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A Finite Element Model of Skin Subjected to a Flash Fire

A variable property, multiple layer finite element model was developed to predict skin temperatures and times to second and third degree burns under simulated flash fire conditions. A sensitivity study of burn predictions to variations in thermal physical properties of skin was undertaken using this model. It was found that variations in these properties over the ranges used in multiple layer skin models had minimal effects on second degree burn predictions, but large effects on third degree burn predictions. It was also found that the blood perfusion source term in Pennes' bioheat transfer equation could be neglected in predicting second and third degree burns due to flash fires. The predictions from this model were also compared with those from the closed form solution of this equation, which has been used in the literature for making burn predictions from accidents similar to flash fires.

Introduction

One hazardous situation encountered in the petrochemical industry is the flash fire. Flash fires can result from the release of combustible gas, such as gas leaks at well head sites, compressor stations, and in petrochemical and plastics plants. Flash fires are of short duration, typically less than 5 s, and involve intense heat fluxes (e.g., 84 kW/m^2) [2]. In order to minimize or prevent burns from these accidents, workers wear protective clothing. One method of evaluating protective clothing is to simulate flash fire conditions around an instrumented mannequin dressed in the clothing. Heat flux data from these tests can be used to predict the burns a person would receive in a similar flash fire when wearing this protective clothing. These predictions are made using either an analytical or numerical model of the heat transfer in the skin under flash fire conditions. Here, a one-dimensional finite element model of human skin was developed for this purpose.

A flash fire is quite different from many other exposures studied in the literature, such as the medical uses of lasers, skin under normal temperature distributions, and long duration, low heat flux exposures. Therefore a heat transfer model of skin subjected to a flash fire may be different from a model of one of these other exposures. Many of the thermal physical properties used in the model are difficult to measure, or vary widely from person to person. The heat transfer model developed here was used to decide how important these variations are, and if a heat transfer model for this type of exposure must be modified to account for these factors. A comparison was also made between the heat transfer model developed here and other models proposed in the literature for conditions similar to flash fires.

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Mathematical Model

Heat transfer in the skin was assumed to be transient and one-dimensional. The bioheat transfer equation for blood perfused skin, first proposed by Pennes [16] is:

$$\rho c \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} - G(\rho c)_b (T - T_c) \tag{1}$$

To model the exposure to a flash fire, the following initial and boundary conditions were used:

$$T(x, t=0) = T_i(x) \tag{2}$$

where $T_i(x)$ is some initial temperature gradient in the skin.

$$T(x=L, t) = T_c, t>0 \tag{3}$$

$$k\left(\frac{\partial T}{\partial x}\right) + q(t) = 0 \quad (x=0, t) \tag{4}$$

where $q(t)$ is the heat flux incident on the surface of the skin from the flash fire as a function of time. In this case, the incident heat flux was assumed to be a square wave of an intensity and duration typical of flash fires. When the exposure ended, an insulated boundary condition was used.

The skin was assumed to be opaque, so as to simplify the analysis of the problem. As the emissivity of human skin is 0.94 [17], this assumption produces only slightly higher surface temperatures, and slightly lower temperatures at depth (and therefore burn damage) than with actual diathermanous skin. The energy lost due to evaporation of moisture in the skin, and carborization of the skin at very high exposures was also neglected, such as in Mehta and Wong's work [12]. Since the object of this study was to predict second and third degree burns, evaporation of moisture or carborization of skin that may occur after second and/or third degree damage has already been sustained would not be of interest here. The slightly higher burn predictions which result from these latter assumptions should also be at least partially compensated for by the slightly lower burn predictions made by assuming opaque skin. The rate of metabolic energy production, typically between 100 and

