^2} \right] + C_3 - C_4 \chi_T + C_5 + C_6 \frac{\partial^2 \chi_T}{\partial \zeta^2} \tag{2}$$

where

$$C_1 = \frac{W_b C_b T_a}{K}; \quad C_2 = \left(\frac{W_b C_b}{K}\right)(T_a - T_f); \quad C_3 = \frac{W_b C_b T_a}{K(T_a - T_f) 2\pi f};$$
$$C_4 = \left(\frac{W_b C_b}{K}\right)\left(\frac{1}{2\pi f}\right); \quad C_5 = \frac{T_f W_b C_b}{(T_a - T_f) 2\pi f K}; \quad C_6 = \frac{1}{L^2(T_a - T_f) 2\pi f}$$

The energy balance equation for the air region can be written as,

$$\frac{\partial T_A}{\partial t} = -V(t, z) \frac{\partial T_A}{\partial z} + \frac{P(z)}{\rho_A C_A A(z)} [h_f(T_t - T_A) + l_1] \tag{3}$$

Boundary conditions are

- During Inspiration: $T_A = T_f$ at   z=0

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- During Expiration: $\frac{\partial T_A}{\partial z} = 0$ at   z=L

Initial conditions are
The burn process is modeled using the following Initial condition

- $T_A = T_{A_0}$ at   t=0

To calculate the transient air temperature field, the initial air temperature distribution T_{A0} before inhalation injury needs to be known. It can be obtained by solving equation (3) with the following boundary conditions:

- $T_{A0} = T_{f_0}$ at   z=0

in which T_{f0} is the initial surrounding air temperature.
Dimensionless quantities

$$\chi_A = \frac{T - T_f}{T_a - T_f}; \quad \zeta = \frac{z}{L}; \quad \xi = \frac{r}{r_w}; \quad \tau = 2\pi f t$$

using the above dimensionless quantities the boundary conditions are,

(vi) $\chi_A = 0$ at $\zeta = 0$

(vii) $\frac{\partial \chi_A}{\partial \zeta} = 0$ at $\zeta = 1$

(viii) $\chi_A = 1$ at $\tau = 0$

(ix) $\chi_A = 0$ at $\zeta = 0$

Using the dimensionless quantities in the equations (3), we get,

$$(T_a - T_f)2\pi f \frac{\partial \chi_A}{\partial \tau} = -\frac{V}{A}\left[\left(\frac{T_a - T_f}{L}\right)\frac{\partial \chi_A}{\partial \zeta}\right] + l_2\left[h_f[((T_a - T_f)\chi_A + T_f) - T_A] + l_1\right]$$

$$\frac{\partial \chi_A}{\partial \tau} = -\frac{V}{A}\frac{1}{L(2\pi f)}\frac{\partial \chi_A}{\partial \zeta} + \left(\frac{l_2 h_f}{2\pi f}\right)\chi_A + l_3 \tag{4}$$

where

- $V(t, z) = \frac{V}{A}$ = constant velocity,
  where V is the local volumetric longitudinal air velocity and A is the local airway cross-section.

- $l_2 = \frac{P(z)}{\rho_A C_A A(z)}$

- $l_3 = \frac{l_2(l_1 - h_f T_A)}{2\pi f(T_a - T_f)}$

The dimensionless form of tissue region (2) can be written as,

$$\frac{1}{\alpha}\frac{\partial \chi_T}{\partial \tau} = \frac{1}{r_w^2 2\pi f}\left[\frac{1}{\xi}\frac{\partial \chi_T}{\partial \xi} + \frac{\partial^2 \chi_T}{\partial \xi^2}\right] + C_3 - C_4\chi_T + C_5 + C_6\frac{\partial^2 \chi_T}{\partial \zeta^2}$$

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2   Mehtod of Solution

$$\frac{1}{\alpha}\frac{\partial \chi_T}{\partial \tau} = \frac{1}{r_w^2 2\pi f}\left[\frac{1}{\xi}\frac{\partial \chi_T}{\partial \xi} + \frac{\partial^2 \chi_T}{\partial \xi^2}\right] + C_3 - C_4\chi_T + C_5 + C_6\frac{\partial^2 \chi_T}{\partial \zeta^2}$$

