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Modelling Heat-Moisture Transport through Firefighters' Protective Fabrics from an Impinging Flame Jet by Simulating the Drying Process

Abstract
Abstract In this paper, a mathematical model for coupled heat and moisture transfer through a firefighters' protective clothing system exposed to high flux is proposed by simulating the drying process in fire. This model is based on Fick's Second diffusion law, simulating an impinging fire jet drying a moist fabric and takes account into the dynamic diffusion effect on the fire drying process. Other non-constant physical and thermal properties are also included in the model, validated by comparing the predictions with experimental data, and good agreements are found. The model can find application in thermal protective clothing design. Also the experimental model approach and model findings are expected to be useful to the drying industry.

Key words: *heat and moisture transport, mathematical model, drying, moisture diffusion, fire protective clothing.*

Nomenclature

c_p – *specific heat of moist fabric*
c_{p0} – *specific heat of dry fabric*
c_{pw} – *specific heat of water*
L – *thickness*
M – *moisture content*
M_{gap} – *moisture content in the air gap*
h_h – *heat transfer coefficient*
h_m – *mass transfer coefficient*
Q_r – *radiation heat souce*
q – *radiation heat flux*
ΔE – *activation energy*
A – *pre-exponential frequency factor*
Nu – *Nusselt number*
Pr – *Prandtl number*
Re – *Reynolds number*
Sc – *Schmidt number*
d_p – *effective pore diameter*
ρ – *density*
γ – *extinction coefficient*
τ – *transmissibility*
ν – *kinetic viscosity*
σ – *Stefan-Boltzmann constant*
ε – *porosity*
$\Im$ – *rate of turbulent heat flux dissipation per unit mass of water vapor*

Subscript
eff – *effective*
rad – *radiant*
conv – *convection*
amb – *ambient*
airrad – *radiant in the air gap*
aircon – *convection in the air gap*
fab – *fabric*
copp – *copper sensor (calorimeter)*
e – *equilibrium*
i – *initial*
M – *moisture*

Introduction

Models of heat and moisture transfer through porous media under high temperature or high flux conditions have been reported in literature during the past decade. Francis [1] investigated the heat and moisture characteristics of a continuous industrial drying process for a moist semi-porous textile composite under jet impingement drying conditions. Costa et al. [2] modelled and simulated a barrier system consisting of highly humid porous media. In the physical model, the outflow mass transfer was dictated by the water effusion and not by the convection transfer mechanism between the exposed surface and the environment. Ang et al. [3] presented a numerical study of heat and moisture transfer in gypsum plasterboard under natural fire conditions in buildings. The effect of mass transfer in gypsum plasterboard on its specific heat value was evaluated.

Textile material can be treated as a porous medium. Therefore, there are many existing models for simulating heat and moisture transport in porous fabrics [4 - 6]. Then these theoretical methods are applied successfully to heat and mass transport within heat resistant fabrics exposed to high flux. Jiang et al. [7] reported an integrated numerical simulator to estimate the thermal protective performance of firefighters' protective clothing. In the simulator, the fluid flow and transfer through in the scene of fire were computed by a general-purpose computational fluid dynamics program, and conductive heat transfer through the clothing and human skin was calculated by a one-dimensional program. Chitrphiromsri and Kuznetsov [8] investigated the coupled heat and moisture transport in firefighter protective clothing during flash fire exposure. The distribution of the temperature and moisture content in the fabric during the exposure to the flash fire were computed. Ghazy and Bergstrom [9] developed a finite volume model to simulate the transient heat transfer in a protective clothing system accounting for transient combined conduction-radiation heat transfer within the air gap and including the variation in the air gap properties with temperature.

The behaviour of heat- moisture transportation within heat resistant fabric exposed to fire dictates the jet impingement drying process. Diffusion considered as a chemical kinetics process was presented in studies of modelling heat-moisture transfer within wet cotton fabric under simulated fire [10]. Moisture diffusivity was considered as a function of temperature. However, water vapor diffusion is dependent on not only temperature but also on the moisture content within moist fabric. However, to our knowledge, there is no study reported in literature on the application of a mathematical model to predict heat and moisture transfer within porous protective fabric using variant diffusivity with the moisture content.

