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Heat and mass transfer in the condensing flow of steam through an absorbing fibrous medium

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Abstract—This paper presents a model for the interactive heat and mass transfer which occurs in the forced convection of steam through an absorbing fibrous textile assembly. Application of the model to the steaming of a wool fabric bed reveals a fast front which is associated with condensation and a sharp rise in temperature, and a slow and much broader front which brings equilibrium to the moisture content of the bed. Steaming a dry wool fabric bed is marked by a characteristic rise in the bed temperature whereas, for a wool fabric bed at a high initial regain, the temperature changes are reflected by the condensing and drying fronts propagating through the bed. Experiments carried out on a specially built steaming apparatus gave good agreement on the fabric temperatures and regains.

1. INTRODUCTION

Many textile processes, such as drying, moisture conditioning and decatizing, involve heat and moisture transfer to fabric. In the pressure-decatizing process wool fabric is steamed at about 120°C, and control of the fabric temperature and regain during this process is critically important to the fabric quality. Currently there is a lack of understanding of the heat and moisture transfer during steaming processes. Measurements of the steam humidity and the fabric regain are not always easy or possible, particularly in a process like pressure decatizing, where steaming is carried out inside a pressurized vessel.

Henry was first to propose a diffusion model [1] and was soon followed by Cassie [2] with the forced convection model for the flow of moist air through a textile fibre assembly. Both models rely on analytical solutions which require assumptions of instantaneous thermal equilibration and mass transfer. Cassie's work demonstrates that a fast and a slow front propagate through the fibre bed. Later experiments confirmed the two fronts but showed that the mass transfer front (slow front) is broadened, unlike that predicted by Cassie's model. Daniels proposed a combined convection–diffusion model [3] to explain the broad mass transfer front; however, McMahon and Downes [4] pointed out that it was due to a definite rate of mass transfer between water vapour and wool fibres.

With the advent of computers, Nordon [5, 6] proposed a forced convective model in which he assumed a finite rate for the mass transfer. Similarly to McMahon and Downes's work, Nordon's work assumes a local thermal equilibrium between vapour and fibre. The solutions from their models are therefore limited to cases of a small difference in temperature between a penetrating gas phase and the fibre bed, and hence to the phenomena associated with the mass transfer front.

However, all previous models for heat and mass transfer in a fibre assembly do not account for the existence of a liquid phase in the bed [7, 8]. During the last two decades many models have been developed for granular beds, insulation, grain, etc. [9–14] with rigorous treatment of the liquid phase and condensation. In spite of that, the steaming or moisture treatments of textile fabrics, due to their unique characteristics and their practical importance, need to be considered separately.

The model presented in this paper accounts for the presence of liquid water in the bed; this enables the model to be applied to a general case of a blend fabric made from non-absorbent and absorbent fibres, or to the case where an absorbent fabric is steamed interleaved with a non-absorbent one. The non-local thermal equilibrium approach of the model is necessary for calculation of the changes associated with the condensation front. The use of the Darcy equation to describe the flow of the steam permits the calculation

NOMENCLATURE

A	area [m^2]
a	fraction of the capillary site
a_s	specific volume [m^{-1}]
$C_{p,i}$	heat capacity [J kg^{-1} K^{-1}]
C	moisture concentration in fibre [kg m^{-3}]
c	constant relates to the adsorption energy
d	fibre diameter [m]
D_f	diffusion coefficient of water in wool fibre [m^2 s^{-1}]
D_v	vapour diffusivity [m^2 s^{-1}]
G	mass flow rate [kg m^{-2} s^{-1}]
H	relative humidity [Pa Pa^{-1}]
h	heat transfer coefficient [W m^{-2} K^{-1}]
h_m	mass transfer coefficient [m s^{-1}]
Δh_{vap}	heat of evaporation or condensation [J kg^{-1}]
Δh_{diff}	differential heat of absorption [J kg^{-1}]
K	permeability [m^2]
k	Kozeny factor (non-dimensional)
L	characteristic length of fabric bed [m]
M	regain or fraction of moisture content in fibre [kg kg^{-1}]
M_e	equilibrium regain of fibre with the steam [kg kg^{-1}]
M_{mo}	regain of fibre at complete monolayer coverage [kg kg^{-1}]
n	number of adsorption layers at the capillary site
P	pressure [Pa]
p	number of adsorption layers at the pore site
T	temperature [K]
t	time [s]
V	volume [m^3]
v	velocity [m s^{-1}]
x	distance [m].

Greek symbols

α	thermal diffusivity [m^2 s^{-1}]
Γ	rate of mass transfer [kg m^{-3} s^{-1}]
γ_{ls}	liquid-to-solid proportionality constant for rate of absorption [kg m^{-3}]
γ_{gs}	gas-to-solid proportionality constant for rate of absorption [kg m^{-3}]
ε	volume fraction [m^{-3} m^{-3}]
Θ	rate of heat transfer [W m^{-3}]
λ_ϕ	effective thermal conductivity of wool fabric [W m^{-1} K^{-1}]
μ	viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}].