Apply Hankel on the above equation we get,

$$\frac{1}{\alpha}\left[\int_{0.95}^{1}\frac{\partial \chi_T}{\partial \tau}\xi J_0(P\xi)d\xi\right] = \frac{1}{r_w^2 2\pi f}\int_{0.95}^{1}\left(\frac{\partial^2 \chi_T}{\partial \xi^2} + \frac{1}{\xi}\frac{\partial \chi_T}{\partial \xi}\right)\xi J_0(P\xi)d\xi$$
$$+ \int_{0.95}^{1}(C_3 - C_4\chi_T + C_5)\xi J_0(P\xi)d\xi + C_6\int_{0.95}^{1}\frac{\partial^2 \chi_T}{\partial \zeta^2}\xi J_0(P\xi)d\xi$$

$$\frac{1}{\alpha}\frac{\partial \tilde{\chi}_T}{\partial \tau} = \frac{1}{r_w^2 2\pi f}\left[\xi J_0(P\xi)\frac{\partial \chi_T}{\partial \xi}\right] - \int_{0.95}^{1}\frac{\partial \chi_T}{\partial \xi}[P\xi J_0'(P\xi) + J_0(P\xi)]d\xi + \int_{0.95}^{1}\frac{\partial \chi_T}{\partial \xi}J_0(P\xi)d\xi$$
$$+ (C_3 + C_5)\frac{J_1(P)}{P} - C_4\tilde{\chi}_T + C_6\frac{\partial^2 \tilde{\chi}_T}{\partial \zeta^2}$$

$$\frac{1}{\alpha}\frac{\partial \tilde{\chi}_T}{\partial \tau} = C_8[J_1(P)100P - J_1(P\beta)(100P\beta) - P^2\tilde{\chi}_T + (C_3 + C_5)\frac{J_1(P)}{P} - C_4\tilde{\chi}_T + C_6\frac{\partial^2 \tilde{\chi}_T}{\partial \zeta^2}]$$

where

$$C_8 = \frac{1}{r_w^2 2\pi f}$$

$$C_6\frac{\partial^2 \tilde{\chi}_T}{\partial \zeta^2} - \frac{1}{C_8\alpha}\frac{\partial \tilde{\chi}_T}{\partial \tau} - (C_4 + P^2)\tilde{\chi}_T = -J_1(P)100P + J_1(P\beta)(100P\beta) - (C_3 + C_5)\frac{J_1(P)}{P}$$
$$\tag{5}$$

Apply Laplace transform on the equation (5), we get,

$$\int_0^{\infty}C_6\frac{\partial^2 \tilde{\chi}_T}{\partial \zeta^2}e^{-s\tau}d\tau - \frac{1}{C_8\alpha}L\left[\frac{\partial \tilde{\chi}_T}{\partial \tau}\right] - (C_4 + P^2)\int_0^{\infty}\tilde{\chi}_T e^{-s\tau}d\tau = C_9\int_0^{\infty}e^{-s\tau}d\tau \quad (6)$$

where

$$C_9 = -[J_1(P)100P - J_1(P\beta)(100P\beta) + (C_3 + C_5)\frac{J_1(P)}{P}]$$

Using initial condition (v) in equation (6) and simplifying we get,

$$C_6\frac{\partial^2 \tilde{\tilde{\chi}}_T}{\partial \zeta^2} - \frac{1}{C_8\alpha}[s\tilde{\tilde{\chi}}_T] - \frac{1}{\alpha C_8}\frac{J_1(P)}{P} - (C_4 + P^2)\tilde{\tilde{\chi}}_T = \frac{C_9}{s}$$

$$C_6\frac{\partial^2 \tilde{\tilde{\chi}}_T}{\partial \zeta^2} - \frac{1}{C_8\alpha}[s\tilde{\tilde{\chi}}_T] - (C_4 + P^2)\tilde{\tilde{\chi}}_T = \frac{C_9}{s} + \frac{1}{C_8\alpha}\frac{J_1(P)}{P}$$

$$\frac{\partial^2 \tilde{\tilde{\chi}}_T}{\partial \zeta^2} - \left[\frac{1}{C_6 C_8\alpha}s + \frac{C_4 + P^2}{C_6}\right]\tilde{\tilde{\chi}}_T = \frac{C_9}{C_6 s} + \frac{1}{C_8 C_6\alpha}\frac{J_1(P)}{P} \tag{7}$$

