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Modeling of heat and moisture transport by periodic ventilation of thin cotton fibrous media

Kamel Ghali [a,1], Nesreen Ghaddar [b,*], Byron Jones [c,2]

[a] *Faculty of Engineering, Beirut Arab University, Beirut, Lebanon*
[b] *Department of Mechanical Engineering, Faculty of Engineering and Architecture, American University of Beirut, P.O. Box 11-0236, Riad ElSolh, Beirut 1107-2020, Lebanon*
[c] *Kansas State University, 148 Rathbone Hall, Manhattan, KS 66506-5202, USA*

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Abstract

In walking conditions, the air spacing between the fabric layer of a porous clothing system and the human skin changes with the walking frequency. This change will cause air penetration in and out of the clothing system depending on the fabric air permeability. The air passing through the fabric can considerably reduce the heat and moisture transfer resistance of the clothing system and its suitability for a given thermal environment. In this work, the coupled convection heat and moisture exchange within the clothing system subject to sinusoidal air layer thickness variation about a fixed mean is experimentally investigated and theoretically modeled to predict the periodic fabric regain, the fabric temperature and the transient conditions of the air layer located between the fabric and the skin.

Experiments were conducted in environmental chambers under controlled conditions using a sweating hot plate at 35 °C that represents the human skin and a gear motor to generate the oscillating fabric motion. The first set of experiments was done using a dry isothermal hot plate to measure the sensible heat transfer. The second set of experiments was conducted with an isothermal sweating hot plate and the total heat (sensible and latent) transport from the plate was recorded.

A mathematical model was developed for the heat and mass transport through the air spacing layer and the fiber clothing system. In the fabric, a three-node adsorption model was used to describe the effect of fabric motion (ventilation) on the sensible and latent heat flows from the human skin under different environmental conditions. The fiber model was linked to the transport model of the oscillating air spacing layer that falls between the fiber and the fixed boundary (human skin). The transport equations were solved numerically. The sensible and latent heat transport quantities at the moist solid boundary were calculated. A reasonable agreement was observed between the model predictions of heat loss or gain from the hot plate and the experimentally measured results. © 2002 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Transient thermal analysis is important in evaluating the response of clothing systems and its relation to the human thermal comfort. The purpose of clothing is to maintain a uniform body temperature under different temperature environments and to prevent the accumulation of sweat on the human skin by allowing the respired body water to flow to the outside environment when activity level increases. Thus, heat exchange between human body and the environment is significantly affected by the dynamic response of the clothing system and the way the clothing layers mediates the flow of heat and moisture from the human skin to the environment.

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[*] Corresponding author. Tel.: +11-961-1655-102; fax: +11-961-1744-642.

E-mail addresses: amro@aub.edu.lb (K. Ghali), farah@aub.edu.lb (N. Ghaddar), jones@ksu.edu (B. Jones).

[1] Tel.: +11-961-1-350000x3594; fax: +11-961-1-744-642.

[2] Tel.: +11-785-532-5844; fax: +11-785-532-7810.

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Nomenclature

A_f	area of the fabric (m^2)
C_f	fiber specific heat (J/kg K)
f	frequency of oscillation
h_{fg}	heat of vaporization of water (J/kg)
h_{ad}	heat of adsorption (J/kg)
h_c	heat transport coefficient from the skin to the trapped air layer (W/m^2 K)
H_{ci}	conduction heat transfer coefficient between inner node and outer node (W/m^2 K)
H_{co}	convection heat transfer coefficient between outer node and air flowing through fabric (W/m^2 K)
h_m	mass transfer coefficient between the skin and the air layer (kg/m^2 kPa s)
H_{mi}	diffusion mass transfer coefficient between inner node and outer node (kg/m^2 kPa s)
H_{mo}	convection mass transfer coefficient outer node and air flowing through fabric (kg/m^2 kPa s)
k_{air}	thermal conductivity of air (W/m K)
L	fabric length (m)
P_{air}	air vapor pressure (kPa)
P_i	vapor pressure of water vapor adsorbed in inner node (kPa)
P_o	vapor pressure of water vapor adsorbed in outer node (kPa)
R	total regain in fabric (kg of adsorbed H_2O/kg fiber)
R_v	water vapor gas constant
RH	relative humidity
t	time (s)
T	Temperature (°C or K)
t_f	fabric thickness (m)
u_{ad}	internal energy of water in adsorbed state (J/kg H_2O)
u_f	total internal energy of fiber containing adsorbed H_2O (J/kg of dry fiber)
W	fabric width (m)
w	humidity ratio (kg of water/kg of air)

Greek symbols

α	fabric air permeability
ε	fabric emissivity
ρ	mass density of fabric (kg/m^3)
γ	fraction of mass that is in the outer node
σ	Stefan–Boltzman constant $= 5.669 \times 10^{-8}$ $W/m^2 K^4$

Subscripts

air	conditions of air in the spacing between skin and fabric
i	inner node
o	outer node
skin	conditions at the skin surface
void	local air inside the void

The heat and mass transport processes from the human skin to the ambient air are not only of diffusion type and are enhanced by the ventilating motion of air through the fabric initiated by the relative motion of the human with respect to the surrounding environment. The size of the air spacing between the skin and the fabric is continuously varying in time depending on activity level and location, thus inducing variable airflow in and out of the fabric. This induced airflow contributes to the augmentation of the rate of condensation and adsorption in the clothing system and the amount of heat and moisture loss from the body. During body motion, air must go in and out and ventilation is obtained without gross environmental air movement. Harter et al. [1] called this particular aspect in clothing comfort "ventilation of the microclimate within clothing". The ventilation rate is affected mainly by the walking velocity as described by Lotens [2] who derived empirically the steady ventilation rate through apertures of clothing assembly as function of the air permeability of the fabric and the effective wind velocity. His model was derived from experimental considerations of forced convective flow through apertures of outer garments during motion and the air penetration through the outer material. Lotens' [2] clothing ventilation model, however, is not based on thermal principles, and has not taken into account any non-equilibrium heat and moisture adsorption processes that take place in the fabric layers.

