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Heat transfer in a cylinder sheathed by flame-resistant fabrics exposed to convective and radiant heat flux

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Abstract

A numerical model is developed which investigates heat transfer in a cylinder sheathed by flame-resistant fabrics when suddenly exposed to convective and radiant heat flux from simulated pre-flashover fire radiation. The column inside the cylinder system simulating the human body is assumed to keep at a constant temperature. This model incorporates characteristics of the heat-induced changes in flame-resistant fabrics and dry air thermo-physical properties. Temperature distribution was calculated with the help of a one-dimensional radial heat transfer model. A skin burn equation is quoted to predict second-degree skin burn injuries based on the numerical model. The effects of air gap thickness on mean incident heat flux to the skin simulant surface are also discussed. Results from the numerical model contribute to a better understanding of the heat transfer process within flame-resistant fibrous materials and fabrics in intensively high-temperature environment. At the same time, the method in the paper also helps to establish a systematic method for analyzing heat transfer in other cylindrical applications.

Keywords: Numerical model; Cylinder; Flame-resistant fabrics; Heat transfer; Heat flux; Air gap

1. Introduction

Because of its technological relevance in, for instance, fire fighting and energy conservation, heat transfer through thin fibrous material layer exposed to high heat flux has been widely studied. Common bench-scale tests are used to evaluate thermal protective performance of fabrics and full-scale thermal manikin tests have also been conducted to assess entire clothing assemblies. At present, there are different standards applicable to each of the various type of clothing used by firefighters. One of the primary test standards used to evaluate the thermal protection of fabric is ASTM D 4108 [1]. In the test, a laboratory burner is used to expose candidate fabric ensemble to a nominal heat flux of $84\,kW/m^2$. The heat flux is meant to simulate direct fire exposure. A modified version of this test is utilized in the National Fire Protection Association's NFPA 1971 [2] which called for a test method to measure the total heat transferred through a protective ensemble exposed to a nominal 50% convective and 50% radiant heat flux of $84\,kW/m^2$, simulating a direct flame contact exposure. However, the recent edition of NFPA 1977 [3], Protective Clothing and Equipment for Wildland Fire Fighting required that textile fabrics used for wildland protective clothing be exposed to $21\,kW/m^2$ from a bank of five quartz lamps. In most cases, relatively high incident radiant heat flux value close to $21\,kW/m^2$ can be often experienced by firefighters several meters away from the flash fire's source under windy condition.

Additionally, a large number of researchers have considered modeling heat transfer through fibrous materials under high heat flux condition [4–8] and low heat flux exposure [6]. These models were based on planar geometry bench-top tests. Though researchers [6] had given a detailed description that the curvature of the human body does not have an effect on modeling skin and

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bench-top-test apparatus system, the influence of cylinder geometry such as human limb on thermal shrinkage of fabric should be addressed and heat transfer due to radiation and convection between fabric and skin (test sensor) in a cylindrical enclosure is considerably different with that in horizontal or vertical orientation. Therefore, it is necessary to set up a cylindrical testing apparatus that better represents the curvature of the human limb and to numerically model heat transfer in the cylindrical system. For the cylindrical model, Pennes [9] had used a series of hollow cylinders to obtain his bioheat transfer equation. Other experimental work on a cylinder sheathed by fabric was implemented by Marsh [10] and Lamb [11]. However up to date, no systematic study of modeling heat transfer to a cylinder sheathed by a porous layer in a high-temperature environment has been performed.

The purpose of the work is to investigate heat transfer around and within a cylinder enclosed with protective fabrics subjected to a combined convective and radiant heat flux of 21 kW/m^2 representative of pre-flashover fire field environment. An improved numerical modeling study and experimental validation are presented, and the question of to what extent thermal protective performance is altered by the varied air gap thickness is also addressed. Although the focus is on application to the system of a human limb cylinder covered by a layer of clothing fabric, results of this work should also be valid for other high-temperature resistant materials and energy transfer in vertical cylinder enclosure, such as filtering and separation industry.

