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Prediction of radiative protective performance of multilayered clothing

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Performance of protective clothing assembly exposed to pure radiant heat source has been modeled and time to cause the second degree burn injury is predicted by solving the model equation. These findings have been compared with experimentally determined values. Good agreement has been found with experimental and predicted data. Effect of different fabric parameters and boundary conditions has been estimated by varying these parameters and then solving the equations. Fabric reflectivity and thickness appear to be the most important parameters dictating the heat transfer process. Temperature dependent thermal conductivity and specific heat are the other critical parameters governing the heat flow.

Keywords: Multilayered protective clothing, Protective performance, Radiative heat

1 Introduction

Common textile materials normally worn in our daily life are designed to protect us from usual external effects like natural heat and cold, wind, dust and dirt, direct body contact with different external objects and chemicals. Adanur[1] defined protective clothing as garments and other fabric-related items designed to protect the wearer from harsh environmental effects that may result in injuries or death. Firefighters are exposed to heat and fire of different forms, intensities and duration and they are supposed to work in such hazardous working conditions. An intense heat can result burn injuries of different severity and in extreme case can lead to the death of the person involved. Every year considerable number of firefighters gets themselves injured as a result of intense thermal exposures. So, performance of the protective clothing meant for firefighter's and like application namely industrial worker's uniform are very important as the life of the person is involved. Primary purpose of such protective clothing is to provide protection to the person involved for long duration if the heat flux is not intense and if there is flash fire giving the person an opportunity to escape from the fire[2]. As the fabric-human skin being exposed to the incident heat fluxes which is usually a mixture of convective and radiative heat fluxes and sometimes may be conductive only, the face side of the fabric system starts becoming heated up through absorption and transmission of heat and finally causes skin burn injuries.

A number of studies has been carried out over the years to model and predict the thermal protective performance of the fabric[2-5]. Torvi[2] in his work has done modeling of heat transfer through single layer protective clothing, and solved the differential equation representing fabric-airgap-sensor model using finite element methods. Torvi[2] verified the computer program written for solving the heat transfer model, comparing with temperatures obtained from experimental results and with other forms of solutions. Whitaker's theory[6] of coupled heat and mass transfer in a drying body has been applied by Gibson[7], considering textile as a porous material. He developed a set of equations modeling heat and mass transfer through textile materials. Heat and moisture transport in firefighter protective clothing during intense flash fire exposure has been investigated by Chitrphiromsri and Kuznetsov[8]. They showed that the coupled heat and moisture transport in firefighter's protective clothing during such exposure can be modeled successfully, thermal response of the fabric can be successfully comprehended and burn injuries can also be predicted. Modeling of thermal protective clothing exposed to flash fire has been done by Song[9] and it was inferred that the properties of the fabric do remain constant during the first heating period, but changes significantly as the temperature rise is remarkable. Finally, the fabric gets thermally degraded; its structural integrity is destroyed followed by decomposition and combustion. Burns take place

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due to intense thermal attacks on human being. Burn injuries which are time and temperature dependent have been classified as first, second, third or fourth degree burns. Song *et al.*[10] developed numerical model to predict skin burn injury resulting from heat transfer through a protective garment worn by an instrumented manikin exposed to laboratory controlled flash fires. Bamford and Boydell[11] developed a model and computer code for evaluating second degree burn injury caused by thermal irradiation using spectral reflectance and transmittance where spectrum of the radiation source was obtained from colour temperature.

Stoll curve, which has been constructed from Stoll and Chianta's data based on their experiments[12,13],can be used to make a first prediction of second degree burn on continuous heating, using the testing and evaluation procedure given in ASTM F1939-08. From the experimentally obtained data of Stoll and Chianta, an empirical equation of cumulative heat (cumulativeheat in J/cm^2 = 5.0204.t$^{0.2901}$), that is to be absorbed by animal skin to cause blisters or second degree burns, was obtained and used for comparisons. In this study, time taken to cause second degree burn injury has been studied, exposingheat resistantfabric and copper calorimeter system to a given heat flux, using Stoll 2nd degree burn criteria.A second method that detects 1st, 2nd and 3rd degree burn injuries using Henriques burn integral[14], utilizes skin heat transfer model based on Penn's bio-heat transfer equation[15].

