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Research Paper

Estimation of radiative properties of thermal protective clothing

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HIGHLIGHTS

- Absorption and scattering coefficients of thermal protective fabrics are determined.
- Genetic algorithm is applied for the inverse estimation.
- Effects of pyrolysis of fabrics on radiative properties are analyzed.
- Radiative properties of different layers of protective clothing are determined.

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ABSTRACT

Thermal protective clothing provides more safety and time to allow wearer to complete task or escape from external high heat or fire exposures. Radiation heat transfer is significant in such high temperature conditions. In the present work, radiative properties of various fabrics used for thermal protective clothing are estimated. Experimentally measured spectral directional–hemispherical reflectance and transmittance data available from literature are used to predict some of the radiative properties. A coupled finite volume radiative transfer equation solver along with genetic algorithm is used for this purpose. Radiative properties of some commonly used fabrics in thermal protective clothing at various heat source temperatures are predicted. Effects of pyrolysis on these properties are also analyzed. It is found that the extinction coefficient of the outermost layer of thermal protective clothing is very high as compared to the other inner layers, and it plays a significant role in blocking heat transfer to the skin. Scattering in fabrics used for thermal protective clothing is also found significant.

1. Introduction

Firefighters and some industrial workers usually work under hazardous heat conditions. They encounter heat and flame exposures ranging from 2 kW/m^2 to as high as 100 kW/m^2 while performing their duty. Exposure to medium or high level of such heat exposures not only decreases the performance of the workers but may also result in life endangering situations. Specially designed thermal protective clothing is used by firefighters and furnace operators for safety against such high heat flux exposure. Even with the thermal protective clothing, it is not possible to avoid skin burn for more than only a few seconds. Out of total 65,880 firefighter injuries reported in US in 2013, 45.2% reported during fire ground operations [1]. Approximately 28% of these injuries were due to contact with heated objects, fire exposure, radiation exposure or extreme weather. Even with significant advancement in thermal protective clothing, such repeated accident and fatalities are of great concern. There is a need to understand the physics of simultaneous heat and moisture transfer through thermal protective clothing. A reliable numerical model for heat and moisture transfer through thermal protective clothing is the need of the hour. This is not only going to help in developing better quality materials but also to select proper structural parameters for fabrics of thermal protective clothing.

In a typical fire or radiant heat exposure, the temperature of a firefighter or industrial worker may reach up to 2000 K. It has been found that maximum fabric temperature, even for a very short duration (for example, 10 s) exposure to such extreme conditions, is of the order of 1000 K [2]. Radiation mode of heat transfer through fabric is thus inevitable in thermal protective clothing. In fact, it has been found that radiative heating is an important aspect in the design of protective clothing [3]. Basic radiative properties like reflectance and transmittance of fabric used in thermal protective clothing were measured [4–9]. Attempts were made to correlate thermal protective performance of these fabrics with measured reflectance, absorptance and transmittance of the fabrics. This can provide some qualitative results regarding the relative performance of various fabrics in protecting the wearer against high heat exposures, but these values cannot provide any quantitative results. Such qualitative results or information may not be helpful in

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designing and developing better thermal protective clothing for various types of heat exposures. For example, in order to predict the thermal protective performance (tolerance time) of any fabrics used in thermal protective clothing, an accurate numerical model is required. Reflectance and transmittance measured using spectrophotometer [4–9] are not of much importance then. For these numerical models, radiative properties like extinction coefficient and scattering albedo of fabrics are required rather than reflectance and transmittance.

It is observed from literature that some of the models considered only conduction heat transfer [10] and little work has been done to deal with radiation in thermal protective clothing system properly. If considered at all, either both conduction and radiation were treated as uncoupled or radiation was dealt in a very simplified form. Even most widely used model [11,12] also considers fabric as a homogeneous slab with averaged thermal properties. Beer's law was used and it was assumed that radiation can penetrate to certain thickness depending upon the extinction coefficient of the fabric. Some efforts were made in the past to model coupled conduction–radiation in fabrics [13,14]. However, scattering, self-emission and changes in thermal radiative properties due to thermal degradation of fabrics were completely ignored by Mell and Lawson [13]. Jiang et al. [14] considered self-emission but ignored scattering and change in thermal and radiative properties due to the thermal degradation of fabrics. It has been found that fibrous mediums are highly scattering medium [15]. A more realistic and accurate numerical model for fabrics with coupled conduction–radiation heat transfer and particularly with the consideration of absorption, emission and scattering from the fabric is required. Unfortunately, no work is available in the literature which can provide necessary radiative properties (absorption coefficient, scattering coefficient/scattering albedo) of fabrics required to solve radiative transfer equation (RTE). So, in order to model heat transfer through thermal protective clothing more accurately, the main challenge is to get the radiative properties of the fabrics or the clothing samples. In the present study, radiative properties of the thermal protective clothing are estimated using available experimental data of spectral directional–hemispherical reflectance and transmittance. To the authors' knowledge, this is the only work that deals with the study of radiative properties of woven fabric samples. Moreover, as these fabric samples are standard fabric samples usually used in thermal protective clothing, these properties can be used directly in the coupled conduction–radiation models to further analyze their performance. The present study is also an attempt to understand how these properties vary from one layer to another of a thermal protective clothing and for different fabric materials. Optical properties also depend on the temperature and hence wavelength of electromagnetic radiation emitted by the source. In the present study, effects of heat source (flame or radiating medium) temperature and thermal degradation of fabrics due to heat exposures on radiative properties are also analyzed.

