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A SIMPLE SOURCE TEMPERATURE DEPENDENT HUMAN BURN INJURY MODEL

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This paper presents a simple method of modelling the burn injuries caused by a variety of different temperature sources. The model assumes the source delivers energy characteristic of a blackbody radiator. The skin is modelled as a three layer continuous medium, with scattering and absorption taken into account. The time to second-degree burns is found using a finite difference approximation in conjunction with a commonly used burn integral.

The optical skin module has been validated against previous data, whilst the overall model has been validated against trials for both low and high temperature thermal radiation sources. The model has been recommended for use in safety engineering and has been found accurate and conservative.

INTRODUCTION

Over recent years a number of researchers have used finite element and finite difference models to simulate the burning effect of radiation and hot gases upon the skin. The majority of these models assume that the radiant heat is absorbed at the skin's surface, which is a good approximation for low-temperature radiant sources; however for high-temperature sources this approximation is far less accurate because of the penetrating nature of high-temperature radiation. Only one set of figures to the best of the authors' knowledge have been published on the subject of thermal radiation penetrating into human skin. Unfortunately, these figures appear to be for a solar source which is characteristic of a 6000K radiator. So there is a large gap in the knowledge between the low temperature source (1000K) and high temperature source (6000K), which can cause problems when modelling the thermal effects of explosives, due to the fact that many explosive fireballs can be as hot as 4000K. This paper puts forward a modelling procedure for simulating the effect of different temperature heat sources upon the skin.

SKIN OPTICAL PROPERTIES

Radiation penetration of the skin is highly wavelength dependent due to the large number of different chromophores present within the skin. In combination the chromophores create a region of the spectrum known as the “Therapeutic Window” (approximately 600 – 1300 nm), where large amounts of radiation can penetrate the skin. It is this window that most likely causes the significant differences between injuries caused by high temperature and low temperature radiation, because high temperature sources are more likely to deliver radiation with wavelengths in the therapeutic window.

This penetrating radiation can be difficult to model, because of the changes in characteristics between its two predominant upper layers, the epidermis (outermost layer) and the dermis (layer below). The effect on the epidermis is dominated by absorption due to its component chromophores, not optical scattering. In contrast, the optical properties of the dermis are largely determined by scattering, mainly from the collagen fibres to be found there, whilst any absorption is due to hemoglobin, oxyhemoglobin and bilirubin.

This model described below attempts to use knowledge of the skin’s optical properties to predict the effect of thermal radiation upon the skin.

SOURCE MODULE

The model is formed from three parts: the source, optical and thermal modules. The first of these, the source module, calculates the amount of energy radiated by the fireball as a function of wavelength. This is achieved by assuming the fireball is a blackbody radiator, such that the flux emitted at each wavelength is given by eq.(1).

$$F(\lambda) = \frac{2\pi hc^2}{\lambda^5 (\exp(\frac{hc}{\lambda k_b T_F}) - 1)} \qquad (1)$$

The EM spectrum is then sampled at discrete wavelengths and the intensity of radiation at each wavelength is calculated using eq.(1). The intensity of radiation at each discrete wavelength is then passed to the optical module.

Atmospheric absorption is taken into account using data from LOWTRAN, an empirical US model for calculating the absorption spectrum of air. It uses the range to the target to calculate the percentage absorbed. A geometrical View Factor is also included in the model to represent the proportion of the total radiation from the source that is incident upon the target, dependent upon the size of the fireball and the range to that target.

SKIN OPTICAL MODULE

The skin optical module is broken down into two parts, to calculate reflectance and penetration. The first part calculates the total amount of radiation absorbed by the skin from the source. For this, it uses Anderson [1] an empirically measured reflection spectrum of the skin (Figure 1):

