# HEAT AND MOISTURE TRANSFER OF MULTI-LAYER FABRICS

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## INTRODUCTION

Fire fighters often experience sudden changes in exertion, ambient temperature and/or %RH. This transient phase is important in the sense that the wearer becomes most aware of clothing comfort during these times. This research studied parameters which affect transient heat and moisture transfer through fire fighter's clothing assemblies. Fiber type, fabric structure and product design may all affect the rates of transfer, thus limiting comfortable accommodation to variations in climate or activity. Structural fire fighter's protective clothing, called turnout gear, is a multilayer construction consisting of a fire-retardant outer shell, a water vapor barrier and a thermal liner. The resulting high thermal resistance also implies retention of body heat and moisture.

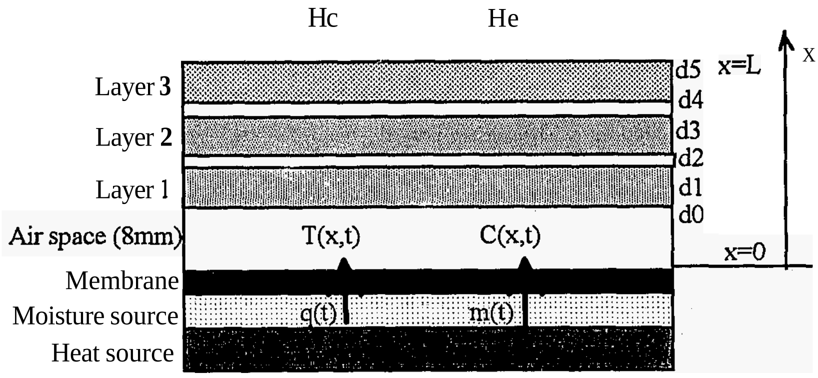
Sweating hot plate or diffusion cell methods are available to determine steady-state heat/moisture transfer of materials. However, non-steady-state measurements can be more informative regarding the thermostatic action of clothing in buffering the body against sudden change in environment or activity

## RESEARCH OBJECTIVES AND APPROACH

**A** model of transient heat and moisture transfer through clothing was developed. The model was verified using an experimental method specially developed for this research.

### Theoretical Model

The model assumes heat and vapor sources below the fabric assembly. *An* **8** mm air space represents the microclimate between the skin and the first layer. Layer 1-3 are the fabric layers representing the clothing system. It is assumed that the governing phenomena of transfer below layer 3 are moisture diffusion through inter yam spaces



and heat conduction through yarns/solids. At the outer surface, convection dominates.

Physical quantities are defined as follows.

$T(x,t)$ = temperature distribution of system at time t (sec) and position x (m), C
$C(x,t)$ = conc. distribution of system at time t (sec) and position x (m), kg/cu. m.
$q_0(t)$ = heat flux at the interface flowing from heat source, W/sq. m.
$m_0(t)$ = mass flux at the interface flowing from moisture source, kg/sq. m. s
$T_a$ = ambient temperature, C $H_a$ = ambient relative humidity, %RH
$C_a$ = ambient concentration, kg/cu m. Ca = $f(T_a,H_a)$

Material constants related to the fabric assembly are as follows.

Hc = convective heat transfer coefficient, W/sq. m. C
He = convective mass transfer coefficient, m/s
S = specific heat of the fabric J/kg C $S_a$ = specific heat of the still air J/kg C
K = thermal cond. of fabric, W/m C $K_a$ = thermal cond. of still air, W/m C
D = mass diffusivity of fabric, sq. m/s $D_a$ = mass diffisivity of *air*, sq. m/s
d = thickness of fabric, m P = density of the fabric, kg/cu. m.
ε = porosity of fabric 5 = tortuosity of the fabric ($\tau=\varepsilon D_a/D$)
t = time, s x = distance, m

## Moisture Diffusion Equation

The partial differential equation and appropriate **boundary and** initial conditions for the determination of distribution of concentration C(x,t) in the system are given as:

$$\varepsilon_k \frac{\partial C_k(x,t)}{\partial t} = \frac{D_k}{\tau_k}\frac{\partial^2 C_k(x,t)}{\partial x^2} \qquad 0\le x\le L \qquad t>0 \qquad k=0,1,2,3,4,5 \qquad (2)$$

**Boundary** conditions:

$$1)\ -D_0\frac{\partial C_0(x,t)}{\partial x}\Big|_{x=0} = m_0(t) \qquad x=o \qquad (3)$$

$$2)\ -D_k\frac{\partial C_k(x,t)}{\partial x}\Big|_{x=\sum_0^k d_k} = -D_{k+1}\frac{\partial C_{k+1}(x,t)}{\partial x}\Big|_{x=\sum_0^k d_k} \qquad \text{and} \qquad C_k = C_{k+1}$$

$$k=0,1,2,3,4 \qquad (4)$$

$$3)\ H_e[C_a - C_5(x,t)|_{x=L}] = D_5\frac{\partial C_5(x,t)}{\partial x}\Big|_{x=L} \qquad x=L \qquad (5)$$

Initial conditions:

$$1)\ C_k(x,0) = C_k \qquad k=0,1,2,3 \qquad (6)$$

## Heat Conduction Equation

The partial differential equation and appropriate boundary and initial conditions for the determination of distribution of temperature T(x,t) in the system are given as:

$$\rho_k C p_k\frac{\partial T_k(x,t)}{\partial t} = K_k\frac{\partial^2 T_k(x,t)}{\partial x^2} \quad t>0 \qquad 0\le x\le L \qquad k=0,1,2,3,4,5 \quad (7)$$