Solving the equation (7)and applying the boundary conditions (iii) and (iv), we get,

$$\tilde{\tilde{\chi}}_T = \left[\frac{30Lh'_f}{K\sqrt{c}(e^{-(2\sqrt{c})}-1)}e^{-2\sqrt{c}}\right]e^{\zeta\sqrt{c}} + \left[\frac{30Lh'_f}{K\sqrt{c}(e^{-(2\sqrt{c})}-1)}\right]e^{-\zeta\sqrt{c}} - \frac{D}{C} \tag{8}$$

where

$$C = \left(\frac{s}{C_6C_8\alpha} + \frac{(C_4+P^2)}{C_6}\right)$$

$$D = \frac{C_9}{C_6s} + \frac{1}{C_8C_6\alpha}\frac{J_1(P)}{P}$$

Applying inverse Laplace transform on equation (8), we get,

$$\tilde{\chi}_T = \frac{30L(h'_f)}{K}\left[\left(\frac{\sqrt{\frac{1}{C_6C_8\alpha}}\zeta}{2\sqrt{\pi\tau^3}}\right)\right]\left[2e^{-\frac{\zeta^2}{4C_6C_8\alpha\tau}}\right] - \frac{C_9}{C_6} \tag{9}$$

Applying inverse Hankel transform on equation (9), we get,
The temperature of tissue region in the human trachea is

$$\chi_T = 2\sum_{i=1}^{i=5}\left[\left(\frac{30L(h'_f)}{K}\right)\left(\frac{\sqrt{\frac{1}{C_6C_8}}\zeta}{2\sqrt{\pi\tau^3}}\right)\left(2e^{-\frac{\zeta^2}{4C_6C_8\alpha\tau}}\right) - \frac{C_9}{C_6}\right]\left[\frac{J_0(P_i\varepsilon)}{[J_1(P_i)]^2}\right] \tag{10}$$

The dimensionless quantities of energy balance equation (4), for the air region can be written as,

$$\frac{\partial\chi_A}{\partial\tau} = -\frac{V}{A}\frac{1}{(L2\pi f)}\left(\frac{\partial\chi_A}{\partial\zeta}\right) + \left(\frac{l_2h_f}{2\pi f}\right)\chi_A + l_3 \tag{11}$$

where $\qquad V_0 = V(t,z) = V/A = $ constant velocity

$$l_2 = \frac{P(z)}{\rho_AC_AA(z)}$$

$$l_3 = \frac{l_2(l_1 - h_fT_A)}{2\pi f(T_a - T_f)}$$

Applying Laplace transform in the equation (11), we get,

$$s\tilde{\chi}_A - 1 = -\frac{V}{A(L2\pi f)}\frac{\partial\tilde{\chi}_A}{\partial\zeta} + \frac{l_2h_f}{2\pi f}\tilde{\chi}_A + \frac{l_3}{s}$$

$$\frac{V}{AL(2\pi f)}\frac{\partial\tilde{\chi}_A}{\partial\zeta} + \left(s - \frac{l_2h_f}{2\pi f}\right)\tilde{\chi}_A - \frac{1}{s}(l_{3+s}) = 0$$

$$\frac{\partial\tilde{\chi}_A}{\partial\zeta} + \left(s - \frac{l_2h_f}{2\pi f}\right)\left(\frac{AL(2\pi f)}{V}\right)\tilde{\chi}_A - \frac{1}{s}(l_{3+s})\left(\frac{AL(2\pi f)}{V}\right) = 0$$

$$\frac{\partial\tilde{\chi}_A}{\partial\zeta} + l_4\tilde{\chi}_A = l_5 \tag{12}$$

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where

$$l_4 = \left(s - \frac{l_2 h_f}{2\pi f}\right)\left(\frac{AL(2\pi f)}{V}\right)$$

$$l_5 = \frac{1}{s}(l_{3+s})\left(\frac{AL(2\pi f)}{V}\right)$$

The required solution of equation (12) is

$$\tilde{\chi}_A = \left[\frac{l_5}{l_4} + Ce^{-l_4\zeta}\right]$$

$$\tilde{\chi}_A = \frac{\frac{1}{s}(l_3 + s)\left(\frac{AL(2\pi f)}{V}\right)}{\left(s - \frac{l_2 h_f}{2\pi f}\right)\left(\frac{AL(2\pi f)}{V}\right)} + Ce^{-\left(s - \frac{l_2 h_f}{2\pi f}\right)\left(\frac{AL2\pi f}{V}\right)\zeta}$$

