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Modeling of heat and moisture transfer within firefighter protective clothing with the moisture absorption of thermal radiation

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ABSTRACT

This paper presents a model to study the heat and moisture transfer through multi-layer firefighter protective clothing with air gaps exposed to low level radiation. The model incorporates the absorption of thermal radiation by the moisture within each wet fabric layer and air gap. Numerical results compare well with the experimental measurements. Numerical simulations are conducted to study heat and moisture transfer through the protective clothing subjected to different levels of thermal radiation and at different moisture distributions. It is found that the temperature distribution and moisture evaporation are significantly impacted by the thermal radiation. In addition, the simulation results show the rate of moisture evaporation is constant when the moisture is located in the inner layers, however, separated in two stages by an initial and a second smaller value when the moisture is located in the outer shell or in both the outer shell and inner layers. It is demonstrated that the developed model can be used as a numerical tool to predict the heat and moisture transfer of the wetted clothing system entrapped with air gaps under different fire scenarios.

1. Introduction

During a fire duty, fire fighters are subjected to a variety of fire conditions with different levels of radiant flux. Moreover, they are generally working under low level thermal radiation over prolonged periods of time, resulting into skin burn injuries and heat strains [1,2]. Skin burn mostly occurs in the low level thermal radiation from 5 to 20 kW/m^2 [3,4].

Moisture accumulation in firefighter protective clothing comes from both the internal and external moisture [5]. Internal moisture is from sweating by fire fighters who often sweat profusely. External moisture sources normally consist of the dousing water from a hose spray and the water from dew or rains [6]. The moisture transfer of the wetted protective clothing strongly affects the heat transfer, by evaporation, condensation, desorption, and absorption. The evaporation and condensation of moisture trapped within the protective clothing can cause steam skin burns [7].

Some previous studies including experiments [4,7–11] and numerical simulations [12–14], evaluated the effects of moisture on the heat transfer and thermal protective performance of protective clothing subjected to the low level thermal radiation. Keiser et al. [7] investigated the evaporation process and evaporation speed of the wetted fabric layers, with the measurement of the temperature distribution irradiated at 5 kW/m^2. The results showed that the temperatures remain constant during the evaporation, the changes of which are used to predict the evaporation speed within the clothing layers. Barker et al. [9] used a thermal testing platform at 6.3 kW/m^2, to study the effect of the absorbed moisture on thermal protective performance. The experimental results showed that the added moisture negatively and most severely affects the predicted burn protection when the amount of added moisture is near 15–20% of the clothing system weight. Fu et al. [10] designed two bench-scale test apparatus with the heat flux range of 1–10 kW/m^2, to study the effects of moisture and the vapor permeability of the moisture barrier. The results showed that the protective performance of the inner layers can be improved with the moisture transfer, while the outer layers can be heated by the external radiation and the moisture evaporation. It could be also seen that the moisture transfer is affected by the vapor permeability of the moisture barrier. These contradictory results, i.e. the moisture increases or decreases the protective performance of clothing can be attributed to the level of thermal radiation [4,8], the amount and location of the moisture [7,9,11], and the type of the fabric materials [10,11].

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Nomenclature;

C	concentration (kg/m^3)
c_v	volumetric heat capacity (J/(m^3 °C))
D	diffusion coefficient of gas (m^2/s)
d	size of the fabric layer or air gap (m)
E_b	emissive power (W/(m^2))
G	incident radiation (W/m^2)
h_c	convective heat transfer coefficient (W/(m^2 °C))
I	radiative intensity (W/(m^2 sr))
I_b	black body intensity (W/(m^2 sr))
J	surface radiosity (W/m^2)
k	thermal conductivity (W/(m °C))
k_D	permeability of the fiber (m^2)
L	thickness (m)
M	molecular weight (g/mol)
m_c	convective mass transfer coefficient (m/s)
Nu	Nusselt number (dimensionless)
P	vapor pressure (Pa)
P_{sat}	saturated water vapor pressure (Pa)
Pr	Prandtl Number (dimensionless)
q	heat flux by radiation (W/m^2)
R	universal gas constant (8.315 J/(mol °C))
RH	relative humidity (%)
Ra	Rayleigh number (dimensionless)
T	temperature (°C or K)
t	time (s)
u	velocity (m/s)
W	water content (g/g or %)
x	distance (m)