Traditionally, models of heat and mass transfer through clothing layers assumed instantaneous equilibrium between the local relative humidity of the diffusing moisture and the regain of the fiber and ignored the effect of ventilation on the heat and moisture exchange between the microclimate of the clothing and the ambient air. Farnworth [3] developed a numerical model that took into account the condensation and adsorption in a multi-layered clothing system by developing linear relations to represent the fiber regain equilibrium. Jones et al. [4] developed another model that used actual empirical relation obtained from experiments to calculate the fiber regain equilibrium. The latter model also took into account the sorption behavior of fibers. More recently, Li and Holocombe [5] presented a transient mathematical clothing model that describes the dynamic heat and moisture transport behavior of clothing and human body.

The above-mentioned models focused on the diffusion process of heat and water vapor transport and assumed instantaneous equilibrium between the local relative humidity of the penetrating air and the moisture content of the fiber. However, the hypothesis of local thermal equilibrium was shown to be invalid during periods of rapid transient heating or cooling in porous media as reported by Mincowycz et al. [6]. Their results for one-dimensionally porous layer show that in presence of flow, local thermal equilibrium is not valid if the ratio of the Sparrow number to Peclet number is small. In absence of local thermal equilibrium, the solid and fluid should be treated as two different systems. Gibson conducted a two-dimensional numerical modeling and experimental testing of steady diffusion/convection processes in textiles, where pressure drops and relative humidities across the fabric are compared [7–11]. He used a dynamic moisture permeation cell for experimental testing, where concentration differences between top and bottom of the fabric were imposed by convective airflow stream above and below the fabric that are parallel to the fabric surface. The numerical model of Gibson included diffusion and convective transport of heat and moisture as well as liquid water wicking through porous textile material. Gibson's model was based on Whitaker's theory [12] for mass and energy transport through porous media that assumes local thermodynamic equilibrium between the three phases: solid, liquid and gas that could exist in the porous textile material and ignored the possible existence of microscale pore-level heat and mass transfer coefficients. Under vigorous movement of a relatively thin porous textile material, the air will pass quickly between the fibers and the assumption of local thermodynamic equilibrium is invalid.

Ghali et al. [13] studied the effect of ventilation on heat and mass transport through fibrous material by developing a theoretical two-node absorption model, aided with experimental results on moisture regain of ventilated fabric, to predict the transfer coefficients of a cotton fibrous medium. Their model was further developed and experimentally verified to predict temporal variations in temperature and moisture content of the air within the fiber in a multi-layer three-node model [14].

In realistic applications, ventilation of the clothing system during the human motion occurs by periodic motion of air in and out of the air spacing as the fabric moves outward or inward towards the skin. There are two objectives of this paper. The first objective is to present original experimental data on sensible and latent heat transport initiated by sinusoidal motion of a fabric plane about a fixed mean air spacing thickness above a sweating isothermal hot plate placed in a controlled environment. The second objective is to develop a mathematical and numerical model to study the effect of fabric motion (ventilation) on the sensible and latent heat transport through the fiber clothing system due to a sinusoidally varying air layer thickness between the fiber and a wet isothermal skin. The transport in the air spacing will be coupled to a lumped single layer three-node model of the fabric developed by Ghali et al. [14], to predict the periodic fabric regain, the fabric temperature and the transient conditions of the air space between the fabric and skin. The results of the mathematical model will be verified by comparison of the experimentally measured values of heat loss or gain from the hot plate.

2. Experimental model

Untreated cotton was chosen as a representative of a most common worn fabric to test behavior when subject to periodic motion above the skin. The cotton was obtained from Test Fabrics (Middlesex, NJ-08846), and is made of unmercerized cotton duck, style #466 of thickness of 1 mm.

Fig. 1(a) shows a front view of the experimental setup, which is composed of two square wooden frames, hinged to each other. Both frames have an inner open area of 50.8 cm × 50.8 cm and an outer area of 55.4 cm × 55.4 cm for the upper frame and an area of 58.5 cm × 58.5 cm for the lower frame. The upper frame is connected to a rotating shaft. The shaft is connected to a gear motor having a constant frequency of 25 rpm. When the shaft rotates, the upper frame moves sinusoidally in a vertical path away and towards the lower frame in a stroke of 12.7 mm. The side view of the experimental setup is shown in Fig. 1(b), where the four-bar linkage mechanism by which the fabric is moved up and down can be spotted. The hinges (piano hinges) were necessary to insure that the upper frame is moving in a horizontal plane without tilting. The cotton fabric was tapped to the upper frame by an aluminium tape and the exposed surface of both wooden frames was also covered by aluminium tape. To insure a planar movement of the fabric (no flattering) the fabric sample was placed between two metallic screens that were made of 12.7 mm open squares.

The movement of the fabric that is attached to the upper frame will cause air to move back and forth across the fabric. To reduce the possibility of air escaping through the hinges or through the lower frame, the hinges were covered with plastic wrapping and plastic foam was taped to the outer rim of the lower frame as shown in Fig. 1(a). A minimal layer of plastic wrapping was used to minimize possible horizontal movement of the air layer between the lower and upper frames. In the plane slightly above the fabric frame plane, an air circulation fan is placed to provide sufficient circulation of air (0.7 m/s) for maintaining the constant chamber