$$\tilde{\chi}_A = \frac{\left(\frac{l_3}{s} + 1\right)}{\left(s - \frac{l_2 h_f}{2\pi f}\right)} + Ce^{-\left(s - \frac{l_2 h_f}{2\pi f}\right)\left(\frac{AL(2\pi f)}{V}\right)\zeta}$$

$$\tilde{\chi}_A = \frac{\frac{l_3}{s} + 1}{\left(s - \frac{l_2 h_f}{2\pi f}\right)} + C\left[e^{-s\left(\frac{AL2\pi f}{V}\right)\zeta}\right]\left[e^{\left(\frac{l_2 h_f AL}{V}\right)\zeta}\right] \quad (13)$$

Taking inverse Laplace transform in equation (13), we get,

$$L[\tilde{\chi}_A] = L^{-1}\left[\frac{\frac{l_3}{s} + 1}{\left(s - \frac{l_2 h_f}{2\pi f}\right)}\right] + CL^{-1}\left[e^{-s\left(\frac{AL(2\pi f)}{V}\right)\zeta}\right]\left[e^{\left(\frac{l_2 h_f AL}{V}\right)\zeta}\right]$$

$$\chi_A = L^{-1}\left[\frac{l_3}{s\left(s - \frac{l_2 h_f}{2\pi f}\right)}\right] + L^{-1}\left[\frac{1}{s - \frac{l_2 h_f}{2\pi f}}\right] + Ce^{\left(\frac{l_2 h_f AL}{V}\right)\zeta}L^{-1}\left[e^{\left(-\frac{sAL(2\pi f)}{V}\right)\zeta}\right]$$

by using the partial fraction, we get,

$$\chi_A = L^{-1}\left[-\frac{l_3 2\pi f}{l_2 h_f s}\right] + L^{-1}\left[\frac{l_3 2\pi f}{l_2 h_f\left(s - \frac{l_2 h_f}{2\pi f}\right)}\right]$$

$$+ L^{-1}\left[\frac{1}{\left(s - \frac{l_2 h_f}{2\pi f}\right)}\right] + Ce^{\left(\frac{l_2 h_f AL}{V}\right)\zeta}L^{-1}\left[e^{\left(\frac{-sAL2\pi f}{V}\right)\zeta}\right]$$

$$\chi_A = -\left(\frac{l_3 2\pi f}{l_2 h_f}\right) + \left[1 + \frac{l_3 2\pi f}{l_2 h_f}\right]e^{\left(\frac{l_2 h_f}{2\pi f}\right)\tau} + Ce^{\left(\frac{l_2 h_f AL}{V}\right)\zeta}(1) \quad (14)$$

Applying the boundary condition (ix) on the equation (14), we get,

$$\chi_A = -l_6 + e^{\left(\frac{l_2 h_f \tau}{2\pi f}\right)}[1 + l_6] + \left[l_6 - e^{\left(\frac{l_2 h_f \tau}{2\pi f}\right)}[1 + l_6]\right]e^{\zeta} \quad (15)$$

where

$$l_6 = \frac{l_3 2\pi f}{l_2 h_f}$$

The temperature of air region of the human trachea is

$$\chi_A = \left[l_6 - e^{\left(\frac{l_2 h_f \tau}{2\pi f} \right)} (1 + l_6) \right] \left[e^{\zeta} - 1 \right] \tag{16}$$

2.1 Burn Evaluation

F.C. Henriques and A.R. Moritz have proposed the quantitative burn degree evaluation based on the tissue damage, can be represented as an integral of a chemical rate process.

$$\Omega = \int_0^1 P e^{\left(-\frac{\Delta E}{RT} \right)} dt \tag{17}$$

where P is a constant that varies with tissue and local temperature, ΔE and R are the activation energy and ideal gas constant.

If both the conditions $T > 44^o C$ and $\Omega > 0.53$ are satisfied at the entrance of the human trachea ($z = 0$), then it is defined as the first degree burn. Figure 7.11 is the dimensionless Henriques burn integral distribution at the surface of the tissue $[0.65cm < r \leq 3.65cm]$ during fire. Obviously, due to the surface water evaporation cooling, the burn injury often occurs at certain position underneath the skin surface near the inlet of the trachea.

Most of the tissues near the surface suffer injury immediately after the exposure, while in the deeper tissues, serious damage occurs after a relatively longer time period.