Dimensionless variables

E_b^*	normalized volume fraction of absorbed water, $\varepsilon_b/\varepsilon_{b,m}$
E_l^*	normalized volume fraction of liquid accumulation, $\varepsilon_l/\varepsilon_{b,m}$
G^*	normalized mass flow rate, G/G_{in}
Le	Lewis number, α_ϕ/D_ϕ
Pe	Peclet number, vL/α_ϕ
T^*	dimensionless temperature, $(T_s - T_{s,o})/(T_{g,in} - T_{s,o})$
X^*	dimensionless distance, x/L.

Subscripts

a	air
b	bound water
e	equilibrium
f	dry fibre
g	gas phase
i	phase or species
l	liquid phase
m	maximum
s	solid phase
v	vapour
0	initial
ϕ	porous medium.

Symbols

$\langle T \rangle\ (1/V)\int_v T\,\mathrm{d}V$

$\langle T_s \rangle\ (1/V)\int_{v_s} T\,\mathrm{d}V$

$\langle T_s \rangle^s\ (1/V_s)\int_{v_s} T\,\mathrm{d}V.$

Superscripts

cond	condensation
cr	critical value
evap	evaporation
g	gas phase
in	inlet
l	liquid phase
out	outlet
s	solid phase
sat	saturation
*	dimensionless value.

of the steam flow velocity as it varies with the pressure drop across the bed and the permeability of the fabric bed.

2. FORMULATION OF THE PROBLEM

Consider a packed bed consisting of layers of textile fabric subjected to a flow of steam from one side to the other. The packed bed is thermally insulated from the environment and is assumed to exchange heat and mass only with the penetrating gas stream. The ideal gas law is assumed for the gas phase. The flow is considered to be of Darcian type: one-dimensional and natural convection and gravitational effects are ignored. For the range of convective velocities studied, the diffusion of moisture in the gas phase is negligible. The liquid phase is assumed to be immobile and in thermal equilibrium with the solid phase. The heat transfer by radiation and conduction between fibres is also negligible.

The mathematical formulation in this work uses the method of local volume average described by Whitaker [15]. The definitions of the volume average symbols are given in the Nomenclature.

2.1. *The solid phase* (*s*)

In this model, in order to account for the variation in fibre physical properties with the amount of water uptake, the fibres and absorbed moisture are assumed to form a homogenous solid whose properties are specified by the moisture content.

The continuity equation for the solid phase is expressed as

$$\frac{\partial}{\partial t}(\varepsilon_s\langle\rho_s\rangle^s) = \Gamma_{ls}+\Gamma_{gs} \tag{1}$$

where Γ is the rate of mass transfer between the solid phase and other phases.

The solid mass may be expressed in terms of the volume fraction and intrinsic density of dry fibre and bound water; thus

$$\varepsilon_s\langle\rho_s\rangle^s = \varepsilon_f\langle\rho_f\rangle^f+\varepsilon_b\langle\rho_b\rangle^b. \tag{2}$$

The intrinsic density and volume fraction of dry fibres do not vary; therefore equation (1) can simply be expressed as

$$\langle\rho_b\rangle^b\frac{\partial}{\partial t}\varepsilon_b = \Gamma_{ls}+\Gamma_{gs}. \tag{3}$$

When condensation occurs, liquid water formed at the fibre surface is assumed to equilibrate instantaneously to the fibre temperature. The combined thermal energy equation for the solid and liquid phase is expressed as

$$\begin{aligned}[\varepsilon_s\langle\rho_s\rangle^s C_{p,s}+\varepsilon_l\langle\rho_l\rangle^l C_{p,l}]\frac{\partial\langle T_s\rangle^s}{\partial t} &= ha_s[\langle T_g\rangle^g-\langle T_s\rangle^s]\\ &\quad+\Delta h_{vap}(\Gamma_{gs}+\Gamma_{gl})+\Delta h_{diff}(\Gamma_{ls}+\Gamma_{gs}).\end{aligned} \tag{4}$$

2.2. *The liquid phase* (*l*)

The liquid phase accounts for the condensed water present on the fibre surface before it becomes absorbed into the fibre or re-evaporates to the gas phase. For the normal physical conditions which prevail during steaming of a textile assembly, the volume fraction of condensed water at any stage is well below the critical value for mobility [13]. The model therefore assumes no movement of liquid water, and the continuity equation for the liquid phase is expressed by

$$\frac{\partial}{\partial t}(\varepsilon_l\langle\rho_l\rangle^l) = \Gamma_{sl}+\Gamma_{gl}. \tag{5}$$

The thermal equilibrium equation for the liquid phase is given in combined form with that of the solid phase in equation (4).