2. Mathematical model formulation

The covered cylinder system is schematically illustrated in Fig. 1. The skin simulant is represented by backslash shells. The fabric forms another layer enclosing the skin simulant. It is the heat flux exposure interface between the heat exposure source and the fabric layer.

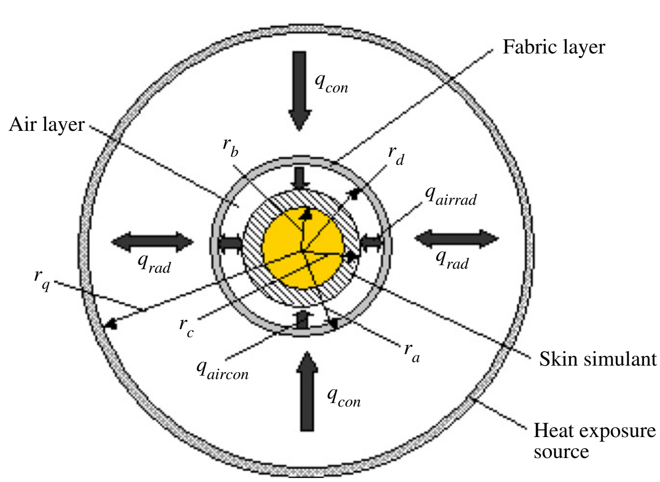

Fig. 1. Schematic for heat transfer in cylinder sheathed by fabric layer.

2.1. Heat transfer model for fabric and air gap

The geometrical system in this study for heat transfer is a vertical cylinder of radius r, enclosed with thin porous media referred to as a flame-resistant fabric, as shown in Fig. 1. In order to make the problem manageable, heat transfer is considered be one-dimensional in cylindrical coordinates. In developing the model, the following assumptions are made:

1. The fabric is considered as a gray body.
2. Mass transfer is neglected.
3. The incident heat flux to the surface of fabric is assumed to be uniform over the heated surface of the fabric.
4. The convection portion of the heat flux transfers energy to the fabric's surface, while the radiative portion can penetrate to a certain depth or pass completely through, depending on the fabric's structure and the incident radiation's wavelength distribution.
5. While ultraviolet radiation is often a concern with fabrics for comfort conditions, only infrared radiation is considered here, as the amount of ultraviolet radiation from the radiant source of interest is exceedingly small.
6. The thermal properties of the fabric are taken to be a function of temperature T.
7. The body core is assumed to be maintained at a constant temperature equivalent to 37 °C.

According to the above assumptions, a one-dimensional radial heat transfer mathematical equation was developed based on Torvi and Dale's [6] one-dimensional planar formation and Liu's cylindrical model [12] for the fabric as follows:

$$\rho_{\text{fab}}(T)c_{\text{fab}}(T)\frac{\partial T}{\partial t} = \frac{\partial}{\partial r}\left(\lambda_{\text{fab}}(T)\left(\frac{\partial T}{\partial r}\right)\right) + \frac{\lambda_{\text{fab}}(T)}{r}\frac{\partial T}{\partial r} - \gamma q_{\text{rad}}\exp(\gamma(r - r_{\text{of}})), \tag{1}$$

where T is fabric temperature and ρ_{fab}, c_{fab}, and λ_{fab} are the temperature-dependent density, specific heat, and thermal conductivity, respectively. q_{rad} is the portion of the directly transmitted incident heat flux on the surface of the element due to thermal radiation from the heat source and γ_{fab} is the extinction coefficient for the fabric. Hence, the term $\gamma_{\text{fab}}q_{\text{rad}}\exp(\gamma_{\text{fab}}(r - r_{\text{of}}))$ represents the internal heat generated by the radiation transferred to the internal region of the fabric by the transmissibility of the fabric τ_{fab}. γ_{fab} is evaluated as:

$$\gamma_{\text{fab}} = -\frac{\ln \tau_{\text{fab}}}{L_{\text{fab}}}, \tag{2}$$

where L_{fab} is the thickness of the fabric.

Between the skin simulant and fabric there is a layer of air within which convection or conduction may occur, depending upon air layer thickness. As we know, a stagnant air space can be a good insulator. It is also well-understood that if an air space is stagnant, its insulating