300 W/m^2 [1], was also negligible relative to the large heat fluxes from flash fires.

Thermal damage begins when the temperature at the basal layer (the interface between the epidermis and the dermis) rises above 44°C [13]. Henriques [9] found that skin damage could be represented as a chemical rate process, and that a first order Arrhenius rate equation could be used for the rate of tissue damage,

$$\frac{d\Omega}{dt} = P \exp\left(-\frac{\Delta E}{RT}\right) \quad (5)$$

This equation can be integrated to produce

$$\Omega = \int_0^t P \exp\left(-\frac{\Delta E}{RT}\right) dt \quad (6)$$

For predicting first and second degree burns, T is the temperature of the basal layer. First degree burns are said to occur when the value of the burn integral, Ω, reaches 0.53 at the basal layer, while second degree burns are said to occur when $\Omega = 1.0$ at this location. For predicting third degree burns, T is the temperature of the dermal base (the interface between the dermis and underlying subcutaneous region). Third degree burns are said to occur when $\Omega = 1.0$ at this location. The integration in Eq. (6) is performed over the time the appropriate temperature is greater than or equal to 44°C.

Numerical Model

A variable property, multiple layer finite element model was developed to predict skin temperatures and times to second and third degree burns under simulated flash fire conditions. The finite element method was selected, because future work may involve extending the model to include the complex three-dimensional geometry of the human body. The skin was divided into three layers, the epidermis, the dermis, and the subcutaneous region, with blood perfusion being included in the latter two regions. The finite element matrix equation was derived using Galerkin's weighted residual method from the one-dimensional Pennes' bioheat transfer equation for blood-perfused skin and a step heat flux surface boundary condition. Five cubic Hermitian temperature interpolation polynomial elements (one for the epidermis, and two each for the dermis and subcutaneous region) were used. These were of the form

$$T = \lfloor f_{h1} f_{h2} f_{h3} f_{h4} \rfloor \begin{pmatrix} T_a \\ \left(\frac{\partial T}{\partial x}\right)_a \\ T_b \\ \left(\frac{\partial T}{\partial x}\right)_b \end{pmatrix} \quad (7)$$

Where f_{h1}, f_{h2}, f_{h3}, f_{h4} are the cubic Hermitian temperature interpolation polynomials described by Wu et al. [21]. It was found that these five Hermitian elements provided the same, or better accuracy as nine quadratic or eighteen linear elements. The Crank-Nicholson method was used to solve the resulting ordinary differential equations in time. A quadratic initial temperature distribution between 32.5°C at the surface and 37°C at the base of the subcutaneous region was used. The initial values of the nodal heat fluxes were set to zero as a result of tests performed here and Emery and Carson's work [7].

Henriques' burn integral was used to calculate the times to second and third degree burns. Based on the work done by Morse et al. [14], Weaver and Stoll's [20] values of the pre-exponential factor and activation energy for the burn integral were used for calculating epidermal burn damage, while Takata's [18] values were used for calculating dermal burn damage. These, and the values of other thermal physical properties used in the model, can be found in Tables 1 and 2. A variable time step scheme was introduced to help reduce or eliminate numerical oscillations, and to deal with other numerical problems which may be introduced when the large step heat flux is removed at the end of an exposure.

Results

Thermal physical properties of the skin vary widely by person and body location. A sensitivity study of burn predictions to these variations was undertaken using the finite element model. Heat fluxes of 83.2, 41.6, and 24 kW/m^2 for 3 s were used as test cases. These correspond to a typical exposure of a propane gas flash fire on nude skin (83.2 kW/m^2—about 2 cal/cm^2•s, which is used in tests such as the Thermal Protective Performance (TPP) test for flame resistant fabrics [2]), while the two smaller heat fluxes might represent the heat flux incident on skin from such a fire when covered with a cloth. Three seconds is also a typical length of exposure for an instrumented mannequin test of protective clothing under simulated flash fire conditions [5]. A literature search was conducted to determine the range over which to vary the values of the thermal physical properties in the model. These ranges are shown in Tables 1 and 2. The results of the sensitivity study for each parameter are summarized separately below. Additional details can be found in Torvi [19]. Due to the wide variations in thicknesses throughout the body, and from person to person, the effects of variations in the thicknesses of skin on the temperature and burn predictions from the model were not investigated. The values for the thicknesses of the individual layers shown in Table 1, which are consistent with other investigators, were used in this study.