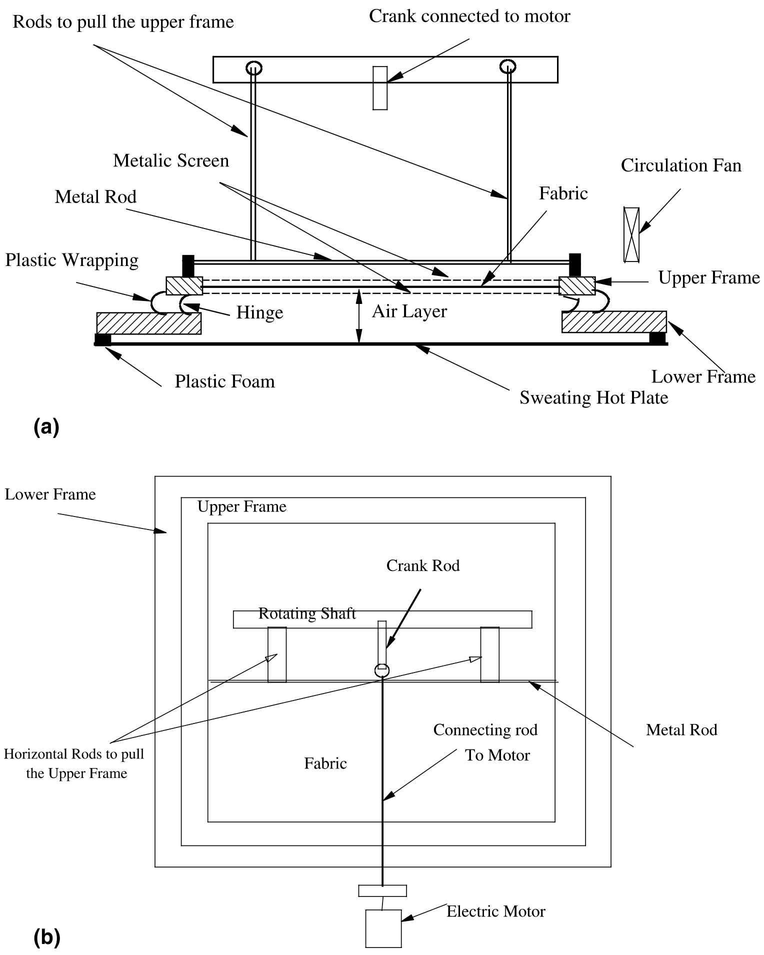

Fig. 1. (a) Front view of the experimental setup; (b) top view of the experimental setup.

ambient conditions above the fabric. Before the start of the experiment, the whole frame was conditioned for 16 h inside an environmental chamber, not shown in the figures, at conditions of 25 °C and 50% RH. Then the frame was placed on top of a sweating hot plate. The precision in the set conditions of the climatic chamber temperature was ±0.5 °C and chamber relative humidity was ±2%.

A Dynatech sweating guarded hot plate apparatus Model TCB-TX was used in the environmental chamber for measuring the sensible and latent heat transport from the skin. The apparatus simulates the function of human skin and the plate consists of three temperature-controlled heaters: main, guard and bucking heaters. The measuring section of the main heater is a 25.4 cm square plate surrounded by a guard section, which increases the total size of the plate to 50.8 cm × 50.8 cm. The function of the guard heater is to eliminate lateral heat flow from the main heater. The third bucking heater located beneath the main heater eliminates the heat flow in the axial direction below the main heater. These two heaters (guard and bucking) thereby force all of the heat generated in the main heater to flow in the direction away from the oscillating fabric. The plate temperature was set to be 35 ± 0.5 (°C). The mean air spacing between the fabric and the hot plate was 38.1 mm. The amplitude of oscillation is 6.35 mm. The heat flow through the sample is equal to the power supplied to the main heater. The power scanned by the device is averaged over the desired time interval with a repeatability of ±1% and accuracy of ±4%.

Two experiments were conducted. The first experiment was performed with a dry plate to measure the sensible heat flow from the plate caused by the fabric sinusoidal movement. In this experiment, the oscillating fabric frame was placed on top of the horizontal plate and was allowed to reach steady-state conditions by monitoring the temperature of the plate and the power needed to keep the plate at constant temperature. When the plate readings (temperature and power) reached

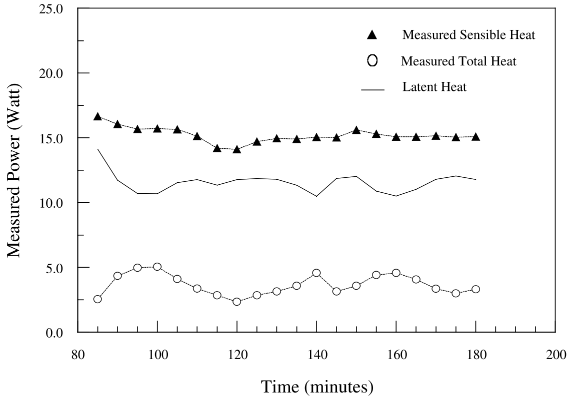

Fig. 2. Experimentally measured hot plate power during the experiment.

steady state, the plate was allowed to stay in equilibrium for 1 h and then time-averaged power readings over every 5 min were collected for one more hour. The second set of experiment was conducted but with a sweating plate to allow the measurement of the total (latent and sensible) heat flow from the plate. In this case the guarded hot plate is saturated with water so that its surface is completely wet. The time-averaged power readings of the device were collected every 5 min. The measured quantities of sensible, latent and total heat loss (time averaged every 5 min) are shown in Fig. 2.

3. Mathematical formulation

The physical domain of interest is shown in Fig. 3, where an air layer separates the moving clothing system (cotton fabric sheet) at the upper boundary and the fixed sweating isothermal plate at the lower boundary (human skin). The upper boundary has a sinusoidal up and down motion that induces air movement through the fabric. The analysis of the airflow through the fabric is based on a single lumped layer of three-node adsorption model of the fibrous medium and an air void. The outer node represents the exposed surface of the yarns, which is in direct contact with the penetrating air in the void space between the yarns (the air void node). The inner node represents the inner portion of the "solid" yarn (fibers on the interior of the yarn), which is completely surrounded by the outer node. The outer node exchanges heat and moisture transfer with the flowing air and with the inner node, while the inner node exchanges heat and moisture by diffusion only with the outer node. The moisture uptake in the fabric occurs first by the convection effect at the yarns surface, followed by diffusion to the yarn interior. The fiber model is best represented by a flow of air around cylinders (yarns) in cross-flow as shown in Fig. 4. The fabric is represented by a large number of these three-node modules depending on the fabric effective porosity. The fabric area is $L \times W$ and the fabric thickness is t_f. The airflow is normal to the fabric plane. The air spacing layer beneath the fabric will be formulated as a lumped compressible layer with the density function of temperature and pressure. In the derivation of the mass balances of the air void node, the air–water vapor mixture is assumed dilute and the bulk velocity of the mixture is very close to the velocity of the void air. This assumption allows simplification of the mass balances by ignoring the effect of counter transfer of the air.