The present study proposes a theoretical model to predict simultaneous heat and moisture transfer based on Fourer's law and Fick's second law. The dynamic diffusivity characterised by the Luikov and Arrhenius equations is involved in the mass transfer equation. In order to validate the mathematical model proposed, fire testing protection (FTP) measurementswere carried out to measure the thermal protective performance of firefighters' protective clothing.

Mathematical modeling

The problem of one-dimensional heat and mass transfer through a "fire-moist fabric-copper calorimeter" system is modelled. An air gap, determining the heat flux transmission through firefighters' clothing, exists between the fabric and sensor. Heat is transferred from the flame jet into the moist materials, which causes the water to vaporize, and the air movement carries the vapor away from the fabric. Drying begins due to the steam pressure differences between the surroundings and the fabric sample, which also cause moisture evaporation from the two surfaces. The moisture removal results in moisture gradients inside the fabric. The moisture will also migrate into the air gap.

Heat transfer model for fabric

Firstly a one-dimensional, unsteady-state was developed to solve simultaneous heat and moisture transfer in the porous fabric. The transient moisture diffusion process of evaporation of a moist fabric takes place in a similar fashion to the heat conduction process in such a moist fabric. In developing this model, the following common assumptions are made:
1) Mass transfer in the fabric only by diffusion; no free liquid exists in the fabric.
2) Negligible shrinkage or deformation of fabric during fire exposure.
3) Physical and thermal properties are assumed to be functions of local moisture content and temperature.
4) Free convection in the porous fabric is negligible.
5) No degradation occurs during thermal exposure
6) Heat and moistrue transfer through the system of the "fire-fabric-copper sensor" is one-dimensional.

Heat and mass transfer equations describing the behaviour of the fabric represented as a porous media made up of capillaries have the following form:

Heat transfer equation:

$$\frac{\partial}{\partial t}\left(T\rho c_p\right)=\frac{\partial}{\partial x}\left(\lambda_{eff}\frac{\partial T}{\partial x}\right)+Q_r \quad (1)$$

Gas mass transfer equation:

$$\frac{\partial M}{\partial t}=\frac{\partial}{\partial}\left(D_{eff}\frac{\partial M}{\partial x}\right) \quad (2)$$

where ρ_f is the effective density of the fabric, c_p the effective specific heat of the fabric, λ_{eff} the effective thermal conductivity of the fabric, Q_r the effective diffusivity of the fabric, M in % the moisture content at any time in the fabric, and Q_r is the radiation heat source term representing the internal heat generated by thermal radiation transferred to the internal region of the fabric. Q_r can be written as [11]

$$Q_r=\gamma q_{rad}e^{-\gamma x} \quad (3)$$

where q_{rad} is the incident radiant heat flux from the thermal source, γ the extinction coefficient of the fabric ($\gamma=-\frac{\ln\tau}{L_{fab}}$, τ - the transmissibility of the fabric; L_{fab} - the thickness of the fabric).

Boundary conditions for fabric

The fabric is heated by gas burner. In the model, the gas-fabric boundaries are represented using the following radiation and convection boundary conditions for heat and mass transfer.

$$\lambda_f\frac{\partial T}{\partial x}=\left(q_{rad}+q_{conv}\right)=h_{h,fla-fab}\left(T_g-T_{fab}\right) \quad (4)$$
$$x=0,\ t>0$$

$$-D_{eff}\frac{\partial M}{\partial x}=h_{m,fla-fab}\left(M_{amb}-M\right) \quad (5)$$
$$x=0,\ t>0$$

where $h_{h,\,fla\text{-}fab}$ and $h_{m,\,fla\text{-}fab}$ is the convective and radiant heat transfer coefficient and mass transfer coefficient between the gas flame and undersurface of the fabric. The convective heat transfer coefficient can be determined by the experimental method using a special sensor that simultaneously measures convective and radiant heat fluxes at locations 10 mm above the surface of the copper sensor [12]. $h_{m,\,fla\text{-}fab}$ is the moisture content in the ambient air.

The mass transfer between the gas burner flame and fabric can be simulated as a jet impingement and horizontal flat plate during drying. The mass transfer coefficient $h_{m,\,fla\text{-}fab}$ is written in terms of the rate heat flux dissipation and kinematic viscosity of the water vapour for the turbulent flow around the fabric [1]

$$h_{m,fla-fab}=2\sqrt{\left(\frac{D_a}{\pi}\right)\left(\frac{\Im}{v}\right)^{1/4}} \quad (6)$$

where D is the water vapor diffusivity of air, $\Im$ the rate of turbulent heat flux dissipation per unit mass of water vapor, and v is the kinematic viscosity.