The effect of relative humidity of surrounding air can be ignored in predicting burns for short duration exposures. Further, burn times are predicted based on the classical evaluation criterior.

3 Results and Discussions

The governing equations are solved by analytical method by using Hankel transform and Laplace transform. Blood perfusion, thermal conductivity and heat capacity are assumed to be constant in the temperature responses of tissues and air region of the human trachea. In normal respiration, the air is taken in through the nostrils without making any special effort, and sound or exaggerated movement of the nose or chest. Breathing is a cyclic phenomenon.

The results might help us better understand the development of burn taking place in the respiratory trachea exposed to various fire situations. Figures 2 and 3 give the transient temperature distribution in tissue and air after the exposure. Clearly, the surface tissue temperature decreases immediately after the exposure, while in the deeper tissues, the temperature decreases slightly until after a longer period of time. Thermal injury occurs on exposed external surfaces of nose and mouth; burns below the trachea are nearly not encountered due to the efficiency of the upper airway in absorbing the heat. Figure 2 shows that, no obvious temperature fluctuations throughout the inspiratory and expiratory phases of the breathing cycle. The reason can be attributed to the high air speed and thermal capacity of tissue. Another reason lies in that, thermal capacity of the tissue is much higher than that of the air. However, this small fluctuation can be seen clearly in Figure 4 to Figure 7. Due to heat loss to the tissue, the air temperature

decreases acutely from the inlet of respiratory tract to the outlet during an inspiration phase. However, the air temperature remains almost the same over the expiration stage (Figure 3). The temperature of the inspired air is decreased to that near the body core temperature (37^0C). Thus, almost no heat exchange occurs during expiration.

In order to show the tissue temperature fluctuation clearly, transient tissue temperature responses at two specific positions z=8cm, r=0.635cm and z=12cm, r=0.635cm are particularly given in Figures 4, 5, 6 and 7. One can see that the higher amplitude of the temperature oscillation occurs at the position near the inlet of the respiratory tract. Figures 8 give out the transient air temperature responses at the two sections z=8cm and z=12cm. The oscillations are much larger than that of the tissue temperature due to low thermal capacity of the air. In the inlet of the human trachea, the air temperature is mainly influenced by the surrounding air. Thus, the highest temperature almost does not change during inspiration. However, the influence of the surrounding air will become weak near the outlet of the respiratory tract where the highest and the lowest air temperature both gradually increase with the increase of time.
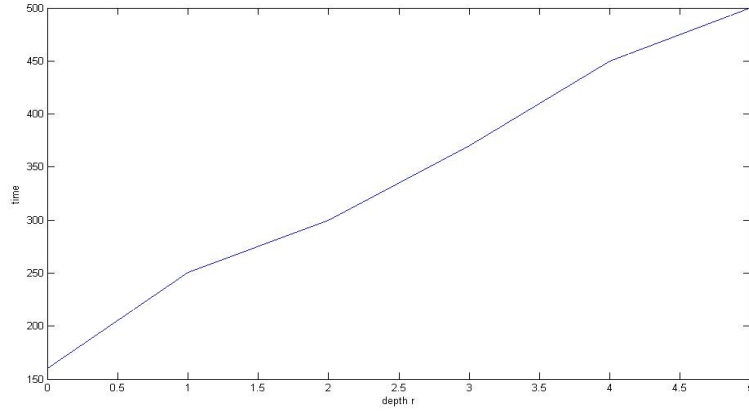

Figure 2: Transient tissue temperature distribution ψ_T with τ during a fire for different values of z (K=0.5, W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
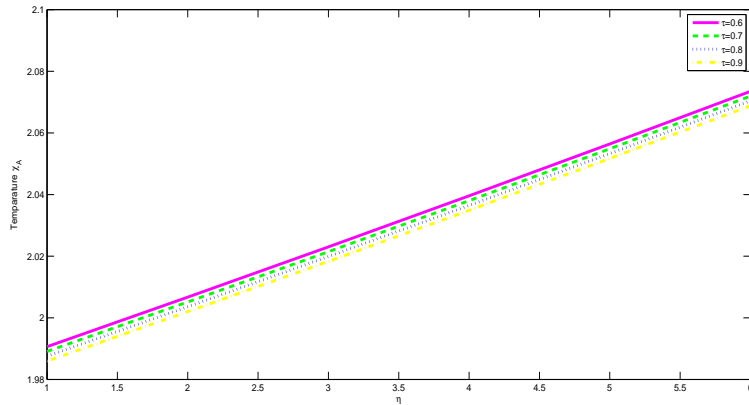