2 Materials and Methods

2.1 Experimental Setup

Experimental setup for evaluating protective performance of fabric is shown in Fig. 1 where radiative heating source has been created by arranging five high power (500W) short wave infrared tungsten quartz heating tubes oriented vertically in a holder. Current has been varied by using a voltage variac through which heat flux can be set to a desired level. Radiative heat protective performance of the fabric specimens was examined, as they were exposed to different radiant heat flux values. All the fabric samples were exposed to three levels of constant heat fluxes (10, 15 and 20 kW/m^2), and the performance of the fabrics was compared at these different heat fluxes. The differential equation which results from the energy balance of an infinitesimal element of the fabric assembly exposed to radiant heat flux was solved with given boundary conditions for predicting thermal response. Data obtained from experimental studies were compared with the obtained solution of the differential equations. Effect of imposed variation by changing fabric properties on the performance of the fabric was also studied.

2.2 Heat Transfer Modelfor Multilayered Protective Clothing

Heat transfer behavior of the fabric assemblies exposed to heat source has been modeled by writing transient heat transfer equation and solved it with suitable boundary conditions. Gas phase convective contribution to the heat transfer, which may occur due to pressure difference because of body movement or external air flow[8] has been neglected. This is reasonable, as in the setup fabric is held stationary and heating source is of radiant type only. Model equation was written following heat transfer equation proposed by Torvi[2] and Lawson[5] with suitable boundary conditions and solved numerically, using MATLAB inbuilt functions.

2.3 Assumptions and Development of Equations

Multilayered clothing was prepared by combining different woven outer layer, nonwoven thermal liner and an inner lining fabric. The fabric assembly is assumed to be a dense multilayered participating media exposed to radiation heating. Heat flow through the fabric is considered to take placeby both conduction and radiation with radiation boundary conditions. All the component layers of protective clothing and copper calorimeter were placed in contact withno gap between them. Radiation thermal energy penetrates the fabric structure only upto a certain depth, depending upon the structure and radiative properties of the fibrous material of the

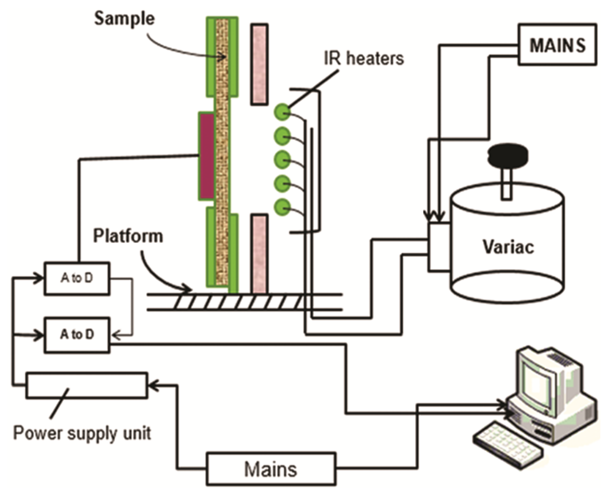

Fig. 1—Schematic representation of developed instrumental setup

assembly[2]. It is assumed that a uniform radiant heat flux is falling on the fabric with copper calorimeter sensor positionedbehind it. Structural effects of clothing layers on the rise in temperature of fabrics were not included in the model.

Specific heat and thermal conductivity were considered as function of temperature only. These parameters were empirically determined from experimental data and subsequently used in the model. Change in density, thermal conductivity, specific heat and optical properties ofdifferent layers from one fabric to other in the multilayered fabric assembly have been considered in the model. Optical properties of the clothing material were considered wave length dependent and determined by spectrophotometer equipped with spherical integrator. Incident irradiation that falls on the fabric is partially reflected by the fabric, some amount is absorbed and rest is supposed to transmit through the fabric. For the multilayered fabric assembly, transmitted heat flux that passes the first layer will be partially reflected, absorbed and transmitted through the second layer and so on. Heat flux that transmits after passing through any fabric layer is assumed to follow Beer Lambert's law. Incident thermal radiation decays exponential by an amount defined by the optical properties of the fabric.