The air gap - fabric boundaries for heat and mass transfer are expressed as

$$\lambda_f\frac{\partial T}{\partial x}=q_{airrad}+q_{airconv} \quad (7)$$
$$x=L_{fab},\ t>0$$

$$D_{eff}\frac{\partial T}{\partial x}=h_{m,fab-sen}\left(M-M_{gap}\right) \quad (8)$$
$$x=L_{fab},\ t>0$$

where M_{gap} is the moisture content in the air gap, q_{airrad} the heat flux by radiation from the fabric to the human skin across the air gap, and q_{aircon} is the heat flux by convection from the fabric to the human skin across the skin gap, which can be given by

$$q_{airconv}=h_{gap}\left(T_{fab}-T_c\right) \quad (9)$$
$$x=L_{fab},\ t>0$$

Radiation heat transfer from the fabric to human skin is also considered. The radiation is modelled simply for the one-dimensional case as radiation exchange between two infinitely parallel plates. Taking the emissivities of the fabric and human skin to be average values of 0.9 and 0.94, respectively, the radiant boundary condition between the fabric and skin can be expressed as

$$q_{airrad} = 0.85\sigma\left(T_{fab}^{\ 4} - T_c^{\ 4}\right)$$
$$x = L_{fab},\ t > 0 \qquad (9)$$

Transport properties of fabric

As mentioned before, there are various physical properties and transport parameters that are required during the solution of differential equations describing the heat-moisture transfer model. These properties were experimentally determined or can be found from other literature

Thermal conductivity

The fabric's thermal conductivity and specific heat capacity change considerably during exposure to intense heat. The effective thermal conductivity of the fabric can be determined by the following equations [13] [14]

$$\lambda_{eff} = \lambda_{cond} + \lambda_{rad} \qquad (11)$$

where λ_{cond}, thermal conductivity due to conduction, can be calculated by the formula $\lambda_{cond} = \lambda_{fib} + \lambda_M$; λ_{fib} is the thermal conductivity of the fabric without moisture, and λ_M is the thermal conductivity of moisture. λ_{rad} is the thermal radiation conductivity and can be written as $\lambda_{rad} = \varepsilon/(1 - \varepsilon)\sigma d_p 4T^3$.

Specific heat:

The effective specific heat c_p of moist fabric can be calculated as [15]

$$c_p = (c_{p0} + 0.01c_{pw}M)/(1 + 0.01M) + A_c \qquad (13)$$

where c_{pw} is the specific heat of water, c_{p0} the specific heat of dry fabric, and A_c is a parameter which is a function of the moisture content and temperature.

Water vapor diffusivity:

The variation in the effective diffusivity of the water with temperature with a constant moisture content is classically represented by the Arrhenius equation:

$$D = A\exp\left(-\frac{E}{RT}\right) \qquad (14)$$

Luikov considered that the mass diffusion coefficient as a function of the water content with constant temperature and gave the following equation

$$D = \frac{B}{1 - C \cdot M} \qquad (15)$$

Combining ***Equation 14*** and ***15***, we get [16]

$$D_{eff} = \frac{B}{1 - C \cdot M}\exp\left(-\frac{F}{T}\right) \qquad (16)$$

Both the influence of the moisture content and temperature are included in Eq. (16), which is different to the one proposed by Crank [17]. The empirical parameters B, C and F can be determined by fitted experimental data.

Heat transfer model for copper sensor

In the research, the governing equation for the one-dimensional heat conduction model for the copper calorimeter can be written as

$$\rho_c c_c \frac{\partial T}{\partial t} = \frac{\partial}{x}\left(\lambda_c \frac{\partial T}{\partial x}\right) \qquad (17)$$

where ρ_c, c_c and λ_c are the density, specific heat and thermal conductivity of the copper calorimeter. Boundary conditions for the sensor:

$$\lambda_c \frac{\partial T}{\partial x} = \left(q_{airrad} + q_{airconv}\right)$$
$$x = L_{fab} - L_{air},\ t > 0 \qquad (18)$$