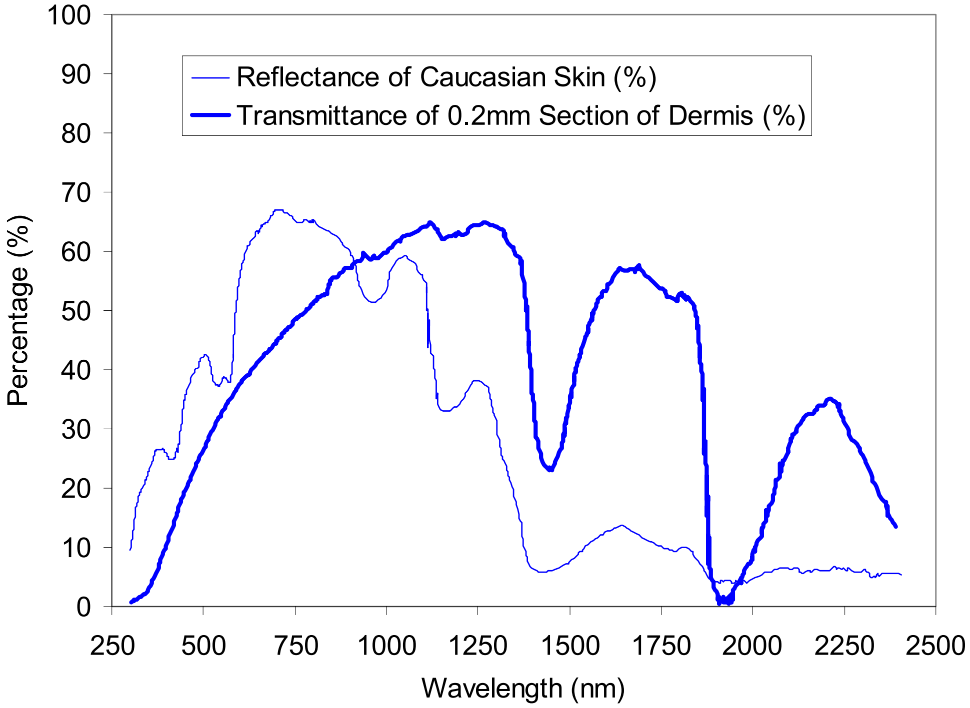

Figure 1: Spectral data for Caucasian Skin

The data from Figure 1 was used to calculate the reflectance at each discrete wavelength from the source model. The energy reflected at each wavelength is calculated and integrated over the entire spectrum to give the total reflectance. For wavelengths outside the range in Figure 1, the reflectance was assumed to be 5% in accordance with Lawton and Laird [2]. The intensity of the absorbed radiation at each sampled wavelength is then passed to the penetration part of the module.

The penetration part of the module calculates the flux profile within the skin using the Kubelka-Munk [3, 4] model, which is a 1-Dimensional flux model for transmission within a turbid material, accounting for both scattering and absorption.

From the Kubelka-Munk model two important equations for transmission through layered mediums can be derived:

$$Q_{1,n} = \frac{Q_{1,n-1}Q_n}{1 - R_{1,n-1}R_n} \tag{2}$$

$$R_{1,n} = R_{1,n-1} + \frac{Q_{1,n-1}^2 R_n}{1 - R_{1,n-1}R_n} \tag{3}$$

Using these two equations (and knowledge of how scattering and absorption within the skin is affected by wavelength) it is possible to find the relation between the energy remaining and the depth of penetration, verses wavelength. Allowing the calculation of how much radiation is absorbed as a function of distance into the skin. The skin is split into 100 nodes and the energy absorbed at each node from the sampled wavelengths is calculated. The total energy absorbed at each node over the entire spectrum is then calculated, leading to a flux profile for the skin. The differential of this profile is then found and passed to the thermal module.

SKIN THERMAL MODULE

In order to calculate the time to burn, *T(x,t)* needs to be calculated, which is achieved by solving eq.(4) using finite element methods for a 3 layer model of the skin, which has the epidermis (outermost layer) 0.1mm thick, the dermis (2 mm thick) and subcutaneous fat (innermost layer) 2 mm thick.

$$\rho c_p \frac{\partial T(x,t)}{\partial t} = k_c \frac{\partial^2 T(x,t)}{\partial x^2} + q_i(x) \tag{4}$$

The values for k_c, ρ and c_p were all taken from Lawton and Laird [2], whilst the value of $q_i(x)$ is an internal heat generation term, which is essentially the radiation absorbed as the flux passes through the skin. This is not the flux, but the differential of the flux profile, which has been passed from the optical module.

This however only gives *T(x,t)*. The time to second-degree burn is calculated by integrating the Henriques and Moritz [5] burn integral eq.(5) over the burning and cooling period at a depth of 0.1mm, the epidermis – dermis interface. A second-degree burn is defined as total destruction of the epidermis:

$$\frac{d\Omega}{dt} = A\exp(-\frac{\Delta E}{RT(t)}) \tag{5}$$

When Ω reaches unity a second-degree burn is judged to have occurred.

VALIDATION

Validation of the optical module was conducted by examining how well predictions matched experimental values for two properties: the skin's reflectivity as a function of temperature, and the flux profile within the skin. The skin's reflectivity was validated against the work of Buettner [6], who found that 5% of radiation was reflected by the skin at 1000 K. The present model predicts 5.19%, which converges to 5% as the temperature becomes lower. For high temperature radiation (6000K), Buettner found 42% of the radiation was reflected. The present model predicts 39.9%. Shown below is a graph of skin reflectance against source temperature as plotted by the optical module (Figure 2).