As radiation passes through the media, it is absorbed and scattered, the total attenuation of the intensity is defined by the absorption and scattering coefficients, which is dependent both on wave length (λ) and temperature (T). It also gains energy by re-emission and in-scattering. As the fabric layers are optically quite thick and radiated heat flux attenuate quickly, only absorption coefficient was calculated and used in solving the equations. Temperature rise on the fabric back side was measured with the copper calorimeter kept close in contact with the back face of the fabric assembly. Effect of air gap inbetween fabrics and calorimeter was neglected as they are kept in close contact. Experiments were not carried out for longer period, as thermal degradation starts and pyrolysis related changes due to application of thermal energy dominate. The energy equation for simultaneous conduction and radiation through a participating media with internal heat generation is given as,

$$\rho c_p \frac{\partial T(r,t)}{\partial t} = -\nabla.(q^c + q^r) + h(r,t) \qquad \ldots(1)$$

The term on the left hand side of the equation represents the increase in internal energy of the infinitesimal element of fabric, and that on the right hand side, ($q^c + q^r$) together represents the conductive and radiative heat fluxes; $h(r,t)$ is the heat generation term and $T(r,t)$ is temperature at any depth r and at any time t. In one dimension the above equation was written in the following way as per Torvi[2] and Lawson[5]:

$$\rho c_p(T).\frac{\partial T}{\partial t} = -\frac{\partial q_{CD}}{\partial x} - \frac{\partial q_R}{\partial x} + \dot{Q}''' \qquad \ldots(2)$$

$$q_{CD} = -k(T)\frac{\partial T}{\partial x}, q_R = (1-\rho_l)q_i \exp(-\beta x);$$

and $\dot{Q}''' = 0$; …(3)

where ρ is the density; $c_p(T)$, the specific heat; $k(T)$, the thermal conductivity; Q''', the internal heat generation term, assumed to be zero; q_{CD}, the conductive heat flux; q_R, the radiative heat flux; ρ_l, the reflectivity of the fabric; q_i, the incident heat flux; β, the absorption coefficient. Absorption coefficient (β) is obtained from optical properties of the fabric and emissive power of the heating source. Specific heat $c_p(T)$ and thermal conductivity $k(T)$ are functions of temperature.

2.4 Boundary Conditions

Left side of the fabric was exposed to a radiant heat flux, and the Neumann boundary condition at $x = 0$,

$$-k\left.\frac{\partial T}{\partial x}\right|_{x=0} = (1-\rho_l)q_i - \sigma\varepsilon(T_f{}^4 - T_a{}^4) \qquad \ldots(4)$$

where $-k\left.\frac{\partial T}{\partial x}\right|_{x=0}$ is the heat flux at the left boundary:; σ, the Stefan Boltzman constant; T_f, the fabric front surface temperature (absolute); T_a, the ambient temperature (absolute); ρ_l, the reflectivity; q_i, the incident heat flux; and ε, the emissivity of the fabric surface.

The first term on the right hand side gives the amount of heat flux that enters the fabric after being reflected and the second term is the amount of heat flux emitted out from the outer side of the fabric towards environment. As a result, net heat flux on the boundary reduces as the temperature of the fabric surface increases. Convective heat losses due to temperature rise on the outer surface have not been considered in defining the boundary conditions. At the back side of copper calorimeter adiabatic boundary conditions has been applied, i.e.

$$k\left.\frac{\partial T}{\partial x}\right|_{x=L}=0 \qquad \text{…(4a)}$$

2.5 Measurement of Heat Flux

Incident heat flux (q_i)was measured by exposing bare copper calorimeter to a steady heat flux. Acrylic lacquer black paint was sprayed on copper calorimeteface side and dried. Black acrylic lacquer painted copper calorimeter has emissivity of ~0.9 or higher. It was checked by measuring the temperature using infrared thermometer at emissivity setting ~0.95. Ignoring thermal losses and assuming incoming heat is absorbed by the copper plate, incident heat flux is calculated according to following formula:

$$\text{Heat flux}=\frac{\text{Mass.Cp.}\Delta\text{T}}{\text{absorptivity(0.9).area.}\Delta\text{t}}+q_{\text{loses}}\text{(neglected)} \qquad \text{…(5)}$$

At some voltage variac setting, bare copper calorimeter was exposed to the incident thermal irradiation and heat flux was calculated. Repeating this test for many days, negligible variation in measured value of heat fluxes was found, which shows that emissivity is not changing as such due to repeated exposures. However, repainting of the surface was done from time to time as quality of paint may deteriorate due to accumulation of deposits or burning. As per ASTM standards protective performance of the firefighter's protective garments can be done with a radiant heat flux of 84 or 21 kW/m^2. Other levels of heat fluxes are also allowed, considering that heat flux used must be stable over the material's exposuretime interval. In present study, performance of the fabrics has been examined at lower steady heat fluxes and at different levels for longer duration of time.