Heat and mass transfer in the air gap between the fabric and copper sensor

Heat transfer by conduction or convection through the air gap can be modelled as resistance to heat flow between the fabric and copper sensor. The heat transfer coefficient between the fabric and sensor is deemed as a function of the size of the air gap and temperature of the trapped air, which can be described as [11]

$$h_{gap}\left(L_{air}, T\right) = Nu\frac{\lambda_{air}\left(T\right)}{L_{air}} \qquad (19)$$

Empirical correlations applicable for laminar and turbulent flow are used depending on the magnitude of the Rayleigh ($Gr \cdot Pr$) number. For laminar flow, the correlation is

$$\mathrm{Nu} = 0.59 \cdot (Gr \cdot Pr)^{1/4} \qquad (20)$$

The vapour density in the air gap will change because the air gap gains moisture content from the fabric. Moisture transportation within the air gap can be characterised by using the convective mass transfer coefficient h_a, which evaluates moisture migration from the fabric into the air gap. Laminar flow is assumed in the horizontal enclosure heated from the under side. Therefore the convective mass transfer coefficient $h_{m,fab\text{-}sen}$ can be given by

$$h_{m,fab-sen}\left(L_{air}, T\right) = Sh\frac{D_a\left(T\right)}{L_{air}} \qquad (21)$$

The following correlations for laminar are used to determine the mass transfer coefficient

$$Sh = 0.664\ Re^{0.5}\ Sc^{0.33} \qquad (22)$$

where Nu, Re, Pr, Sh, Sc are the Nusselt, Reynolds, Prandtl, Sherwood and Schmidt numbers. λ_{air} (T) is the thermal conductivity of the air, L_{air} the size of the air gap, and D_a is the diffusion coefficient of vapor in the air gap.

Numerical procedure

As the parameters involved in ***Equations 1*** and ***2***, such as thermal and physical properties, are functions of the moisture content or temperature, the equations are nonlinear and can be solved by the finite difference method (Crank-Nicolson).

For the fabric, the thickness of the sample was divided into N finite difference points or nodes. Node 1 was the surface, and node N was the other side of the sample. At each node, the general heat and moisture transfer equations apply. In addition, at node 1 and N, the boundary conditions of the two surfaces apply, respectively. Dependence of the results on the grid cell size and length of the time step are investigated by varying each one while keeping the other constant. By using a grid of 10^{-6} m and a time step of 0.1 s, the results are relatively independent of the grid size and time step. Due to nonlinear radiation terms, we have employed the Gauss-Seidel point-by-point iterative scheme to solve these equations. In order to avoid divergence of the iteration method, the under-relaxation procedure is used to solve the resulting ordinary differential equations [18].

The inputs to the mathematical models are known at the initial state and include the following: flame temperature, flame emissivity, fabric sample dimension, fabric density as a function of moisture content, thermal conductivity and specific heat as functions of the moisture content and temperature, moisture diffusivity as a function of the temperature and moisture content, heat and mass transfer coefficients at the surface, and skin thermal physical parameters. The programme is computed in a given time step. The vari-

Table 1. Geometrical properties of the fabrics.

Sample	Fabric structure	Density,kg/m3	Thickness, mm	Weight, mg/cm2	Emissivity ε	Transmissivity τ
PSA	Sateen	388	0.578	22.43	0.85	0.01
Nomex IIIA	Twill	418	0.356	14.89	0.90	0.01

Table 2. Sensor temperature for gas adjustment.

Heat flux, kW/m2	Copper sensor temperature, °C			
	initial	after 5 seconds	after 8 seconds	end temperature
21	31.0	57.7	75.0	88.0
42	22.1	63.4	87.0	101.1

Table 3. Measurements and predictions of thermal protection of moist fabric.

Heat flux, kW/m2	Fabric	HTRI12, s		HTRI24		HTRI24-HTRI12	
		Test	Prediction	Test	Prediction	Test	Prediction
21	PSA	8.6	10.4	15.8	16.1	7.2	5.7
	Nomex IIIA	5.8	9.6	10.3	14.7	4.5	4.9
42	PSA	6.2	8.8	11.0	12.3	4.8	3.5
	Nomex IIIA	5.6	6.2	10.6	11.1	5.0	4.9

ables at the previous time step are used as guessed values for the variables at the current time step. The new values of variables are computed by visiting each grid point in a certain order. Then we can obtain temperature values of the copper sensor surface.