Figure 3: Transient air temperature distribution ψ_A with radial position η during a fire for different values of τ(K=0.5,W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
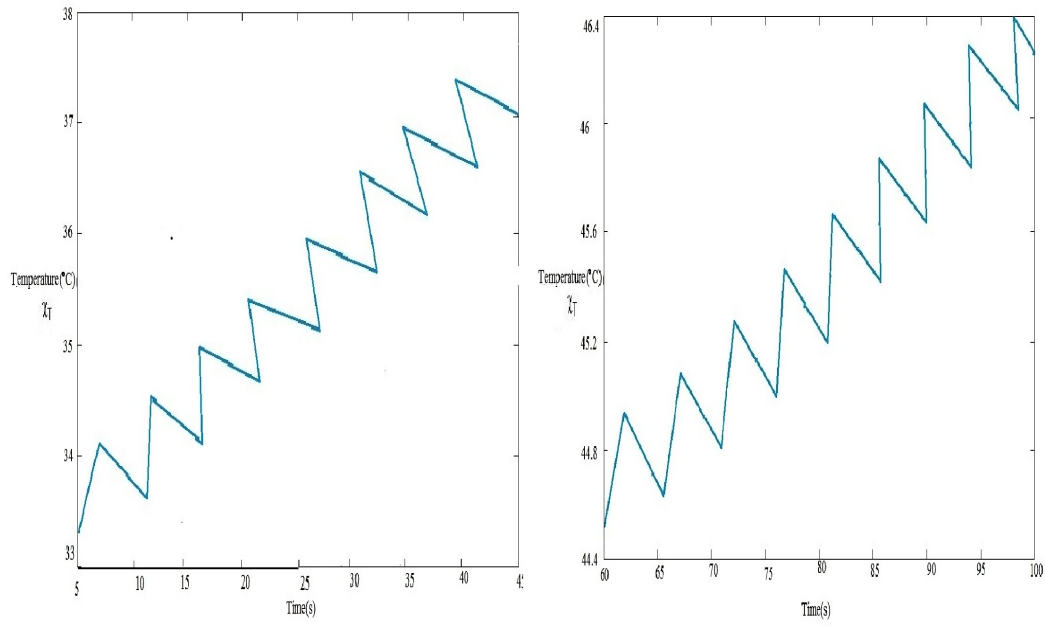
Figure 4: Transient tissue temperature ψ_T responses at specific position z=8(r=0.635, K=0.5, W_b=0.5,Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
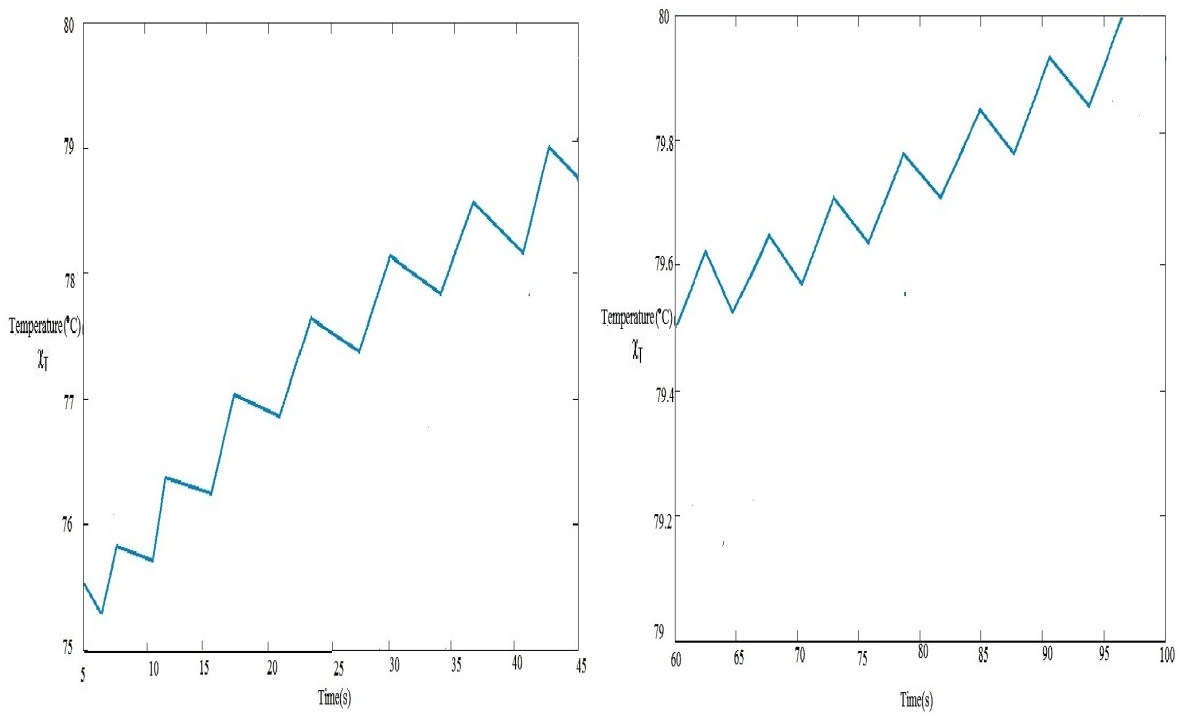