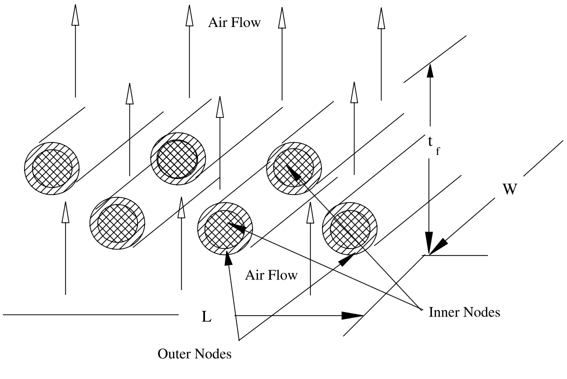

Fig. 4. The fiber model.

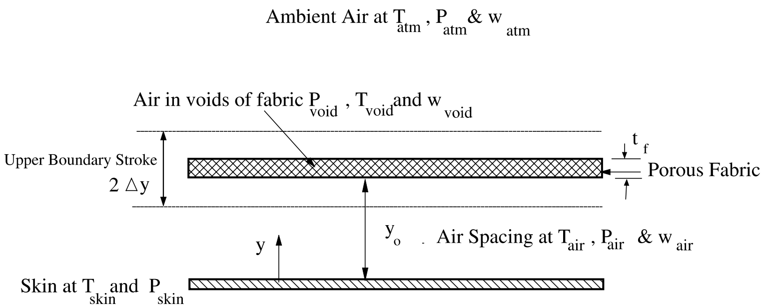

Fig. 3. The physical domain of interest.

3.1. Modeling of the air mass flow rate through the fabric

The fabric sinusoidal motion can be represented by the following equation:

$$y = y_0 + \Delta y \sin(2\pi f t), \tag{1}$$

where f is the frequency of oscillation (25 rpm), y_0 is the mean air spacing thickness (38.1 mm), and Δy is the oscillation amplitude (6.35 mm). Conducting a mass balance for the skin–fabric air layer leads to

$$-\dot{m}_{\mathrm{a}} = \frac{\partial}{\partial t}(\rho_{\mathrm{a}} y), \tag{2}$$

where, $\dot{m}_{\mathrm{a}}$ is the air mass flow rate and ρ_{a} is the air density. Eq. (2) can be expanded to the following:

$$-\dot{m}_{\mathrm{a}} = y\frac{\partial}{\partial t}(\rho_{\mathrm{a}}) + \rho_{\mathrm{a}}\frac{\partial}{\partial t}(y). \tag{3}$$

Note that the air layer above the fabric is moving and represents a boundary condition, with constant temperature and humidity. As the fabric moves down, the airspace between the skin and the fabric moves out through the fabric and is swept away by the moving air stream. When the direction of the fabric reverses, the opposite process occurs. That is, the void created as the fabric rises is filled with air from the moving air stream that passes through the fabric.

Every fabric, when there is pressure difference between the two fabric surfaces, there will be a mass flowing through the fabric. The amount of the air depends on the permeability of the fabric material. The permeability is affected by the type of yarn, tightness of twist in yarns, yarn count and fabric structure. In this study the permeability of the fabric is considered constant at the standard experimentally measured value under the pressure difference of 0.1245 kPa ($\alpha = 4.99\ \mathrm{cm}^3/\mathrm{cm}^2\ \mathrm{s}$). To get the airflow passing through the fabric at other pressure differentials, other than the 0.1245 kPa, the air permeability is assumed to be constant and the amount of airflow is proportional to the pressure differentials. The airflow rate is then represented by

$$\dot{m}_{\mathrm{a}} = \frac{\alpha\rho_{\mathrm{a}}}{\Delta P_{\mathrm{m}}}(P - P_{\mathrm{env}}), \tag{4}$$

where α is the fabric air permeability, and $\Delta P_{\mathrm{m}} = 0.1245$ kPa from standard tests on fabrics' air permeability [ASTM D737-75], P is the air pressure of the air layer between the skin and the fabric and P_{env} is the outside environment air pressure. Substituting the ideal gas relation, $\rho_{\mathrm{a}} = P/R_{\mathrm{a}}T_{\mathrm{air}}$, into Eq. (3) gives the mass balance in the air spacing in terms of the air pressure as

$$-\frac{\alpha P}{R_{\mathrm{a}}T_{\mathrm{air}}\Delta P_{\mathrm{m}}}(P - P_{\mathrm{env}}) = \frac{y}{R_{\mathrm{a}}T_{\mathrm{air}}}\frac{\partial P}{\partial t} + \frac{P}{R_{\mathrm{a}}T_{\mathrm{air}}}\frac{\partial y}{\partial t} + \frac{yP}{R_{\mathrm{a}}}\frac{\partial(1/T_{\mathrm{air}})}{\partial t} \tag{5}$$

from which the pressure P can be determined as a function of time. Substituting P into Eq. (4) gives the instantaneous air mass flow rate, which will be used in the fabric model.

3.2. Modeling of the air spacing layer

During the upward motion of the fabric, the airflow into the air spacing layer comes from the air void node of the fabric and will have the same humidity ratio as the air in the void space of the fabric. The water vapor mass balance for the air spacing layer while the fabric is moving up is given by

$$\frac{\partial(\rho_{\mathrm{a}} y w_{\mathrm{air}})}{\partial t} = h_{\mathrm{m}}[P_{\mathrm{skin}} - P_{\mathrm{air}}] - \dot{m}_{\mathrm{a}} w_{\mathrm{void}} + D\frac{\rho_{\mathrm{a}}(w_{\mathrm{void}} - w_{\mathrm{air}})}{t_{\mathrm{f}}/2}. \tag{6a}$$

During the downward motion of the fabric, the airflow through the fabric out of the air spacing will carry the same humidity ratio of the air spacing. The water vapor mass balance for the air spacing layer during the downward motion is given by

$$\frac{\partial(\rho_{\mathrm{a}} y w_{\mathrm{air}})}{\partial t} = h_{\mathrm{m}}[P_{\mathrm{skin}} - P_{\mathrm{air}}] - \dot{m}_{\mathrm{a}} w_{\mathrm{air}} + D\frac{\rho_{\mathrm{a}}(w_{\mathrm{void}} - w_{\mathrm{air}})}{t_{\mathrm{f}}/2}, \tag{6b}$$

where h_{m} is the mass transfer coefficient between the skin and the air layer, P_{air} is the water vapor pressure in the air layer, w_{air} is the humidity ratio of the air layer, P_{skin} is the vapor pressure at the skin solid boundary, w_{void} is the humidity ratio of the air void and D is the diffusion coefficient of water vapor into air.