Greek symbols

α	absorption (dimensionless)
β	transmissivity (dimensionless)
γ	reflectivity (dimensionless)
ε	volume fraction (dimensionless)
$\tilde{\varepsilon}$	emissivity (dimensionless)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant (5.67·10^{-8} W/m^2 K^4)
λ	enthalpy of water vaporization (2256 kJ/kg)
μ	dynamic viscosity of the water vapor (kg/(m s))
τ	optical thickness (dimensionless)
$\tilde{\tau}$	tortuosity of the porous fiber (dimensionless)
κ	absorption coefficient (m^{-1})
Γ_{ce}	rate of condensation and/or evaporation (kg/(m^{3}s))

Subscripts

a	air
e	external
eff	effective
g	gas
l	liquid
s	solid
sat	saturated
T, t	total
v	water vapor

Numerical simulations have been conducted to predict heat and moisture transfer in protective clothing subjected to the low level thermal radiation [12–14]. In their study, Prasad et al. [13] developed a numerical model to study heat and moisture transfer in firefighter protective clothing with or without air gaps. Prasad et al. [13] found that the temperature distribution is significantly affected by the amount and distribution of moisture. It was shown that the local temperature impacts the added moisture evaporation and condensation on different parts of the fabric. Zhu and Li [14] presented a numerical model of heat and moisture transfer behavior of a fabric, considering the heat-induced changes in fabric thermo physical properties and the drying process with a one-step chemical reaction. It was found that the moisture can increase the heat transfer and decrease the tolerance time. However, these numerical simulations didn't consider the absorption of thermal radiation by the moisture. Water vapor has strong absorption of thermal radiation, especially in the near infrared regime [15]. The capacity of dispersed water to attenuate thermal radiation has been recognized and used in firefighting to protect persons and property [16]. The capability of water to absorb thermal radiation was acknowledged [17], to attenuate heat transfer to the human body exposed to thermal radiation or fire.

The objective of this study is to develop a numerical model to study the heat and moisture transfer of the firefighter protective clothing with air gaps exposed to low level thermal radiation. The moisture transfer and the changes in thermodynamic properties of the wetted fabric saturated with a defined amount of liquid water are considered. In addition, the improved model incorporates the absorption of thermal radiation by the moisture in the fabric layers and air gaps. This improved model is used to predict the relationship of thermal radiation and evaporation speed of moisture, which is helpful for understanding the transient thermal response and moisture transfer of the clothing system subjected to thermal radiation.

2. Mathematical formulation

In this work, a wetted multilayer fabric system with air gaps is modeled, subjected to a radiant heat flux on out surface side. The outer fabric is next to the heat source and the inner fabric is close to human body. Some assumptions to simplify the formulation are shown as below:

(1) Heat and mass transfer is one-dimensional along the thickness of the fabric layers, without lateral transport.
(2) Each fabric layer/air gap is isotropic in fiber arrangement and material properties. It is also assumed that the initial conditions are uniform throughout the fabric layer and air gap at the beginning of the calculations.
(3) Volume changes of the fibers due to the change of moisture content are neglected.
(4) The water vapor is free to convect and diffuse through the void space, and is absorbed/desorbed by the fibers. Mass transfer of moisture caused by diffusion was not considered on the surface or through pores in the cloth fibers (wicking effect), so that the secondary effects such as thermophoresis are also not included.
(5) Local thermal equilibrium exists among the local moisture content with the partial pressure of water vapor. It is also assumed that the rate of equilibration is much faster than the process of vapor diffusion.
(6) Concerning the thin thickness of the fabrics layer and air gap, the heat transfer within each fabric layer and air gap is considered as heat conduction and radiation, without convection.