2.6 Fabric Properties

2.6.1 Physical Properties

Kevlar woven fabric that was constructed in laboratory from 67 tex multifilament yarns was used as the outer most layer, Conex fibre (1.67dtex and 51mm) nonwoven fabric of fixed areal density (~160gsm) prepared in laboratory using Dilo Needle punching loom, was used as the middle layer and a mod-acrylic/cotton fabric was used as lining fabric. Outer layer fabric and the nonwoven thermal liner were prepared with different constructional parameters by varying pick spacing and punch densities, and subsequently there effects were studied. Physical properties of fabrics used are given in Table 1.

Thickness values of the outer layer, nonwoven inner layer and woven inner lining were measured on Instron tensile testing machine, operating in compression mode. Thickness of different fabrics at different pressures was observed, and the values for nonwoven insulation are shown in Fig. 2. Density of each fabric layer used in this model was calculated from areal density (g/m^2) and thickness of fabric.

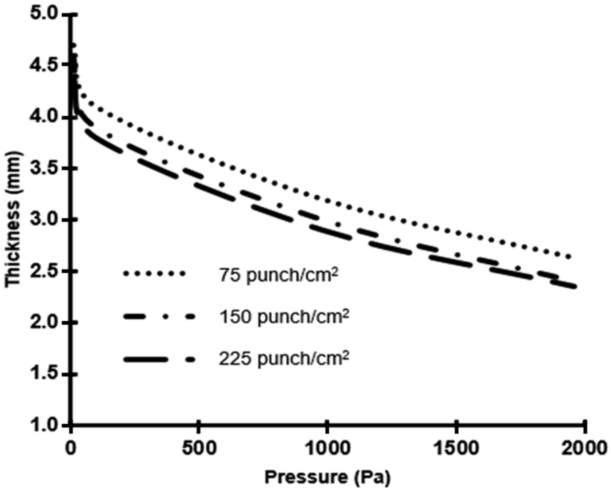

Fig. 2—Change in nonwoven fabric thickness with applied pressure

Table 1—Physical and optical properties of fabric samples used for testing and validation of the model

Fabric	Density kg m^{-3}	Thermal conductivity W m^{-1} K^{-1}	Specific heat capacity J kg^{-1} K^{-1}	Thickness mm	Areal density g m^{-2}	Reflectivity ρ, %	Transmittance (τ), %	Absorption coefficient (*β*), m^{-1}
Kevlar woven	338-390	0.036-0.059	1420-2515	0.65-0.72	220-280	67.2-68.1	19.3-15.5	772-998
Conex nonwoven	39-42	0.031-0.046	1260-2355	3.8-4.1	150-160	13.2-14.5	<1	1470-1360
Woven lining	414	~0.04	~1300	0.47	195	62.5	17.8	1576
Copper calorimeter	8960	401	387	1.82	NA	-	-	-

Under the testing conditions, samples were positioned vertically in front of source as relaxed as possible gripped from top and bottom. Thickness values were considered only at a very low level of compressive force (98 Pa).

2.6.2 Thermal Properties

Thermal conductivity of the fabrics was measured on Alambeta instrument, in which samples are placed between two parallel circular plates, one is at room temperature and the other is kept at 35°C, and at a steady state thermal conductivity was measured. Combined conductive and radiative thermal conductivity is measured by this instrument[16]. Directly observed values of thermal conductivity obtained from Alambeta and temperature dependent thermal conductivity of fabrics were derived and used in the model. Values and trend in temperature dependent thermal conductivity were taken from experimental data obtained by Lawson and Pinder[17]. Regression relationship between thermal conductivity and temperature was developed from thatdata, for fabrics of comparable densities and subsequently combined with the values obtained from Alambetaandused in solving the energy equation.