Figure 5: Transient tissue temperature ψ_T responses at section z = 12 (r=0.635, K=0.5, W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
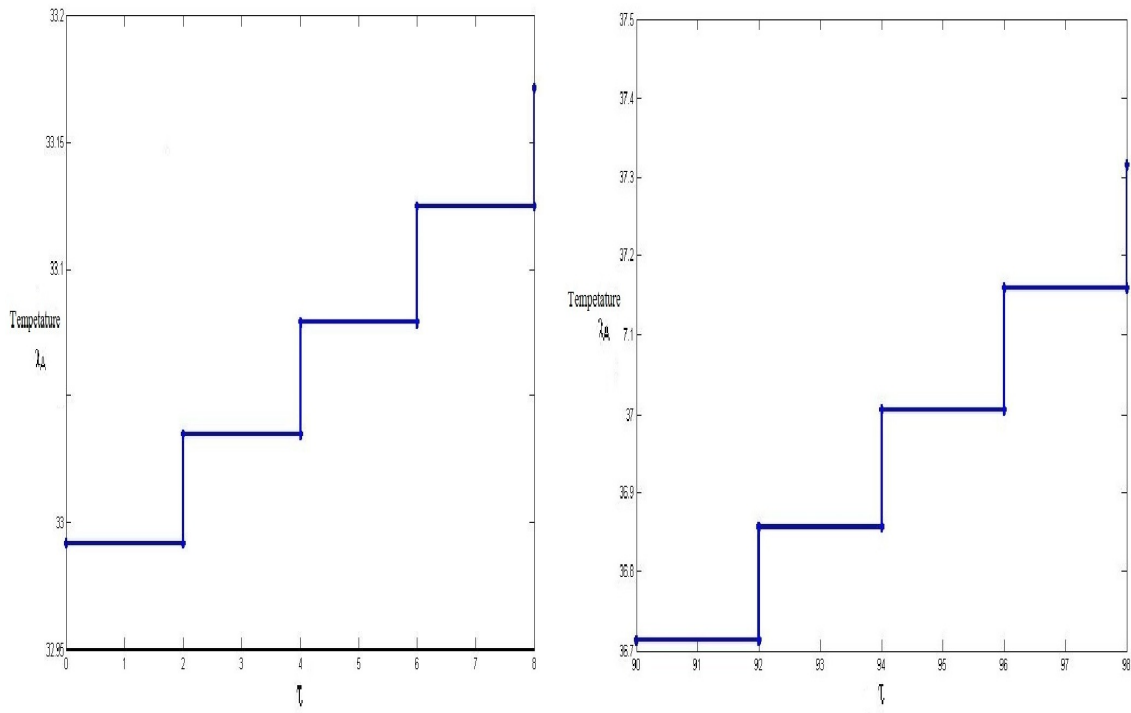
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Figure 6: Transient air temperature ψ_A responses at section z = 8 (K=0.5, W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
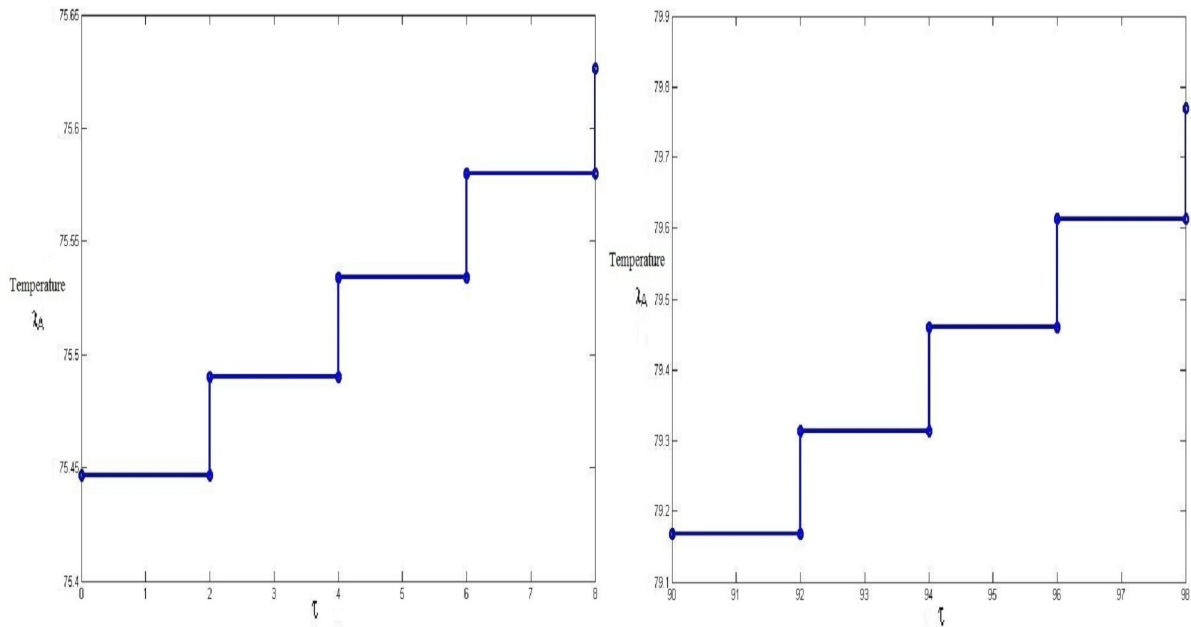