Thermal Properties. The effects of varying values of specific heat and thermal conductivity on temperature and burn predictions were tested. Each property was varied between its lowest and highest values (from the literature search) for each

Nomenclature

c = specific heat (J/kg•°C)
G = blood perfusion rate (m^3/s/m^3 tissue)
k = thermal conductivity (W/m•°C)
L = total skin thickness (m)
l = thickness of one skin finite element (m)
P = pre-exponential factor (s^{-1})
q = heat flux (W/m^2, cal/cm^2•s)
R = ideal gas constant (8.314 J/mol•°C)
$S(t)$ = step function
T = temperature (°C, K)
t = time (s)
x = depth (m)
α = thermal diffusivity (m^2/s)
ΔE = activation energy (J/mol)
ρ = density (kg/m^3)
Ω = Henriques' burn integral value (dimensionless)

Subscripts

a = absorbed, node number
b = blood, node number
c = core
ex = exposure
h = Hermitian
i = initial
o = original

Table 1 Thermal physical properties used in this model

Symbol	Property	Units	Value Range	Reference
c	Specific Heat	J/kg • °C		
	a) epidermis		3578 - 3600	10,15
	b) dermis		3200 - 3400	10,15
	c) sub-cutaneous		2288 - 3060	10,15
	d) blood		3770	12
G	blood perfusion rate	$m^3/s/m^3$ tissue		
	a) epidermis		0	12
	b) dermis		0.00125	12
	c) sub-cutaneous		0.00125	12
k	Thermal conductivity	W/m • °C		
	a) epidermis		0.21 - 0.26	10,6
	b) dermis		0.37 - 0.52	10,6
	c) sub-cutaneous		0.16 - 0.21	10,15
	d) single layer			
	in vivo		0.48 - 2.8	4
	in vitro		0.21 - 0.41	4
L	Thickness	m		
	a) epidermis		80×10^{-6}	12
	b) dermis		0.00200	12
	c) sub-cutaneous		0.010	12
T_c	Body core temperature	°C	37	12
T_s	Body surface temperature	°C	32.5	17
ρ	Density	kg/m^3		
	a) epidermis		1200	12
	b) dermis		1200	12
	c) sub-cutaneous		1000	11
	d) blood		1060	12

Table 2 Values of constants for Henriques' burn integral used with this model

a) Epidermis

Symbol	Property	Units	Investigator: Henriques [9]	Investigator: Weaver & Stoll [20]	Investigator: Mehta & Wong [12]
P	Pre-exponential factor	s^{-1}	3.1×10^{98}	2.185×10^{124} $44 \le T < 50°C$ 1.823×10^{51} $T \ge 50°C$	1.43×10^{72}
ΔE/R	Ratio of activation energy to universal gas constant	K	75 000	93534.9 $44 \le T < 50°C$ 39 109.8 $T \ge 50°C$	55 000

b) Dermis

Symbol	Property	Units	Takata [18]	Mehta & Wong [12]
P	Pre-exponential factor	s^{-1}	4.32×10^{64} $44 \le T < 50°C$ 9.39×10^{104} $50 \le T \le 60°C$	2.86×10^{69}
ΔE/R	Ratio of activation energy to universal gas constant	K	50 000 $44 \le T < 50°C$ 80 000 $50 \le T \le 60°C$	55 000

layer, while keeping the values for the other layers constant. As the variations in these properties are minimal over the individual layers, little variations in temperature and burn predictions were found.

A single layer model was then used to test the sensitivity of temperature and burn predictions to the in vivo (0.48 to 2.8 W/m•°C) and in vitro (0.21 to 0.41 W/m•°C) ranges of thermal conductivity of the entire skin. The times to second and third degree burn predicted over these ranges are shown in Table 3. There were large differences between the results over the range of in vivo thermal conductivities. This was expected because of the large range of thermal conductivity values observed under different conditions. The differences in second degree burn predictions over the range of in vitro thermal conductivities were smaller, and increased as the heat flux decreased and the thermal properties become more important in predicting times to second degree burn (as damage did not occur almost instantaneously, as with the higher heat fluxes).