Experimental

Experimental samples

Fabrics made from inherently heat resistant Nomex IIIA and Polysulfonamide fibre (PSA) fabrics were selected to carry out many experiments to validate the mathematical model. The samples were cut to a defined dimension (140 mm long and 140 mm wide) and mounted on a planar framework. Weighed samples were immersed in water for a given length of time, taken out and shaken to remove the liquid water, and then weighed again to obtain the mass of water absorbed. Geometrical properties of the fabrics are listed in ***Table 1***.

Method

Testing apparatus for evaluating the thermal protective performance of fire clothing is shown in ***Figure 1***, which is called Fire Testing Protection Apparatus (FTP-30). The heat source was provided by a gas burner. Heat is transferred through the fabric specimen, and through the air gap located between the fabric and copper calorimeter surface. Times for a temperature rise of 12 and 24 °C were registered using a thermocouple mounted onto the calorimeter. The mean result for three test specimens is calculated as the "heat transfer index" (HTRI12 and HTRI24). The time differences HTRI24-HTR12 give a good indication of the skin pain alarm time. The heat sources corresponded to ISO 6942 (Protective clothing-protection against the heat and fire-method of the test: Evaluation of materials and material assemblies when exposed to a source of radiant heat) and ISO 91541(Protective clothing-Protection against heat and fire-determination of heat transmission on exposure to flame). The temperature rise versus time and heat flux was measured using a copper calorimeter located above the sample fabrics at a distance of 5.0 cm.

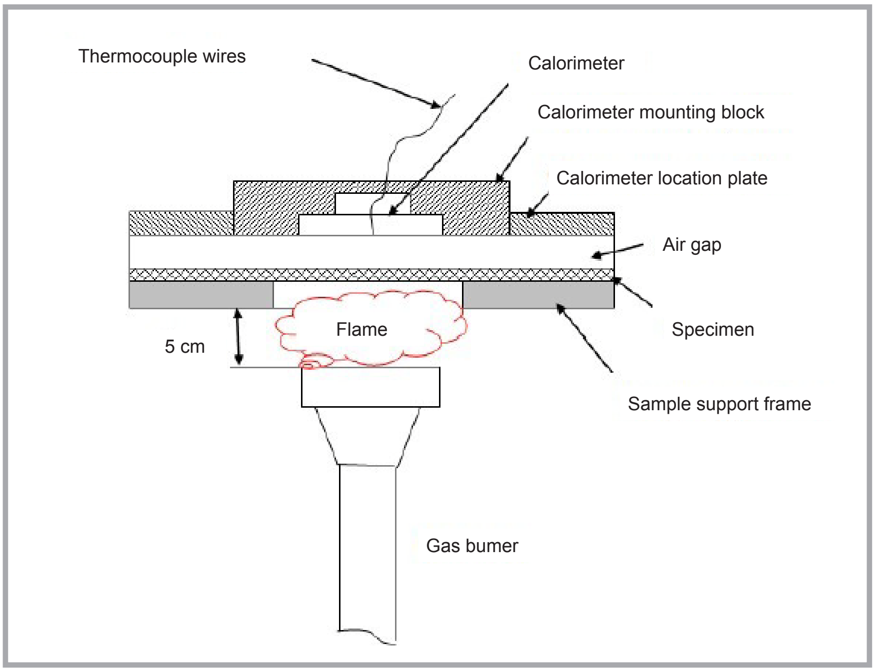

Figure 1. Scheme of testing apparatus.

Before testing, gas adjustment was conducted to calibrate the heat flux from a Meker burner in the desired range. This can be accomplished by comparing the copper sensor's temperature history with set values (***Table 2***) after a period of exposure time. A heat flux of 21 and 42 kW/m2 were set in the experiment.

Results and discussion

To validate the model, the model predictions were compared with experimental data. According to the drying approach, we define a dimensionless index of diffusion moisture (moisture mass loss rate), which can be expressed as [19]

$$MR = \frac{M - M_e}{M_i - M_e} \quad (23)$$

Where M is the moisture content at any time, M_i the initial moisture content, and M_e is the equilibrium moisture content of the sample. The M_e value was set to be equal to the moisture content at which the fabric sample weight became constant with the exposure time. It should be noted that M_e equals 0 when the heat flux of the thermal source is comparatively high (84 kW/m^2) and the exposure time is too long. Then ***Equation 23*** becomes

$$MR = \frac{M}{M_i} \quad (24)$$

The results of the fire experiments and predictions are shown in ***Figure 2*** with PSA fabric, which shows the moisture loss rate curve. The difference between the experimental and predicted curves for both conditions was less than 3.8%, especially during the late period. The model predictions are in good agreement with experimental data. The heat flux significantly affected the moisture change in the fabric. Increasing the heat flux reduced the time required to achieve a specific moisture content.