Values of Specific heat capacity of p-aramid and m-aramids were obtained from empirical relationship developed from data available in fibre manufacturers' (DuPont) website[18] and used in solving the heat equation. Approximate constant value of specific heat capacity of modacrylic/cotton blended lining fabric was calculated from heat capacity of acrylic polymers and cotton at ~ 300°K.

2.6.3 Optical Properties

Reflectivity, absorptivity and transitivity of all individual fabrics were measured on Perkin Elmer Lambda 1050 UV-Vis-NIR spectrophotometer, equipped with a spherical integrator. Optical properties were determined for wave length band between 0.3μm and 2.5μm. UV-Vis-NIR spectrophotometer has capability of determining optical properties upto 3.3μm but due to some noise, there were some disturbances in the curves near and beyond 3.0μm. Optical properties were then determined upto 2.5 μm beyond which most of the textile fabric assemblies are mostly opaque[19]. Spectrally integrated values of reflectivity, transmittance and absorption coefficients were then calculated from spectral values according to the Eqs(6) and (7), where the heating tubes assumed to be a black body source with constant temperature of ~ 2127°C. Calculated optical properties of the fabrics and absorption coefficients are reported in Table 1;the values were subsequently used in solving the energy Eq. (2). The transmissivity and reflectivity are calculated using the following equations:

$$\tau_{[-]} = \frac{\int_0^\infty E_{b\lambda,T}\tau_\lambda d\lambda}{\int_0^\infty E_{b\lambda,T} d\lambda} \quad \ldots(6);$$

$$\rho_{l[-]} = \frac{\int_0^\infty E_{b\lambda,T}\rho_{l\lambda} d\lambda}{\int_0^\infty E_{b\lambda,T} d\lambda} \quad \ldots(6a)$$

absorption coefficient[5] is calculated according to

$$\beta_{[m^{-1}]} = \frac{1}{d_{[m]}}\ln\left[\frac{\left(1-\rho_l\right)}{\tau}\right] \quad \ldots(7)$$

where $E_{b\lambda,T}$ is the emissive power; τ, the transmittance; ρ_l, the reflectance; and *d*, the thickness of the fabric (*m*).

Emissive power ($E_{b\lambda,T}$) of a heating source is a function of both the temperature of the source and the wave length. This ideally follows Planck's law which describes the electromagnetic radiation emitted by a black body in thermal equilibrium at a definite temperature. As spectral emissivity of tungsten is approximately independent of temperature of heating bulb operating temperatures, the spectrum of *I(λ,T)* for tungsten will behave like a blackbody of a some what different temperature[20,21]. Spectral emissivity of tungsten is ~ 0.45 or lower and it substantially reduces the emission and shifts the maximum towards smaller wave length. Pure tungsten coils approximately can be heated upto a maximum temperature of ~3400°C, beyond which it will melt. On its full glow, filament temperature can be very high (~3300°C) and as compared to that maximum experimental flame temperature can reach upto 2200°C[22]. The temperature of the heating tubes is assumed to be 2127°C and based on that we have calculated fabric optical properties. At 2127°C more than 75% of the thermal spectral emission falls within the wave length of 2.5μm.

2.7 Solution of Heat Transfer Equation

The heat transfer equation with a source term in 1-D as written in Eq. (2) was numerically solved using MATLAB in built function with Neumann boundary conditions for the multilayered fabric assembly. Matlab pdepe function[23] numerically solves parabolic and elliptic partial differential equations of the following form:

$$c\left(x,t,u,\frac{\partial u}{\partial x}\right)\frac{\partial u}{\partial t}=x^{-m}\frac{\partial}{\partial x}\left(x^{m}f\left(x,t,u,\frac{\partial u}{\partial x}\right)\right)+s\left(x,t,u,\frac{\partial u}{\partial x}\right) \quad \ldots(8)$$

with boundary conditions,

$$p\left(x,t,u\right)+q\left(x,t\right)f\left(x,t,u,\frac{\partial u}{\partial x}\right)=0 \quad \ldots(9)$$

where m = 0 for slab (fabric assemblies has been considered as combination of slabs exposed to a radiant heat flux), c( ), f( ), s( ) can be function of thickness (x), temperature (u), time (t) and temperature gradient. In the present study,$u$stands for temperature, c( )for product of density and specific heat, f( )for heat flux $\left(k\frac{\partial T}{\partial x}\right)$ and s( ) for the source term.