Figure 7: Transient air temperature ψ_A responses at section z = 12 (K=0.5, W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)
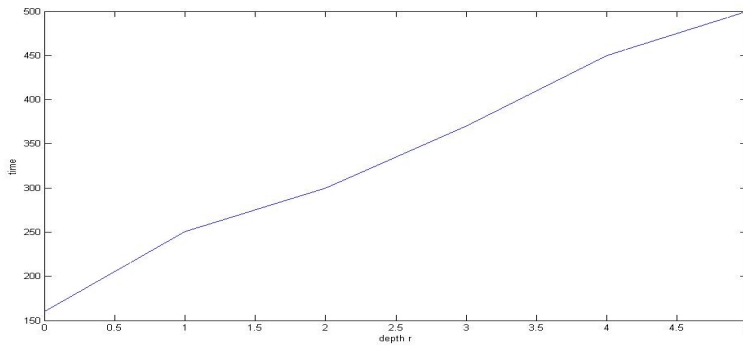
Figure 8: Time prediction of the first-degree burn at the surface of tissue of the trachea during a fire(z=0, K=0.5, W_b=0.5, Q_m=420, T_f=100, V=300, φ=0.3, T^*=3)

4   Conclusion

In this paper, we have developed the effects of inhaled heat transport in human trachea. The problem is solved analytically and the results are represented graphically in Figures 1 to 8 by using Matlab software 9 version.

A transient two-dimensional mathematical model for heat transport across the respiratory tract of human body was established and applied to predict the thermal impact of inhaled hot gas to the nasal tissues during the early stage of fires. A transient theoretical model was established to describe local heat transport, and quantify the burn degree along the airway during the fires. The results might help us better understand the development of burn taking place in trachea exposed to various fire situations. To minimize lung injury when exposed to a fire or natural disaster, the time for the first-degree burns to occur is also theoretically predicted. Most of the tissues near the surface suffer injury immediately after exposure to fire, while in the deeper tissues, serious damage occurs after a relatively longer time period. The method presented a valuable approach to theoretically evaluate the injury of hot air to the human trachea under various fire situations. The effect of transient tissue temperature and air temperature for different positions, thermal conducting and burn with first-degree at the surface of tissue of trachea is studied. Burn evaluation was performed using the classical Henrique's model to predict the time for thermal injury to occur.

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