From the experimental and predicted curves in ***Figure 2***, we can also find no constant moisture loss rate period under both exposure conditions. Maybe it is because the fabric was so thin that it could not provide a constant supply of moisture during the thermal exposure time. However, an abrupt trend can be seen from the two curves with a rapid moisture loss rate. In general, this rapid moisture loss rate period corresponded to the ascending temperature within the sample, which can be explained by the moisture evaporating from the fabric surface due to the rapid temperature increase. Moreover, free liquid water, not considered in the model prediction, will escape in the form of vapour,

Table 3 gives comparisons of the heat protection index RHTI12, RHTI24 and the difference RHTI24 - RHTI12 (indication of the skin pain alarm time) in using the predicted and measured temperature of the thermocouple mounted on the copper sensor with a 5 mm air gap thickness between the fabric and copper sensor. These experiments also demonstrate that the numerical model reasonably simulates the results of actual FTP tests for both fabrics. The skin burns easily for a heat flux of 42 kW/m^2, seen from the skin burn alarm time (HTRI24 - HTRI12). These results (***Table 3***) show that as the intensity of the thermal exposure increases, a predictable diminishment in the HTRI12 and HTRI24 will occur. However, the decrease is not striking for Nomex IIIA fabric.

Figures 3 and ***4*** show comparisons of computational and experimental results of temperature profiles on the surface of the calorimeter for the two kinds of fabrics with a 5 mm air gap configuration under a heat flux of 21 and 42 kW/m^2. The exposure time applied in these tests is 30 seconds. Good agreement can be observed from these comparisons of

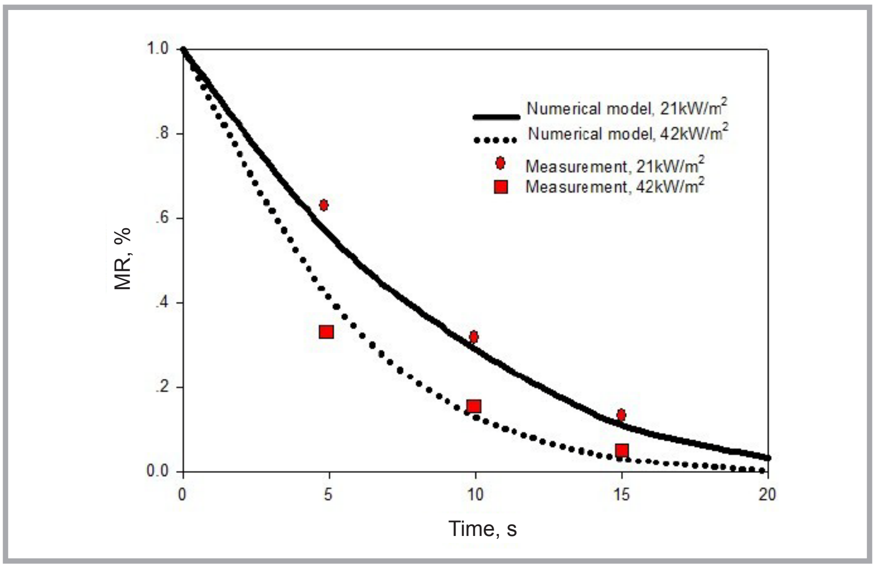

Figure 2. *Comparisons between the experimental values and predicted results of moisture loss rate curve.*