Blood Perfusion. Temperature and skin burn predictions were made using the in vivo value of the thermal conductivity of skin with the perfusion term set to zero. These were then compared with those found using compromised flow and excised skin thermal conductivity values and the normal value of the perfusion term. It was thought that if the temperatures and burn times predicted using the two approaches were found to be equal, then the perfusion term might be responsible for the differences in thermal conductivity values between excised and living, perfused skin. However, no correlation could be found between the predictions made using the different approaches. Therefore, the perfusion term was not responsible for the differences in the thermal conductivity values of the skin in different states.

The volumetric heat capacity of blood was then held constant, and the dermal and subcutaneous layer perfusion rates were given values of 0, 0.00125, and 0.0025 $m^3/s/m^3$ tissue. These values correspond to no perfusion, the normal perfusion rate, and double the normal perfusion rate. The results of these tests are shown in Table 4. There was no difference in times to second degree burns, and some difference in times to third degree burns.

Table 3 Times to second and third degree burn predicted using the lowest and highest common values of in vivo and in vitro thermal conductivity

Heat Flux (kW/m²)	Time to 2° burn (s)		Time to 3° burn (s)	
In Vivo	k = 0.48 W/m·°C	k = 2.8 W/m·°C	k = 0.48 W/m·°C	k = 2.8 W/m·°C
24	2.72	no burn	no burn	no burn
41.6	1.24	no burn	no burn	no burn
83.2	0.50	1.34	no burn	no burn
In Vitro	k = 0.21 W/m·°C	k = 0.41 W/m·°C	k = 0.21 W/m·°C	k = 0.41 W/m·°C
24	1.68	2.38	no burn	no burn
41.6	0.84	1.22	no burn	no burn
83.2	0.40	0.46	no burn	no burn

A lower heat flux kept constant throughout the entire time of interest was also used to test the effect of varying the value of the blood perfusion rate. Here a heat flux of 10.4 kW/m^2 was placed on the skin for the entire 120 s of interest. This flux might represent the smaller heat flux transmitted from a garment in close proximity with the skin after a flash fire exposure. With this heat flux there was practically no difference in second and third degree burn time predictions with and without perfusion. It would appear that the perfusion term will only make a difference if the incident heat flux is not so high as to almost immediately cause burns, and only when the heat flux is removed from the skin.

There has been some question as to what the perfusion term represents and whether it should be included in this skin model. In longer duration exposures of low heat fluxes, the perfusion term is often included because of the ability of the body to react to heat. However, as Lipkin and Hardy [11] point out, *it takes about 20 s for the skin to react by increasing the blood flow.* In flash fire exposures, second degree damage, and even much of third degree damage can already have taken place by the time this increase in blood flow occurs. As well, it has been shown here that the perfusion term has little effect on burn predictions, especially second degree predictions, under conditions where the skin is insulated after exposure, and also when a constant heat flux is applied over a longer period of time. Therefore it is recommended that blood perfusion be ignored in any further model of this type of accident.

Pre-Exponential Factor and Activation Energy in Henriques' Burn Integral. The effects of varying the pre-exponential factor and the activation energy on the predicted times to second and third degree burns were tested over the range

Table 4 Times to second and third degree burns predicted using various blood perfusion rates and heat fluxes

Heat Flux (kW/m²)	G = 0.0 m³/s/m³ tissue	G = 0.00125 m³/s/m³ tissue	G = 0.0025 m³/s/m³ tissue
		Time to 2° Burn	
24	2.78	2.78	2.78
41.6	1.30	1.30	1.30
83.2	0.54	0.54	0.54
166.4	0.24	0.24	0.24
10.4*	9.4	9.4	9.4
		Time to 3° burn (s)	
83.2	31	55	no burn
166.4	7.2	7.3	7.3
10.4*	34	35	35

* the 10.4 kW/m^2 heat flux was kept constant over the entire 120 s time period; the other heat fluxes were only applied for 3 s

Table 5 Comparison of times to second degree and third degree burn predicted using the different values of the pre-exponential factor and activation energy found in the literature

a) Second Degree Burns

	Time to 2° Burn (s)		
Heat Flux (kW/m²)	Weaver and Stoll [20]	Henriques [9]	Mehta & Wong [12]
24	2.78	2.64	2.72
41.6	1.30	1.16	1.22
83.2	0.54	0.46	0.48
166.4	0.24	0.22	0.22

b) Third Degree Burns

	Time to 3° Burn (s)	
Heat Flux (kW/m²)	Takata [18]	Mehta & Wong [12]
83.2	55	no burn
166.4	12	7.3

of exposures typical of flash fires. The values used in these tests are shown in Table 2.