Initial condition is described by the temperature of the fabric and environment at t_0 = 0; mathematically,

$$u(x,t_0)=u_0(x) \quad \ldots(10)$$

Three layers of fabrics along with the copper calorimeter forms a four layer fabrics-copper plate system. For multilayered fabric assemblies, values of density, specific heat $c_p(T)$, thermal conductivity $k(T)$ and optical properties of each fabric layers andthermal properties of copper calorimeter were providedto the computer program. The ordinary differential equations (ODEs) resulting from spatial discretization are integrated to obtain approximate solutions at times specified in time limit. The computer program returnsthe values of the solution for all x and t[23]. From the solutions of the equation fora definite time span, cumulative thermal energy absorbed by the copper calorimeter (J/cm^2), which is a function of temperature at the back side of the copper plate,was plotted together with the Stoll curve and then compared for the determination of the limit of protection for a particular fabric at that heat flux level.
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3 Results and Discussion

Differential Eq.(2)is solved with specific boundary [Eqs (4) and (4a)] and initial condition. Thermal, physical, radiative and dimensional properties of the protective clothing (Table 1) have been used as the input parameters in solving the equations. From the solution of the Eq. (2), temperature rise of the copper calorimeter is predicted at the same time temperature across the thickness of the fabric-sensor system can also be obtained. The temperature trace obtained from the numerical solution is used to calculate cumulative thermal energy acquired by the calorimeter, and then compared with the Stoll's second degree burn criteria to find out the time the fabric combination offers at a particular heat flux, before blistering starts. The typical temperature trace obtained is approximately linear, except at the initial seconds. Three fabric combinations were examined at three different heat fluxes for prediction and comparison with the experimentally obtained temperature traces (Fig. 3). Predicted curves are found to closely follow experimentally obtained curves, and prediction of the time of protection is found to vary from the experimentally observed data by less than 12%. It shows that the solution of Eq. (2) thus obtained can approximately estimate the performance of the fabric combination exposed to radiant heat fluxes.

Relative importance of thermal, physical and optical parameters that govern the heat transfer process through the fabric has been studied to have an insight in the role of these variables. Effect of variation in thermal, physical and other properties of multilayered fabric arrangement isinvestigated by introducing an arbitrary variation of 10% in the values of thickness, density, thermal conductivity, specific heat capacity, and reflectivity for same applied heat flux, using the model. The obtained predicted performances of the fabric combinations due to changes in thickness and reflectivity are shown in Figs 4 and 5. The values of changes in predicted protection time for different parameters are given in Table 2. From the tabulated values, it is observed that the variation in thickness and reflective properties of the fabric assembly has major effect on its protective performance.

Thickness of fabric is an extremely important parameter determining thermal protective performance of fabric. Thickness is subject to change under compressive loading conditions and several modes of compressions are possible when clothing is being practically used. Figure 2 shows decrease in thickness of nonwoven insulation with applied pressure. An increase in pressure from 500Pa to

