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Modeling steam heat transfer in thermal protective clothing under hot steam exposure

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ABSTRACT

Understanding heat and moisture transport in thermal protective clothing is essential to identifying how to protect the safety of workers subjected to steam leakage. This study develops a numerical model for simulating heat and moisture transfer in thermal protective fabric when exposed to hot steam. This model considers the impinging jet flow between steam nozzle and fabric, the non-transient equilibrium between three phases, the steam flow within the fabric induced by the pressure gradient, the dynamic moisture absorption, and possible phase changes during the process. Additionally, skin bio-heat transfer and Henriques burn integral models are incorporated into the steam heat transfer model to predict skin burn. Simulated fabric and skin temperatures from the model are validated with experimental results. The behavior of steam heat transfer and influencing factors on steam protective performance of fabric are analyzed. The results reveal that the pressurized steam can penetrate rapidly through the protective fabric and induce skin burn. The increase of fabric thickness insignificantly improves the steam protective performance, while the initial moisture content and the porosity of fabric both play an important role in improving the steam protective performance of clothing.

1. Introduction

Industrial steam extensively used in oil, gas and food processing sectors presents a potential hazard for workers, such as steam burns and fatalities, because the surrounding ambient air can be heated rapidly in a confined space if steam leaks [1–3]. Steam heat transfer in textiles and clothing is different from heat transfer that is composed of radiation, conduction, and convection as the steam with a large heat-carrying capacity can release a considerable amount of thermal energy by phase change [4]. The traditional thermal protective clothing is generally designed for protection against flash fire and high- or low-intensity radiant heat exposure. It is speculated that the traditional thermal protective clothing does not provide enough protection against steam leakage. Therefore, it is critical to investigate the protective mechanisms of clothing against steam leakage.

There is no international standard for characterizing the steam protective performance of clothing or fabric. Some preliminary studies have been carried out to develop an assessment method for evaluating the steam protective performance under pressurized steams. Ackerman et al. [5] established a horizontal bench top tester that can differentiate the steam protective performance of fabrics under steam exposure with a pressure from 69 to 620 kPa. It was found that the fabric's thickness, density, and air permeability were important characteristics in providing protection against pressurized steam [6,7]. In addition, some researchers developed a vertical test device to evaluate the steam protective performance of fabric. For instance, Derscuell and Schimid [8] established a vertical test device that can adjust the splashing distance and the pressure of steam to simulate different exposure conditions. Su and Li [9] assessed the effect of hot steam on skin burn injury based on an improved vertical test device. Moreover, Sati et al. [3] presented a test device of cylindrical shape to evaluate the effect of body shape on steam protection of clothing in moderately high-pressure steam (69 and 207 kPa). A thermal manikin in a steam climatic chamber was employed to evaluate the protective performance of clothing against steam exposure [8]. The results demonstrated that the steam protective performance of clothing

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Nomenclature

A	surface area, m^2
Ar	specific value between cross-section area of nozzle and surface area of fabric
C	heat capacity, J/kg K
c_p	specific heat at constant pressure, J/kg K
d	diameter, m
D	diffusivity coefficient, m/s
h_c	heat transfer coefficient, W/m^2 K
h_m	mass transfer coefficient, m/s
Δh	enthalpy of phase change, J/kg
m	mass transfer rate, g/s
K	Darcian permeability, m^2
k	thermal conductivity, W/m K
Nu	Nusselt number
Pr	Prandtl number
q	heat flux, W/m^2
P	pressure, kPa
R	fiber regain
Re	Reynolds number
T	temperature, K
t	time, s
V	Dacian flow velocity, m/s
x	linear horizontal coordinate, m
v	kinematic viscosity, m/s
α	specific surface area of fiber, m^{-1}

Greek letters

ε	volume fraction
ρ	density, kg/m^3
Φ	relative humidity
γ	proportionality constant related to the rate of absorption
μ	dynamic viscosity, m^2/s

Subscripts

a	air
amb	ambient
b	blood
bw	bound water
c	convection heat transfer
ds	dry fiber
ep	equilibrium
exp	exposure
all	all phases
f	fiber
fab	fabric
g	gas phase
in	inlet
jet	steam jet
l	liquid water
ls	from the liquid phase to the solid phase
m	mass
out	outlet
P	control volume
s	liquid/solid phase
sat	saturation
skin	human skin
w	rate of blood perfusion
vap	evaporation
vl	from the gaseous phase to the liquid phase
vs	from the gaseous phase to the solid phase

mainly depended on resistance to water vapor diffusion, air permeability, thermal insulation, and total heat loss.

Previous studies mainly focused on the evaluation of steam protective performance under different steam exposures. Few studies were carried out to investigate the mechanism of steam heat transfer in protective clothing under a pressurized steam. Some numerical models have been developed to understand the heat and moisture transfer in thermal protective clothing under exposure to flash fire, high- and low-intensity thermal radiation. For instance, Chen [10] firstly described the heat and moisture transfer in protective clothing under radiant heat exposure based on a simple numerical model in 1959. After that, Prasad et al. [11] developed a heat and moisture transfer model in low heat intensity that considered radiative heat transfer, phase change and absorption/desorption of moisture in protective clothing. The developed model was further improved by Fu et al. [12] in order to investigate the effect of moisture within protective clothing on radiative heat transfer. Based on the heat and moisture transfer model presented by Gibson and Charmchi [13], Song et al. [14] proposed an improved model for exposure to heat and flame, which was used to study phase change, sorption/desorption, molecular diffusion, convection, and capillary liquid diffusion in thermal protective clothing.

Despite the fact that some numerical models have been developed to understand the heat and moisture transfer mechanisms of thermal protective clothing under flame and radiative heat exposures, these models are not capable of dealing with steam heat transfer in thermal protective clothing. This is due to the fact that the steam transfer is simultaneously determined by temperature and pressure differences, and the steam transfer results in non-thermal equilibrium between three phases (including water vapor, fiber and liquid water). Therefore, the objective of this study is to develop a heat and moisture transfer model for investigating the steam heat transfer in thermal protective fabric. The skin burns are predicted by integrating the developed model and the skin burn prediction model. The effect of fabric physical properties on the steam protective performance is examined. This work helps to understand the steam heat transfer behavior in thermal protective clothing and provide theoretical guidance for the safety protection of workers under steam leakage.

2. Numerical model during steam exposure and cooling

Most thermal protective fabrics are generally assumed to be non-hygroscopic porous medium that allows moisture transfer in the interspace of the textile material. Owing to the complexity of steam heat transfer in protective clothing, some assumptions are adopted to simplify the numerical model:

(a) Heat and moisture transfer in protective fabric is simplified as one dimensional model along the fabric's thickness.
(b) Radiative heat transfer in protective fabric is ignored due to the minor hole and the less temperature difference between inside and outside surface of protective fabric during steam exposure.
(c) Effects of phase change and absorption/desorption by fibers on heat transfer are considered.
(d) Considering the rapid steam transfer in protective fabric, the gas phase within protective fabric is not in thermal equilibrium with other phases [15].