An energy balance for the air–vapor mixture in the air spacing layer will be performed taking into account the motion direction of the fabric and its effect on the properties of the air mass that enters the domain during upward motion and that leaves the domain during the downward motion. An energy balance of the air spacing during upward motion of the fabric is given by:

$$\frac{\partial}{\partial t}\left[\rho_{\mathrm{a}} y(C_{\mathrm{v}}T_{\mathrm{air}} + w_{\mathrm{air}}h_{\mathrm{fg}})\right] + P_{\mathrm{env}}\frac{\partial y}{\partial t} = h_{\mathrm{m}}h_{\mathrm{fg}}[P_{\mathrm{skin}} - P_{\mathrm{air}}] + h_{\mathrm{c}}[T_{\mathrm{skin}} - T_{\mathrm{air}}] - \dot{m}_{\mathrm{a}}[C_{\mathrm{p}}T_{\mathrm{void}} + w_{\mathrm{void}}h_{\mathrm{fg}}] + Dh_{\mathrm{fg}}\frac{\rho_{\mathrm{a}}(w_{\mathrm{void}} - w_{\mathrm{air}})}{t_{\mathrm{f}}/2}. \tag{7a}$$

During the downward motion of the fabric, the energy balance in the air spacing layer becomes

$$\frac{\partial}{\partial t}\left[\rho_{\mathrm{a}} y(C_{\mathrm{v}}T_{\mathrm{air}} + w_{\mathrm{air}}h_{\mathrm{fg}})\right] + P_{\mathrm{env}}\frac{\partial y}{\partial t} = h_{\mathrm{m}}h_{\mathrm{fg}}[P_{\mathrm{skin}} - P_{\mathrm{air}}] + h_{\mathrm{c}}[T_{\mathrm{skin}} - T_{\mathrm{air}}] - \dot{m}_{\mathrm{a}}[C_{\mathrm{p}}T_{\mathrm{air}} + w_{\mathrm{air}}h_{\mathrm{fg}}] + Dh_{\mathrm{fg}}\frac{\rho_{\mathrm{a}}(w_{\mathrm{void}} - w_{\mathrm{air}})}{t_{\mathrm{f}}/2}, \tag{7b}$$

where h_m is the mass transport coefficient from the skin surface to the lumped air layer and h_c is the heat transport coefficient from the skin to the lumped air boundary. These coefficients have been determined experimentally.

3.3. Modeling of the fabric

In the fabric, the three-node adsorption model of Ghali et al. [13] will be used to describe the heat and moisture transport through the fabric due to air ventilating motion. Effective heat and mass transfer coefficients, reported by Ghali et al. [13,14], H_{co} and H_{mo} for the outer node of the fabric, and the heat and mass diffusion coefficients H_{ci} and H_{mi} for the inner nodes of the fabric, are used in the model in normalized form as follows:

$$H'_{mo} = H_{mo}\frac{A_o}{A_f}, \quad H'_{co} = H_{co}\frac{A_o}{A_f}, \quad H'_{mi} = H_{mi}\frac{A_i}{A_f},$$
$$H'_{ci} = H_{ci}\frac{A_i}{A_f}, \tag{8}$$

where A_f is the overall fabric surface area, A_o is the outer node exposed surface area to airflow and A_i is the inner node area in contact with the outer node.

The water vapor mass balance in the air void node is given in Eqs. (9a) and (9b) during the upward motion and during the downward motion of the fabric, respectively, as:

$$\begin{aligned}\frac{\partial}{\partial t}(\rho_a t_f w_{void}\varepsilon_f) &= -\dot{m}_a[w_{atm} - w_{void}] + H'_{mo}[P_o - P_a] + D\frac{\rho_a(w_{air} - w_{void})}{t_f/2} \\ &\quad + D\frac{\rho_a(w_{atm} - w_{void})}{t_f/2},\end{aligned} \tag{9a}$$

$$\begin{aligned}\frac{\partial}{\partial t}(\rho_a t_f w_{void}\varepsilon_f) &= \dot{m}_a[w_{air} - w_{void}] + H'_{mo}[P_o - P_a] + D\frac{\rho_a(w_{air} - w_{void})}{t_f/2} \\ &\quad + D\frac{\rho_a(w_{atm} - w_{void})}{t_f/2}\end{aligned} \tag{9b}$$

where ε_f is the fiber porosity and t_f is the fabric thickness. The outer fiber node and the inner fiber node mass balances are given in Eqs. (10) and (11), respectively:

$$\frac{dR_o}{dt} = \frac{1}{\rho\gamma t_f}[H'_{mo}(P_v - P_o) + H'_{mi}(P_i - P_o)], \tag{10}$$

$$\frac{dR_i}{dt} = \frac{H'_{mi}}{\rho(1-\gamma)t_f}[P_o - P_i], \tag{11}$$

where R_o is the regain of the outer node, R_i is the regain of the inner node, and H'_{mo} and H'_{mi} are the mass transfer coefficients between the outer node and the penetrating air and the outer node and the inner node, respectively. The parameter γ is the fraction of mass that is in the outer node and it depends on the fabric type and the fabric porosity. The total regain R in the fiber is given by

$$R = \gamma R_o + (1-\gamma)R_i. \tag{12}$$

According to the previous model of Ghali et al. [13], the value of γ is equal to 0.6. An energy balance for the air–vapor mixture in the air void node is given in Eqs. (13a) and (13b) during the upward motion and during the downward motion of the fabric, respectively, as

$$\begin{aligned}\varepsilon_f\frac{\partial}{\partial t}[\rho_a t_f(C_v T_{void} + h_{fg}w_{void})] &= -\dot{m}_a[C_p T_{atm} + w_{air}h_{fg}] + \dot{m}_a[C_p T_{void} + w_{void}h_{fg}] \\ &\quad + H'_{co}[T_o - T_{void}] + K_a\frac{T_{air} - T_{void}}{t_f/2} + K_a\frac{T_{atm} - T_{void}}{t_f/2} \\ &\quad + Dh_{fg}\frac{\rho_a(w_{air} - w_{void})}{t_f/2} + Dh_{fg}\frac{\rho_a(w_{atm} - w_{void})}{t_f/2},\end{aligned} \tag{13a}$$