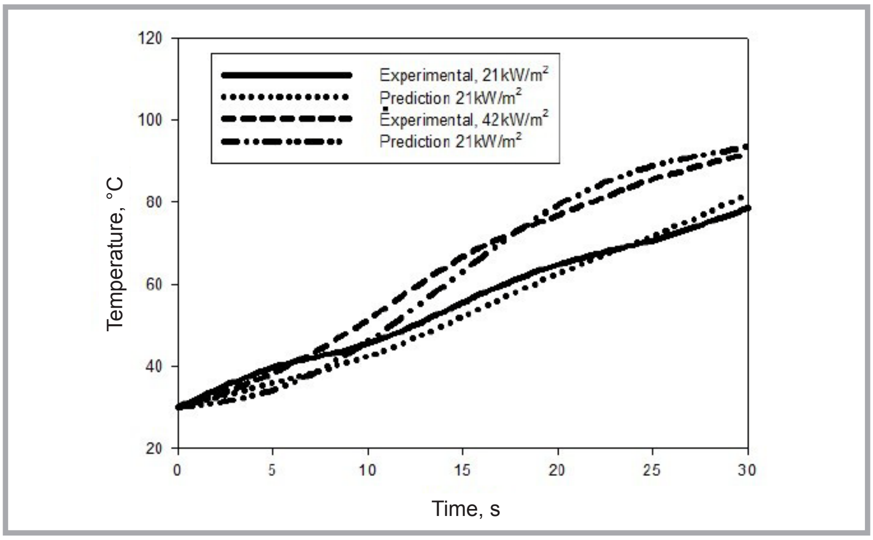

Figure 3. *Temperature profiles for PSA fabrics under different heat flux conditions.*

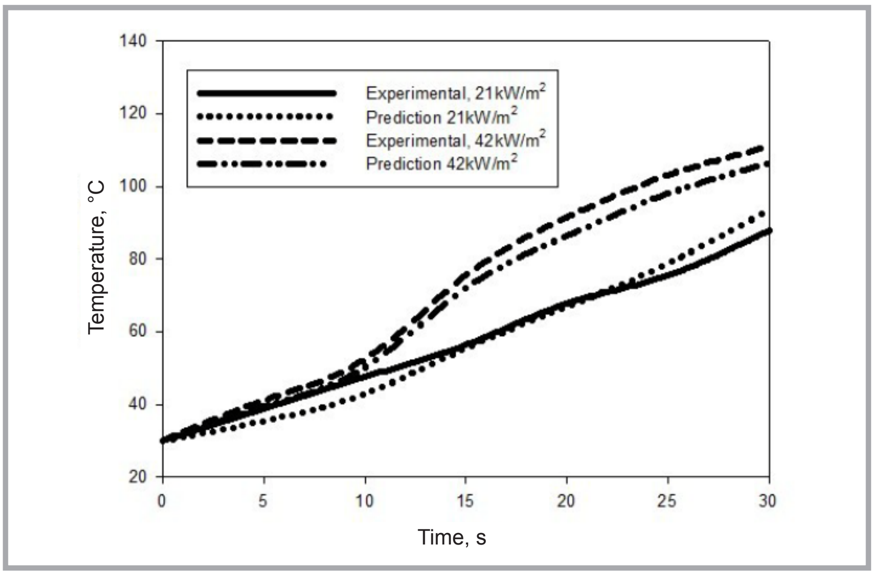

Figure 4. *Temperature profiles for Nomex IIIA fabrics under different heat flux conditions.*

model calculation and experimental results during the middle period. However, a little difference between predicted and experimental profiles can be found at the early exposure stage, except for the Nomex IIIA profiles in ***Figure 4***. The calculated value is slightly higher than the experimental value at this stage. This may be caused mainly by the condensing heat released by condensation water onto the surface of the copper sensor while the effect of water vapour condensation is neglected in the numerical model. After exposure for a period of time, all the moisture evaporates from the fabric and a small portion of the water vapor move inward. Then recondensation of the water vapour will occur on the surface of the copper sensor. The release heat will result in higher temperature increase in experimental profile than that in numerical predicted profile. This conclusion can also be demonstrated from other published experimental data [20]. Under more high flux condition (42 kW/m^2), there is insignificant temperature difference between calculated values and experimental results for Nomex IIIA fabric at the early stage. But the significant difference can be found at the post stage.

Conclusions

A theoretical-physical one-dimensional model was proposed to study the heat and moisture transfer through porous protective clothing fabric system during impinging flame jet exposure based on the governing equations of Fourier's law and Fick's Second law. The results show that heat and moisture transfer through moist fabric exposed flash fire can be considered as drying process described by dynamic diffusion. It is also shown that the obtained drying model can be used to estimate the thermal response of wetted fabrics. The model should provide a theoretical basis for thermal ergonomic design for firefighter protective clothing.

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