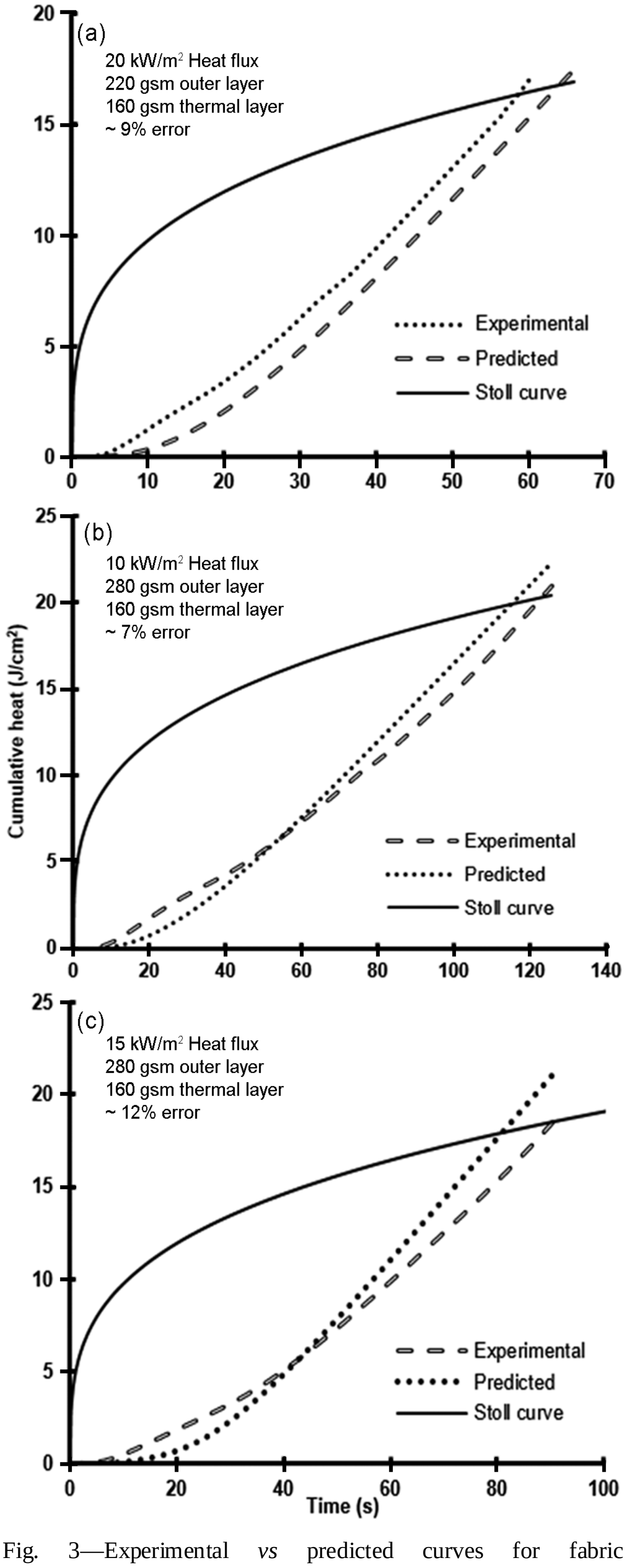

Fig. 3—Experimental *vs* predicted curves for fabric combinations,Kevlar woven fabric as outer shell, Conex fibre needle punch nonwoven as thermal liner with modacrylic/cotton fabric as innermost layer.