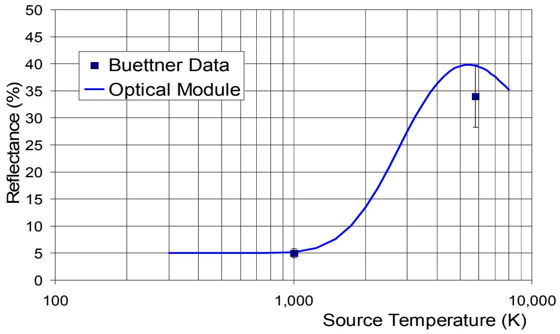

Figure 2: Reflectance of Caucasian skin against Source Temperature by Buettner and the Optical Module.

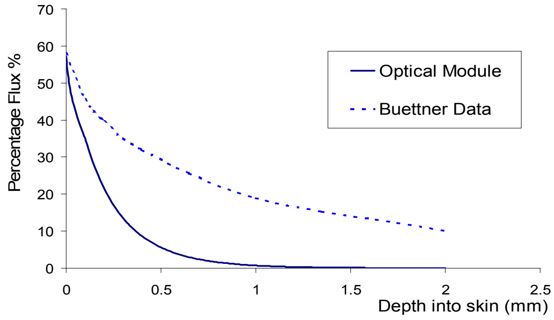

Figure 3: Comparison of flux profiles found by Buettner and the Optical Module.

The second part of the optical module to be validated, was the flux profile calculated within the skin. Here, comparisons between the module and Buettner's data are less conclusive. Buettner found that 95% of the radiation from a low temperature source was absorbed at the surface, whereas the optical module predicts 81.35% absorbed at the surface, with the majority of the rest being absorbed within the first 0.2mm. It would seem very unlikely that Buettner's data is exact because there will always be penetration to some depth, therefore his values are likely to be an approximation to reality.

For the high temperature radiation however, there is a considerable difference between our optical module and Buettner's data (Figure 3), with Buettner predicting at least 10% of the thermal radiation passing through 2mm of skin, whereas the model predicts practically no penetration beyond 1mm. Two possible explanations arise. Either there is a factor, that is not allowed for in our optical module, e.g. the optical properties of skin changing with increasing temperature, or the Buettner data is incorrect. Unfortunately it is not immediately obvious in his paper how he measured the flux profile. If he used other researchers' measured values of transmissivity then his values may be flawed. More recent researchers than Buettner have claimed that a lot of the early work on skin transmissivity did not account fully for the effect of melanin within the epidermis or the effect of scattering by the dermis.

Because the optical part of the model is crucial and totally new, some attention should be paid as to why the results from it are so similar to Buettner's results for the reflectance and low temperature flux profile, yet are so different for the high temperature flux profiles. Although Buettner is not explicit in how he arrived at his results, it would seem likely that to find the reflection profile of the skin, all that is needed is a spectrometer, with no knowledge of the optical properties of the skin, it is possible to treat the skin, simply as a black box. However, for flux profiles some knowledge of the skin's optical properties is needed and as already stated, many of the early researchers did not fully take into account the effect of melanin and scattering by the dermis. There is then the question as to whether Buettner's work is correct or our optical module is correct for the high temperature flux profile.

Additionally from Anderson [1], we can look at data for the transmission spectrum of a 0.2 mm strip of the dermis (Figure 1). This shows that the maximum transmission through a 0.2mm layer at any wavelength is around 68 %. For a total skin thickness of 2mm the transmittance would hence be approximately 2%, even at the wavelength of greater transmittance. This would indicate that the data of Buettner is predicting far more flux penetration of the dermis than is indeed possible. Our optical module validation results thus appear sensible and more accurate for high temperature sources.

BURN SIMULATIONS

The true test however of the optical module is how well it functions with the thermal module to predict skin burns. In order to validate the optical and thermal modules in combination. The Burn Injury Model was compared against low temperature and high temperature radiation source experiments.

The low temperature source results come from work undertaken by Stoll and Greene [7]. This radiation source is usually characterised as a low temperature source in the region of 1000K. It is not a perfect match to the model as the skin was blackened to make it absorb more of the radiation. Shown below is a comparison for the simulated times to burn by the thermal module, when used in conjunction with the optical module and the Buettner data.

Table 1: Comparison of simulated Times to Burn against observations for Low Temperature source.

Flux (kW/m^2)	Simulated Time to Burn (s)		Observed Time to burn (s)
	Buettner Data	Optical Module	
4.168	46.4	47.3	33.8
6.252	23.5	24.16	20.8
8.336	14.4	14.8	13.4
12.504	7.28	7.6	7.8
16.672	4.54	4.75	5.6

The results show a generally good relationship at higher fluxes. Only high fluxes are interesting from a safety modelling point of view, because at low fluxes, anyone in danger will be able to vacate the area quickly before burn injuries become dangerous.

To validate the model at higher source temperatures, data from "Recent Advances in Surgery" [8] was used. The data collected from this research was for a 5800K black body radiator. Shown below are the results. Once again our optical module has been compared with the data from Buettner.