Various studies involving different degrees of complexities were conducted in the past to determine the radiative properties of fibrous insulations [15], foams [16–18] and other porous materials [19]. Theoretical [18], experimental [16,17] or numerical methods [19] were used for the purpose. Details regarding various approaches used to determine radiative properties can be found in [20,21]. Determination of radiative properties of textile fabrics theoretically/numerically or modeling of radiative heat transfer through actual fabrics is cumbersome as it involves many complexities that are listed below:

- Radiation emitted by source may pass directly through the pores (space between yarns) of the fabric,
- Solid fibers or yarn present in the fabrics may scatter part of the radiation,
- Yarns (bundles of fibers) may allow the radiation to be transmitted,
- Fibers, yarns or fabric may absorb part of the radiation, and
- Fibers, yarns or fabric may itself emit radiation depending upon its temperature and emissivity.

Hence, a combined experimental and numerical approach is employed in the present study. In the current study, experimental data for the spectral directional–hemispherical reflectance and transmittance are directly taken from different literature. There exist well defined methods like modified two-flux approximation which has been used widely and can estimate radiative properties accurately [22–24]. It has been found quite accurate especially for highly scattering mediums [25,26]. However, it has been found that such simplified models cannot provide reliable results in special cases like the one with both forward and backward peaks [21]. Moreover, numerical methods like discrete ordinates method (DOM) and finite volume method (FVM) can handle such situations more accurately and are more general. Fu et al. [27] used DOM to estimate radiative properties of cellular ceramics. Zhao et al. [28] used DOM to determine conduction–radiation parameters using steady state and transient temperature measurements. Similarly, various gradient based methods have been used for optimization purpose like Levenberg–Marquardt and Gauss linearization methods. These gradient based algorithms are problem specific whereas Genetic algorithm (GA) is stochastic search-based algorithm and it is quite robust. In the present work, FVM is used for modeling radiation and GA is used as an optimization method.

2. Methodology

In the present study, normalized reflectance and transmittance are calculated first using experimentally measured spectral directional–hemispherical reflectance and transmittance. An optimization technique coupled with finite volume method (FVM) for solving radiation heat transfer is then used to estimate radiative properties of fabrics. Radiative properties of interest here are extinction coefficient and scattering albedo (or absorption and scattering coefficients). Experimental results already available in the literature are used. Finite Volume Method (FVM) is used for solving radiative transfer equation (RTE) and genetic algorithm (GA) is used as an optimization technique. Major steps involved are summarized in Fig. 1.

2.1. Experimental data

Data of spectral directional–hemispherical reflectance and transmittance available in the literature are used in the present study to estimate extinction coefficient and scattering albedo for different fabric samples. Integrated reflectance and transmittance, normalized by the blackbody function, are calculated from spectral directional–hemispherical reflectance and transmittance using Eq. (1) and Eq. (2), respectively [9].

$$\rho = \frac{\int_{\lambda_1}^{\lambda_2} \rho_\lambda E_{b\lambda}(T,\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{b\lambda}(T,\lambda)d\lambda} \tag{1}$$

$$\tau = \frac{\int_{\lambda_1}^{\lambda_2} \tau_\lambda E_{b\lambda}(T,\lambda)d\lambda}{\int_{\lambda_1}^{\lambda_2} E_{b\lambda}(T,\lambda)d\lambda} \tag{2}$$

where λ_1 and λ_2 are lower and upper limits of the wavelengths considered. T is temperature in K. ρ_λ and τ_λ are measured spectral directional–hemispherical reflectance and transmittance. $E_{b\lambda}$ is