A comparison between the times to second and third degree burn predicted using the different values is shown in Table 5. Little difference in times to second degree burn resulted from changing the values of the pre-exponential factor and activation energy for this range of heat fluxes. The effect of changing the values on third degree burn predictions was much larger than with the second degree burn times. As the times to third degree burn are much longer, this would be expected. It is often difficult to distinguish between deep second degree, and third degree burns. Therefore, it would be more difficult to get accurate values for the pre-exponential factor and activation energy in third degree burn experiments than in first and second degree burn experiments. Using Takata's [18] values results in predictions of shorter times to third degree burns over the heat fluxes studied than if Mehta and Wong's [12] values were used. Therefore using Takata's values will result in more conservative estimates of the protection offered by fabric or clothing.

Comparison of Skin Burn Models. Temperature-time histories predicted by the variable property, multiple layer finite element program, and a constant property, single layer closed form solution were compared with experimental results. For a step heat flux incident on the skin, the closed form solution to Pennes bioheat transfer equation, ignoring perfusion, is

$$T(x,t)=T_i+\frac{2q_o}{\sqrt{k\rho c}}\left[\sqrt{t_{ex}}\,ierfc\left(\frac{x}{2\sqrt{\alpha t}}\right)-\sqrt{t-t_{ex}}\,ierfc\left(\frac{x}{2\sqrt{\alpha(t-t_{ex})}}\right)S(t)\right] \quad (8)$$

Hardee and Lee [8] recommend using this solution for predicting burns from accident scenarios similar to flash fires. (Similar closed form solutions for boundary conditions representing other heat exposures were presented by Buettner [3].) For the constant property, single layer model, the entire skin was assumed to be at an initially uniform temperature of 32.5°C. The values of thermal conductivity and volumetric heat capacity recommended by Hardee and Lee for a single layer model were used, namely, $k=0.764$ W/m•°C and $\rho c=3.35\times10^6$ J/m^3•°C.

Predictions were also compared to the experimental results of Stoll and Greene [17] who determined the exposure times and temperatures for pain and blister thresholds using blackened skin irradiated with heat fluxes between 4.186 and 16.744 kW/m^2. Stoll and Greene measured the skin surface temperatures during these exposures, and calculated the basal layer temperatures using these surface temperatures.

The temperature-time histories for the basal layer are shown in Fig. 1 for an incident heat flux of 4.186 kW/m^2 for 34 s (the time to blistering or second degree burn according to Stoll and Greene for this heat flux). The agreement between the finite element solution and the values which Stoll and Greene presented was good, except for the initial portion of the exposure. There the temperatures predicted by the closed form solution were much closer to Stoll and Greene's values. Later in the exposure, the temperatures predicted by the closed form solution were considerably different from those measured by Stoll and Greene. This would indicate that the variable property, finite element model predicts temperatures better than the single layer, constant property closed form solution, at least for these lower intensity, continuous exposures.

The predictions of times to second and third degree burns made by the two models were compared with each other, and with Stoll and Greene's experimental results in the case of second degree burns. These comparisons were made for high intensity, short duration exposures typical of flash fires, and

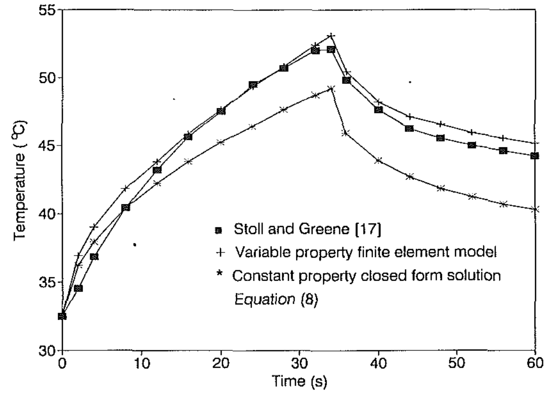

Fig. 1 Basal layer temperature-time histories determined using finite element and closed-form solutions and reported by Stoll and Greene [17] (exposure of 4.186 kW/m^2 for 34 s)