$$\begin{aligned}\varepsilon_f\frac{\partial}{\partial t}[\rho_a t_f(C_v T_{void} + h_{fg}w_{void})] &= \dot{m}_a[C_p T_{air} + w_{air}h_{fg}] - \dot{m}_a[C_p T_{void} + w_{void}h_{fg}] \\ &\quad + H'_{co}[T_o - T_{void}] + K_a\frac{T_{air} - T_{void}}{t_f/2} + K_a\frac{T_{atm} - T_{void}}{t_f/2} \\ &\quad + Dh_{fg}\frac{\rho_a(w_{air} - w_{void})}{t_f/2} + Dh_{fg}\frac{\rho_a(w_{atm} - w_{void})}{t_f/2},\end{aligned} \tag{13b}$$

where H'_{co} is the heat transfer coefficients between the outer node and the penetrating air in the voids and K_a is the thermal conductivity of air.

The energy balance on the outer nodes gives

$$\begin{aligned}\rho_f(1-\gamma)\left[C_{pf}\frac{dT_o}{dt} - h_{ad}\frac{dR_o}{dt}\right] &= \frac{H'_{co}}{t_f}[T_{void} - T_o] - \frac{H'_{ci}}{t_f}[T_o - T_i] + \frac{h_r}{2t_f}(T_{skin} - T_o) \\ &\quad + \frac{h_r}{2t_f}(T_{atm} - T_o),\end{aligned} \tag{14}$$

where H'_{ci} is the heat diffusion coefficient between the outer node and the inner node and h_{ad} is the enthalpy of the water adsorption state. The density of the adsorbed phase of water is similar to that of liquid water. The high density results in the enthalpy and internal energy of the adsorbed phases being very nearly the same. Therefore, the internal energy, u_{ad}, can be replaced with the enthalpy of the adsorbed water. Data on h_{ad}, as a function of relative humidity, are obtained from the work of Morton and Hearle [15]. Also the fabric is exchanging radiation heat with the plate and the chamber. The energy balance on the inner node gives

$$\rho_f\gamma\left[C_{pf}\frac{dT_i}{dt} - h_{ad}\frac{dR_i}{dt}\right] = \frac{H'_{ci}}{t_f}[T_o - T_i]. \tag{15}$$

The set of the above-coupled differential equations (6a), (6b), (7a), (7b), (8), (9a), (9b), (10)–(12), (13a), (13b), (14), and (15) describes the time-dependent convective mass and heat transfer from the skin-adjacent air layer through the fabric induced by the sinusoidal motion of the fabric. Numerical integration will be performed to predict during the periodic motion the fabric regain, the fabric temperature, the air void temperature, air layer temperature and humidity ratio and the heat loss from the skin.

4. Numerical method

The coupled eight mass and heat transport equations (6a), (6b), (7a), (7b) and (9a), (9b), (10)–(12), (13a), (13b), (14), and (15) of the outer and inner nodes of the fabric and the air void are integrated numerically using first-order Euler–Forward scheme with a time step size of 0.003 s over a total integration period of 1800 s. The number of time steps per period of oscillation is more than 3000 steps in a period of 2.61 s. The saving of the various parameters was done every 0.3 s of real time. The vapor pressure of the flowing air in the air spacing layer or in the fabric voids is related to the air relative humidity, RH, and temperature and is calculated using the psychrometric formulas of Hyland and Wexler to predict the saturation water vapor pressure and the hence the vapor pressure at the specified relative humidity [16]. The regain of the cotton material has a definite relation to the relative humidity of the water vapor through a property curve of regain versus relative humidity [15]. The graphical relation of R as a function of relative humidity, RH, has been interpolated with third order polynomials for 10 relative humidity intervals from zero to 100%. The interpolation functions are used in the simulation to calculate the inner and outer nodes' relative humidities corresponding to the values obtained of inner and outer regains, respectively. At every time step, the air mass flow rate is updated and the total regain, and temperatures of all the nodes are evaluated. When the solution converges to a steady periodic solution, the cycle time-averaged (sensible and latent) total heat loss from the skin is calculated using the experimentally evaluated heat and mass transfer coefficients h_c and h_m in the air spacing layer as

$$q = LW\left[h_c\left\{\frac{1}{\tau}\int_t^{t+\tau}(T_{\text{skin}} - T_{\text{air}})\,dt\right\} + h_{fg}h_m\left\{\frac{1}{\tau}\int(P_{\text{air}} - P_{\text{skin}})\,dt\right\}\right]. \tag{16}$$

The method by which the mass transfer coefficient h_m between the skin and the air layer is measured, is given in Appendix A, and then from the Lewis relationship the heat transfer coefficient h_c can be estimated. The simulation results will be discussed in the following section in comparison with experimental data obtained on heat loss from the hot plate.

5. Results and discussion

The predicted total moisture regain is shown as a function of time in Fig. 5. The regain increases sharply

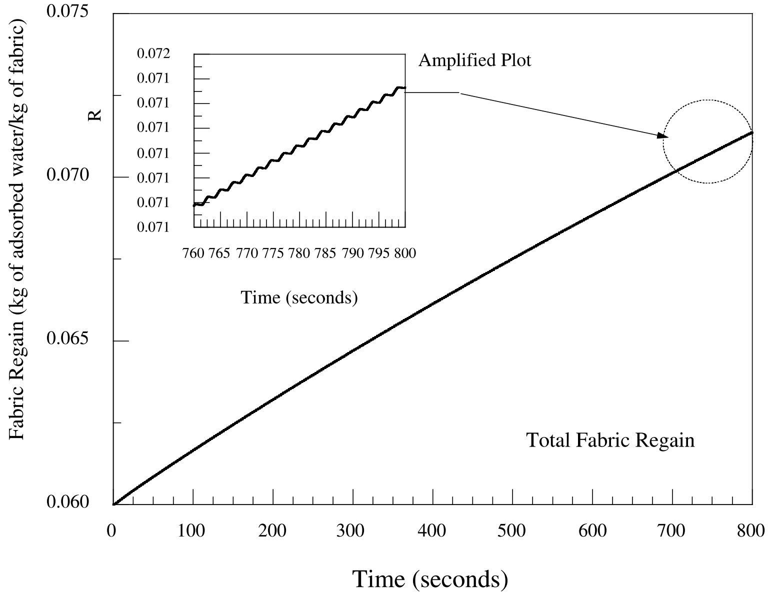

Fig. 5. The predicted total moisture regain as a function of time.