Table 2: High source temperature results for Time to Burn using flux profiles from Buettner and Optical Module. Observed burns are from a 0.54 second burst.

Flux (kW/m^2)	Simulated Times to Burn (s)		Observed Degree of Burn
	Buettner Data	Optical Module	
154	No Burn	No Burn	No Burn
246	No Burn	0.42	1st – 2nd
301	No Burn	0.34	2nd

As the results show, the new optical module appears to give better predictions than Buettner's data. The optical module appears to be slightly conservative, as it predicts a second-degree burn, when in reality the observation was only of somewhere between a 1st and 2nd degree burn. This could be due to a difference in the classification of burns by different researchers, or the inherent variability of thermal properties of biological tissues. For example, measurements of k_c, c_p and ρ have indicated a range of possible values for each parameter. The model was rerun for a flux of 246 kW/m^2 using figures for these parameters that lay within the ranges measured, but which maximised the time to burn. The resulting time to burn was predicted to be 0.514 seconds, which is much closer to the experimental figure observed.

RESULTS

Figure 4 shows the results generated by the optical module in conjunction with the three layer model for the Time to Burn against heat dose.

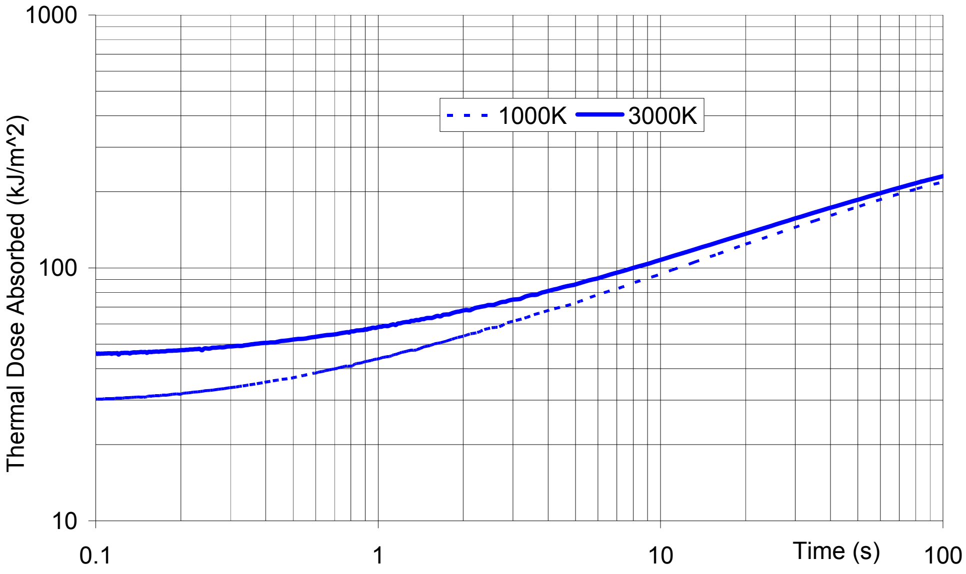

Figure 4: Time to Second-Degree Burns

DISCUSSION

The results show a general trend. Higher temperature sources require greater heat doses to inflict second-degree burns. The reason for this, is that a greater proportion of the energy is delivered in the "Therapeutic Window" (600 – 1300 nm) part of the spectrum. This penetrating radiation is thus less dangerous, since its energy is absorbed through a larger skin volume. Of particular interest is Figure 2, this predicts that Caucasian skin has maximum reflectance of 40% at solar source temperatures.

CONCLUSION

A new model has been built to simulate the optical properties of the skin, using the Kubelka-Munk model and the reflection spectrum of skin. This was applied to a three layer skin model to simulate burn injuries, the results were reasonably close at both high and low temperatures.

NOMENCLATURE

ΔE – Activation energy for cell destruction (J/mol)
Ω – Damage within skin as judged histologically
A – Empirically derived constant (1/s)
c_p – Specific heat capacity of skin (J/kg/K)
h – Planck constant (J.s)
k_c – Thermal conductivity of skin (W/m/K)
$Q_{1,n}$ – Transmittance through layers from 1st to nth
$R_{1,n}$ – Remittance from layered material with layers 1 - n
R_n – Remitted from nth layer
$T(x,t)$ – Temperature in skin (K)
x – Depth into skin (m)
λ – Wavelength (m)
ρ – Density of skin (kg/m^3)
c – Speed of light (m/s)
F – Spectral Intensity (W/m^2/m)
k_b – Boltzmann constant (J/K)
q_i – Internal heat generation (W/m^3)
Q_n – Transmission through nth layer
R – Gas constant (J/mol/K)
T_F – Fireball temperature (K)
t – Time (s)

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