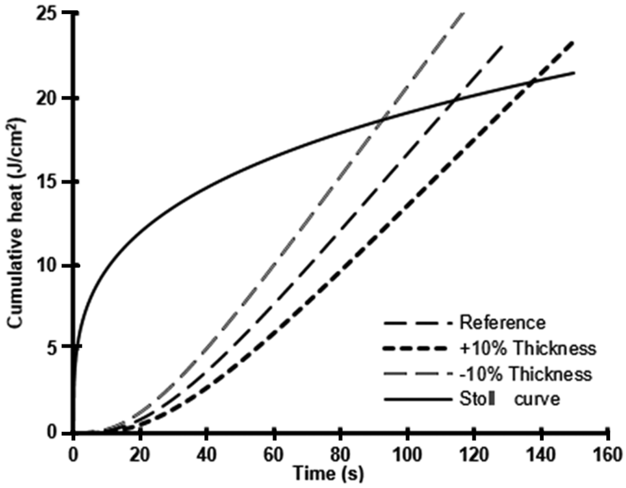

Fig. 4—Effect of ±10% variation in thickness on protective performance

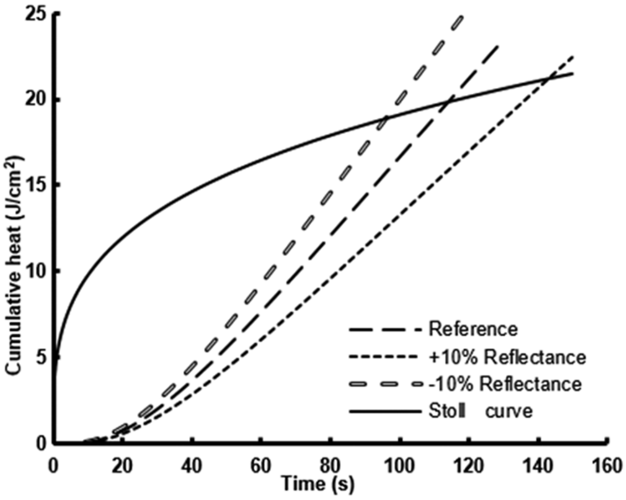

Fig. 5—Effectof ±10% variation in fabric reflectivity on protective performance

Table 2—Effect of variation in fabric properties on protective performance

Factors	Variation of factor from control level, %	Percentage change in protection time
Thickness	±10	±20.0
Thermal conductivity	+10 –10	–6.2 +13.7
Specific heat	±10	±4.0
Density	±10	±4.0
Reflectivity	+10 –10	+25.6 –15.9

1000Pa decreases thickness of nonwoven felt by more than 0.5mm which is approximately 10% decrease in fabric thickness and can cause 15-20% drop in protective performance of the clothing. A decrease in thickness causes air spaces entrapped between the fibres to be decreased, number of contact point to increase, average distance between fibres to decrease, density to increase and causes thermal conductivity of fibrous mass to increase as well. In this work, fabric is placed well relaxed in front of heating source without imposing any compression on the fabric. If increase in thermal conductivity along decrease in thickness is considered as it is going to occur in practice, predicted temperature trace will be shifted further towards left and would showpoor protective performance.

As heat flux increases from lower to higher levels, time taken by the fabric-skin, before a second degree burn injury occur, as determined by the Stoll 2^{nd} degree burn criteria, decreases from higher to lower values. Increasing punch densities of the nonwoven fabric causes lowering of thickness of the fabric and reduction in time limit of protection. Increasing number of picks/cm in the woven fabric causes increase in thickness, higher cover and higher areal density and resultsin more protection for the same applied heat flux level. Effect of changes in the heat flux can be easily shown from solution of the model equation by changing values of incident heat flux.

Increase in source temperature will result in emissive power curve to be shifted towards shorter wave length, thus resulting in increase in reflectivity of fabric. The fabric reflectance is higher in short wave length region as compared to that in longer waves. A 10% variation in source temperature can cause a 40-50% increase in the heat flux produced, as heat flux is proportion to the fourth power of absolute temperatureand the effect will be more pronounced at higher temperature. The same amount of variation in source temperature causes only about 2% change in optical properties. It implies variation in source temperature, when it is already at high level, and have little effect on prediction of thermal response of protective fabric assemblies.

A 10% variation in thermal conductivity $k(T)$ and specific heat capacity $c_p(T)$ of porous textile material shows less significant shifting of the predicted curve. But temperature dependent thermal conductivity and specific heat capacity may increase by more than 50% with rise in temperature. Constant thermal conductivity of the fabric, determined by parallel plate type thermal conductivity measuring instrument (Alambeta), which evaluates k (thermal conductivity) of textile material based on steady state method, was initially applied in the model, resulting in an over prediction (higher protection) due to relatively lower values of thermal conductivity. The approximation made in determining values of temperature dependent thermal conductivity $k(T)$ and specific heat capacity $c_p(T)$ based on earlier experimental data gives better prediction, indicating importance of temperature dependency of thermal conductivity and specific heat capacity.

4 Conclusion

Protective performance of the fabrics exposed to a given radiant heat flux can be predicted from the knowledge of heat flux and fabric properties like density, specific heat, thermal conductivity, and optical properties, by solving the energy equation with suitable boundary conditions, using computer programs in MATLAB. Variation in the fabric properties and their effect on the protective performance can be predicted easily by using the model. From the analysis of introducing arbitrary variation in properties and then solving the equation it appears that reflectivity, thickness, temperature dependent thermal conductivity and specific heat capacity of the fabric are the most important parameters for determining its protective performance. Accurately determined values of temperature dependent thermal conductivity and specific heat capacity by experimentation, can be used to predict fabric thermal response. Effect of variation in source temperature in pure radiant heat exposure does not alter fabric optical properties that much, whereas marginal increase in temperature can cause large change in heat flux values. Effects of moisture and thermo-chemical reactions has not been taken into account in the present work.

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