in the initial period of exposure and then increases at a slower mean rate in an oscillating pattern. When the thickness of the air layer increases, the air flows from the outside, and the fabric regain decreases due to the lower humidity of the outside air. When the thickness of the air layer decreases, fabric regain increases since the higher humidity air flows out from the inside air layer. The temperature variation in time of the fabric inner and outer nodes is shown in Fig. 6, which also amplifies the steady periodic solution. The outer node temperature attains a sinusoidal pattern similar to the forcing motion, but the inner node is less sensitive to external variations since heat and mass transfer diffusion to the inner node is a slower process than the ventilation of the outer node. The air void node and the air spacing temperature variations are shown in Fig. 7, while the variation of the air void and the air spacing humidity ratios are shown in Fig. 8. Since the air spacing is adjacent to

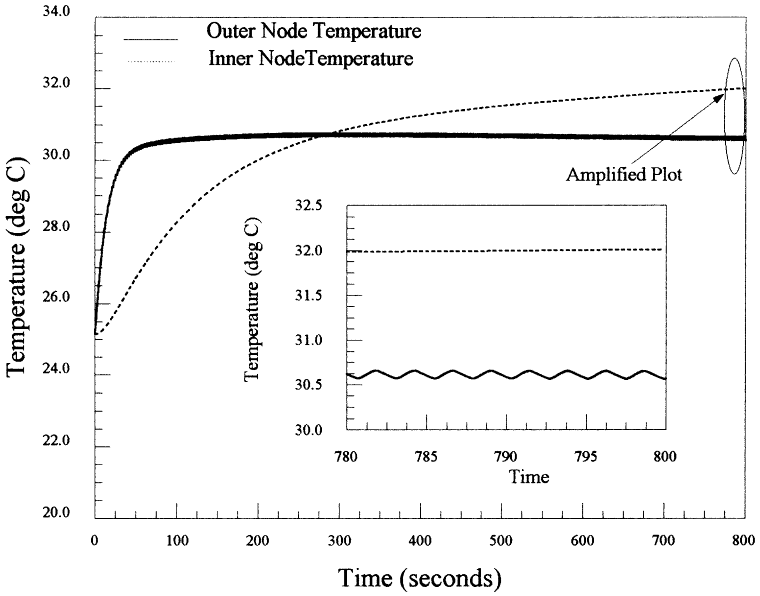

Fig. 6. The temperature variation in time of the fabric inner and outer nodes.

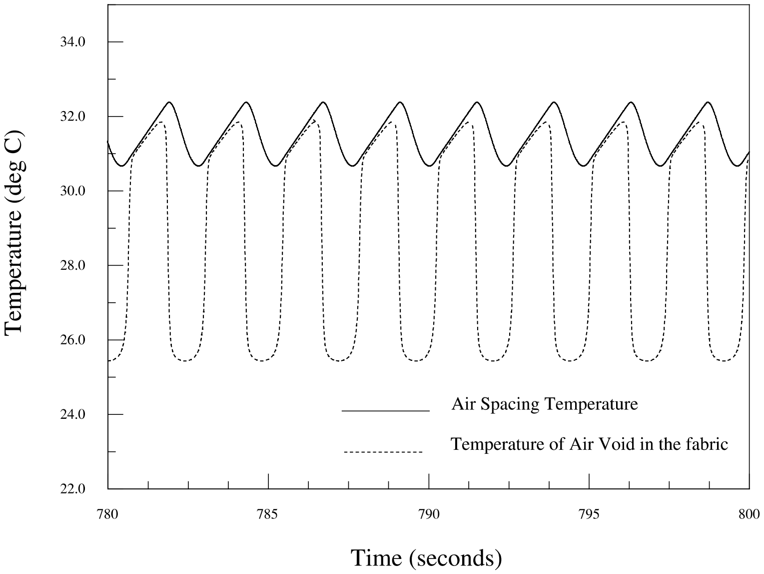

Fig. 7. The air void node and the air spacing temperature variations.

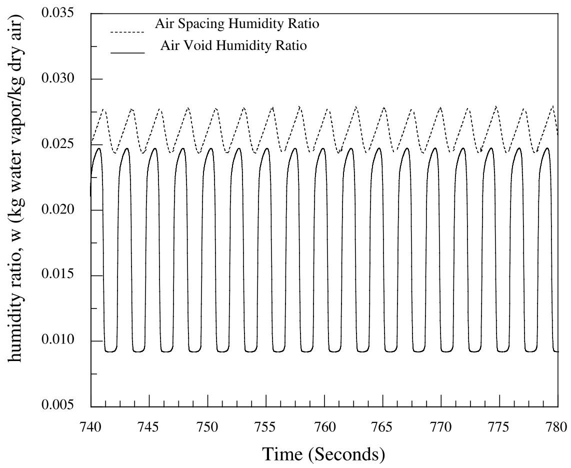

Fig. 8. The variation of the air void and the air spacing humidity ratios.

the isothermal 35 °C surface, its temperature remains close to that temperature but following also a low amplitude sinusoidal variation. However, the air void temperature oscillates in a sinusoidal pattern at a mean value of 30 °C and with about 9 °C amplitude of oscillation. The humidity ratio variation in the air void is significant compared to close to saturation state in the air spacing layer.

The sensible and latent heat losses are estimated using Eq. (16). Fig. 9 shows the predicted steady periodic sensible and latent heat losses from the skin. The heat loss is mainly latent during the downward stroke of the fabric motion, and mainly sensible during the upward stroke. On the same plot, the experimentally measured time-averaged sensible and latent heat losses are shown. The average sensible heat loss calculated from the theoretical model (2.47 W) and the experimentally measured value (3.87 W) agree marginally well with a relative error of 31%. The average latent heat loss calculated from the theoretical model (15.79 W) and the experimentally measured value (11.35 W) agree marginally well with a relative error of 28.8%. If we consider the simplification assumptions of the theoretical one-dimensionally model of the present work, the discrepancy with the experimental data is acceptable. The physics of the process has been captured correctly with the predicted results and the model could very much be improved and then integrated with a general model of the human body system.