**Boundary** conditions:

$$1)\ -K_0\frac{\partial T_0(x,t)}{\partial x}\Big|_{x=0} = q_0(t) \qquad x=0 \qquad (8)$$

$$2)\ -K_k\frac{\partial T_k(x,t)}{\partial x}\Big|_{x=\sum_0^k dk} = K_{k+1}\frac{\partial T_{k+1}(x,t)}{\partial x}\Big|_{x=\sum_0^k dk} \quad \text{and} \quad T_k = T_{k+1} \quad k=0,1,2,3,4 \qquad (9)$$

$$3)\ Hc[T_a - T_5(x,t)|_{x=L}] = K_5\frac{\partial T_5(x,t)}{\partial x}\Big|_{x=L} \quad x=L \qquad (10)$$

Initial conditions:

$$1)\ T_k(x,0) = T_k \quad k=0,1,2,3 \qquad (11)$$

There are a total of six elements of different thermal properties in the model consisting of 3 fabric layers and **3** air layers. They constitute 12 heat and moisture diffusion equations. The analytical solutions are difficult to derive, hence, the finite difference method is implemented to solve the one-dimension, timedependent diffusion equations. The time step of 9.6 seconds and the largest value of **Ax** chosen, give a stability criterion r ($r = \alpha\Delta t/(\Delta x)^2$) bigger than 0.5. Hence the fully implicit scheme given below is used.

$$\frac{T_m^{i+1} - T_m^i}{\mathrm{At}} = a\frac{T_{m-1}^{i+1} - 2T_m^{i+1} + T_{m+1}^{i+1}}{(\Delta x)^2}$$

where

$T_m^i$ = temperature or concentration at node m and time i, C or $kg/m^3$

$\alpha$ = thermal diffusivity or diffusion coefficient, $m^2/s$

At = time step, s Ax = distance between two nodes, m

To determine the node temperature $T_m^i$, a simultaneous solution of all the equations for the nodes at each time step is calculated.

## RESULTS

Some of the measured fabric properties used in the heat and moisture diffusion equations are listed in Table 1. Detailed description of these properties and their test methods are given in [1]. Diffusion coefficient (Dfab) and thermal diffusivity ***(a)*** of the fabrics are the two main parameters that control heat and moisture transfer through them. Wide ranges of thermal diffusivities and diffusion coefficients seen in Table 1, result in different rates of heat and moisture transfer for each 3 layer combination.

Model Verification

From the incident heat and moisture flux and using the formula given by Olesen and Dukes-Dobos, the heat transfer coefficient (Hc) is calculated for air velocity of 50 cm/sec to be 6.1 $W/m^2$ C. From the Lewis relationship one *can* readily find **mass** transfer coefficient (Hm) equal to 0.0069 m/s. The mean and standard deviation of differences between theoretical and observed values of temperature and relative humidity at all different locations were calculated and are described in [1]. The low diffusion coefficient of MB4 makes it impermeable to moisture diffusion. Therefore, the microclimate above

Table 1. Diffusion properties of specimens

| Specimen | (d). at 5 gf/cm$^2$ x$10^{-3}$m | **(p).** kg/m$^3$ | (Dfab) x $10^{-6}$ m$^2$/s | (K) W/m C | ($\rho$Cp) kJ/m$^3$ C | ($\alpha$) x $10^{-7}$ m$^2$/s | ($\varepsilon$) % |
|---|---|---|---|---|---|---|---|
| **Thermal Liner** | | | | | | | |
| TL1 | 5.38 | 62.63 | 7.04 | 0.050 | 95.39 | 5.24 | 97.70 |
| TL6 | 2.76 | 86.54 | **4.53** | 0.050 | 258.17 | 1.94 | 93.79 |
| **Moisture Barrier** | | | | | | | |
| MB1 | 0.57 | 213.45 | 0.71 | 0.037 | 1049.86 | 0.35 | 85.96 |
| MB4 | **0.38** | 920.58 | 0.01 | 0.062 | 3626.29 | 0.17 | 40.12 |
| **Outer Shell** | | | | | | | |
| os 2 | 0.69 | 297.99 | 0.55 | 0.047 | 1388.41 | 0.34 | 79.94 |
| OS3 | 0.71 | 341.76 | 1.23 | 0.050 | 1494.63 | 0.34 | 73.86 |

**MB4** shows low relative humidity while that below gains moisture resulting in higher relative humidity. The theoretical model assumes moisture diffusion in the upward direction and an impermeable moisture barrier like MB4 obstructs this flow of moisture. This is evident from the larger deviation of predicted values from measured values of **%RH** for all the microclimates. Table 2 compares the mean difference and standard deviation of predicted %RH values from measured %RH values for two moisture barriers.

The range of difference for all 27 assemblies tested between predicted and measured values of temperature is -0.37 to 0.42 C and that of %RH is -3.74 to 2.99 %RH. Corresponding ranges for standard deviation are 0.10 to **0.35** C for temperature and 0.48 to 4.12 %RH for relative humidity

Table 2. Mean difference and standard deviation **of** difference in %RH for the model

| Moisture barrier | Mean difference | Standard deviation |
|---|---|---|
| MB1 | -0.04 | **0.88** |
| **MB4** | **-0.54** | **1.76** |

## CONCLUSIONS

The model developed predicts momentary temperature and relative humidity of the microclimates between fabric layers as observed using the experimental method developed for this research for measurement of heat and moisture transfer under transient conditions.

## REFERENCE

1. Chen, **P.L.** 1994, Heat and Moisture Transfer Properties of Multi-Layer Fabric Assemblies, Doctoral Dissertation, College of Textiles, North Carolina State Univ., Raleigh, N.C.