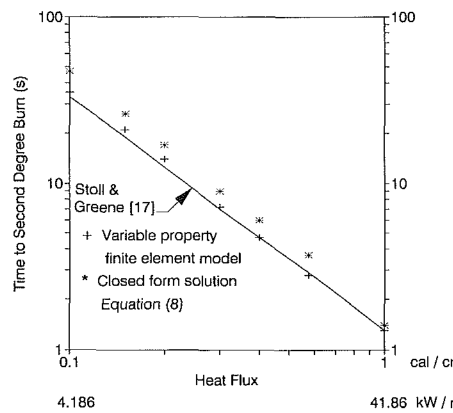

Fig. 2 Times to second degree burn as predicted by finite element and closed-form solutions, and observed by Stoll and Greene [17]

for the lower intensity, continuous exposures used by Stoll and Greene.

For the high intensity, short duration (3 s) exposures the times to second degree burn predicted by the models were practically the same. The times to second degree burn for the lower intensity exposures are shown in Fig. 2. The finite element predictions were every close to the times observed by Stoll and Greene. The closed form solution predictions were not as close as those of the finite element program at lower heat fluxes, but were closer at higher heat fluxes.

The times to third degree burns predicted by the variable property, multiple layer finite element model, and the constant property, single layer closed-form solution are shown in Table 6. The predictions made by the closed form solutions were different from those made by the finite element model, just as with second degree burns. The differences between the closed form and finite element predictions increased as the heat fluxes decreased. It cannot be said that the finite element predictions are more accurate than the closed form solution predictions, as no experimental data were available with which to compare to the two models. However, based on the results for second degree burns, and intuition, it would again make sense that a multiple layer model of the skin using different properties for each layer would make more accurate predictions of deeper burns than a single layer model of the skin. As well, the closed-form solution uses a constant initial temperature gradient of 32.5°C, whereas the finite element model uses a quadratic initial temperature gradient. It was found during initial development of the finite element model that such a difference in initial dermal base temperatures (32.5°C for the closed form

Table 6 Times to third degree burn calculated by the finite element model and closed-form solutions

Heat Flux (kW/m²)	Time to 3° Burn (s)	
	Finite Element	Closed Form Solution
	3 s exposures	
83.2	55	no burn
166.4	7.3	6
	Continuous exposures	
4.2	79	120
6.2	53	74
8.3	41	53
12.5	30	34
16.6	24	26

solution and 33.9°C for the finite element solution) can make a large difference in predicted times to third degree burns, or whether third degree burns will in fact be predicted for heat fluxes typical of flash fires.

Based on all of the results to date, a closed form solution will predict the time to second degree burns from a typical flash fire exposure slightly less accurately than a finite element model. It is, however, computationally quicker. As long as the heat fluxes incident on the skin do not become too small, then the difference between second degree burn predictions using the closed form solution and the finite element solution should not be very large. Fairly high heat fluxes (e.g., 15 to 83.2 kWm^2) are expected through most clothing, so this should not be a problem in flash fire modeling. Therefore in such cases, the closed form solution may be sufficient. However, if third degree burn predictions are required, the finite element model should be used.

Conclusions

The multiple-layer, variable property finite element model of the heat transfer in the skin subjected to a flash fire was used to test the effects of variations in thermal physical properties on skin temperature and burn predictions. It was found that variations in thermal physical properties over the ranges used in multiple layer skin models had minimal effects on second degree burn predictions, but larger effects on third degree burn predictions. It was also found that the blood perfusion term in Pennes' bioheat transfer equation can be neglected in predicting second and third degree burns due to flash fires. Variations in the pre-exponential factor and activation energy in Henriques' burn integral had minimal effect on second degree burn predictions, but a larger effect on third degree burn predictions. The variable property, multiple layer finite element model developed here is more accurate in making temperature and burn predictions than the constant property, single layer closed form solution for a step heat flux. However, if only second degree burn predictions must be made, the closed-form solution may be adequate.

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