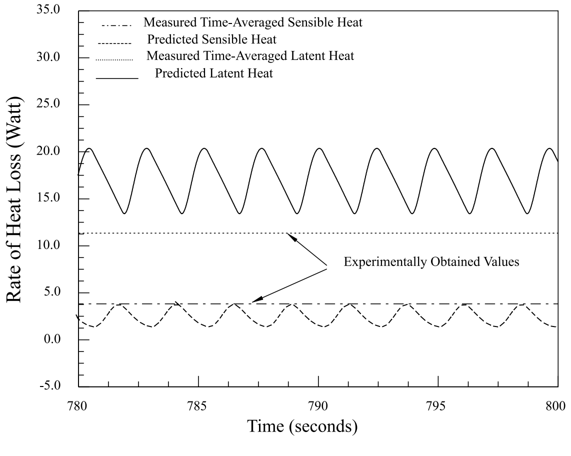

Fig. 9. The predicted steady periodic sensible and latent heat losses from the skin. On the same plot, the experimentally measured time-averaged sensible and latent heat losses are shown.

6. Conclusion

The coupled convection heat and moisture exchange within the clothing system subject to sinusoidal air layer thickness variation about a fixed mean is experimentally investigated and theoretically modeled to predict the periodic fabric regain, the fabric temperature and the transient conditions of the air layer located between the fabric and the skin. The developed mathematical model, for the heat and mass transport through the air spacing layer and the fiber clothing system, has predicted the sensible and latent heat transport quantities at the moist solid boundary. These quantities compared marginally well with the experimentally measured time-averaged values. The discrepancy between measured and calculated heat losses was less than 32%.

The simplicity of the model will allow its integration into other models of walking humans to predict fabric response of heat and moisture transport. Future work will address the effect of oscillation frequency and amplitude, air spacing thickness and fabric kind on the transient heat loss from a moving human body.

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Appendix A

The film coefficients at the skin are needed for the model simulation. However, no correlation for estimating these coefficients is reported in the literature. Most of the research is focused in estimating the heat transfer coefficient at the external exposed surface of

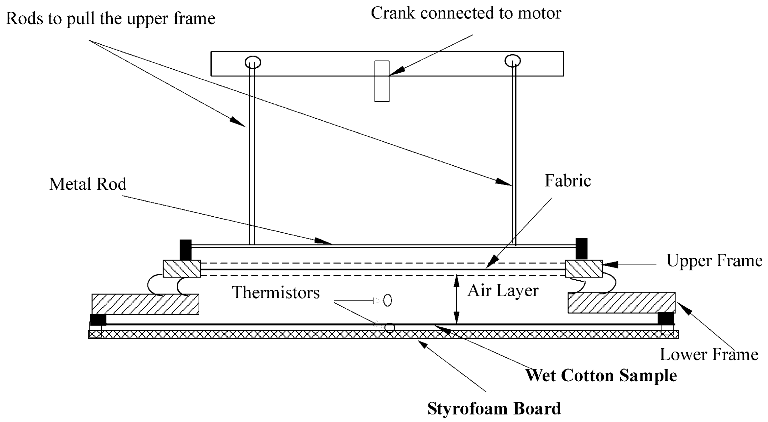

Fig. 10. The experimental setup used for measuring the skin mass transfer coefficient, h_m.

clothing subject to elevated air velocities [17]. Such correlation would not be applicable for estimating the film coefficients in an enclosed air subject to an oscillatory flow. For this reason, additional experiments were conducted to measure the mass transfer coefficient at the skin to the air spacing and then using the Lewis relationship to estimate the heat transfer coefficient as well from the skin to the air layer.

The sweating hot plate in the main experiment was replaced by a water saturated cotton sample (50.8 cm × 50.8 cm). This wet cotton sample representing the skin was placed on top of an insulating Styrofoam board to create an adiabatic saturated boundary condition. The oscillating fabric frame of the previous setup was placed over the wet adiabatic cotton sample. The whole setup (fabric oscillating frame, wetted cotton sample and Styrofoam board shown in Fig. 10) was placed inside the environmental chamber whose temperature conditions were set at 25 °C and 50% RH. At the beginning of the experiment, the saturated fabric sample (skin) was weighed and its weight loss of moisture was monitored every half an hour for a total of 4 h. So every half hour the wet fabric sample was quickly removed and placed inside a plastic bag for weighing using a sensitive scale of accuracy ±0.01 g. The experiment started with oscillating the upper fabric and frame at the same frequency and amplitude conditions of the main experiment. Temperature measurement of the wetted cotton sample was monitored by a thermistor, while the temperature measurement of the air layer was taken by radiation-shielded thermistor. One thermistor was placed on the lower surface of the wet cotton sample and above the Styrofoam board, while the other thermistor was placed in the enclosed air spacing between the oscillating fabric and the wet cotton surface. The accuracy of the temperature readings was ±0.1 °C.

Knowing the amount of water evaporated from the fabric, the temperature of the cotton wet sample and the temperature of the air layer, the skin mass transfer coefficient can be estimated as follows:

$$m_s = h_m A (P_{\text{skin}} - P_{\text{air}}), \tag{A.1}$$

where m_s is the measured mass flux, g/s; P_{air} is the vapor pressure of the air, kPa; P_{skin} is the vapor pressure at the skin, kPa; and A is the area of the fabric cm^2. P_{skin}, is estimated at the equilibrium vapor pressure at the skin temperature which remained at a uniform value of 21.0 ± 0.7 °C. P_{air} is estimated from the temperature of the air layer and from the wet bulb temperature of the air layer. The wet bulb temperature of the air layer is taken as that of the saturated skin temperature since the setup is similar to an adiabatic saturator for the enclosed air. The measured temperature of the wet skin sample did not change since the sample was wet during the time of the experiment. The measured evaporation rate starting from the second hour became steady at a value of 5 g every half an hour from which the mass transfer coefficient (0.00008 kg/s m^2 kPa) was experimentally determined.

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