2.3. *The gas phase* (*g*)

The pressure difference between the two sides of the bed causes the steam to flow and displace air as it penetrates the bed. In normal industrial steaming processes the velocity of steam-flow through the fabric bed is small and the flow can be assumed to be of Darcian type [16]. For a constant pressure drop, the convective velocity of the flow depends on the permeability of the bed, which changes as the steaming progresses, and is calculated by

$$\begin{aligned}\frac{\partial}{\partial x}\langle P_g\rangle^g &= \frac{\partial}{\partial x}[\langle P_v\rangle^g+\langle P_a\rangle^g]\\ &= \frac{(P_{in}-P_{out})}{L} = -\frac{\mu_g}{K}\langle v_g\rangle\end{aligned} \tag{6}$$

where K is the fabric permeability, calculated from the Kozeny–Carman equation [17]:

$$K = \frac{\varepsilon_g^3}{ka_s^2(1-\varepsilon_g)^2} \tag{7}$$

where ε_g is linked to ε_s and ε_l through the volume constraint: $\varepsilon_s+\varepsilon_l+\varepsilon_g = 1$; k is the Kozeny factor. In a bed of fibre with circular cross-section, its value is given by Labrecque's empirical relation [18]:

$$k = 5.0+\exp[14(\varepsilon_g-0.8)]. \tag{8}$$

The specific surface area (a_s), calculated for a fibre bed of $(1-\varepsilon_s)$ porosity and indefinite fibre length is given as

$$a_s = \frac{\text{total solid surface}}{\text{volume of unit bed}} = \frac{4\varepsilon_s}{d}. \tag{9}$$

Inert air does not exchange mass with fibre; therefore, in the mass balance equation only water vapour is considered:

$$\frac{\partial}{\partial t}(\varepsilon_g\langle\rho_v\rangle^g)+\frac{\partial}{\partial x}(\langle\rho_v\rangle^g\langle v_g\rangle) = -\Gamma_{gs}-\Gamma_{gl}. \tag{10}$$

The thermal equilibrium equation will account for the brief existence of air inside the bed. The combined thermal energy equation is expressed as

$$\begin{aligned}&[\varepsilon_g\langle\rho_v\rangle^g C_{p,v}+\varepsilon_g\langle\rho_a\rangle^g C_{p,a}]\frac{\partial}{\partial t}\langle T_g\rangle^g\\ &\quad+[\langle\rho_v\rangle^g C_{p,v}\langle v_g\rangle+\langle\rho_a\rangle^g C_{p,a}\langle v_g\rangle]\frac{\partial}{\partial x}\langle T_g\rangle^g\\ &\quad= -ha_s(\langle T_g\rangle^g-\langle T_s\rangle^s).\end{aligned} \tag{11}$$

2.4. *The heat and mass transfer rates*

The first term on the right-hand side of equation (4) is the rate of convective heat transfer at the fibre–gas interface, expressed as

$$\Theta = ha_s(\langle T_g\rangle^g-\langle T_s\rangle^s). \tag{12}$$

The condensation rate is proportional to the vapour density difference between that in the gas phase and that at the condensing surface, and is given as

$$\Gamma_{\mathrm{lg}}^{\mathrm{cond}} = h_{\mathrm{m}} a_{\mathrm{s}}(\langle\rho_{\mathrm{v}}\rangle^{\mathrm{l}} - \langle\rho_{\mathrm{v}}\rangle^{\mathrm{g}}) \tag{13}$$

where h_{m} is the mass transfer coefficient that is related to the heat transfer coefficient by the heat and mass transfer analogy [19]:

$$h_{\mathrm{m}} = \frac{h}{\langle\rho_{\mathrm{g}}\rangle^{\mathrm{g}}\, C_{\mathrm{p,g}}\, Le^{2/3}}. \tag{14}$$

The evaporation rate of the liquid water is proportional to the water vapour density difference and the fraction of surface covered by liquid water which, according to this model, is proportional to the normalized volume fraction of the liquid phase:

$$\Gamma_{\mathrm{lg}}^{\mathrm{evap}} = h_{\mathrm{m}} a_{\mathrm{s}}(\langle\rho_{\mathrm{v}}\rangle^{\mathrm{l}} - \langle\rho_{\mathrm{v}}\rangle^{\mathrm{g}}) \frac{\varepsilon_{\mathrm{l}}}{\varepsilon_{\mathrm{l}}^{\mathrm{cr}}} \tag{15}$$

where $\varepsilon_{\mathrm{l}}^{\mathrm{cr}}$ is the critical value of the liquid fraction at which the liquid phase becomes mobile. $\varepsilon_{\mathrm{l}}^{\mathrm{cr}} = 0.1\varepsilon_{\mathrm{g}}$ for a porous bed as assumed in ref. [13].

The mass transfer rate of liquid water to the absorbing fibre is given as

$$\Gamma_{\mathrm{ls}} = -\Gamma_{\mathrm{sl}} = h_{\mathrm{m}} a_{\mathrm{s}} \gamma_{\mathrm{ls}} \frac{\varepsilon_{\mathrm{l}}}{\varepsilon_{\mathrm{l}}^{\mathrm{cr}}} \left(\frac{M_{\mathrm{sat}}}{M_{\mathrm{s}}} - 1 \right). \tag{16}$$

The relative humidity of the surrounding determines the equilibrium regain in wool fibre. The adsorption isotherm represents that relationship at a fixed temperature. For an absorbent material, two of the present authors have derived an adsorption isotherm equation from the multilayer adsorption theory [20], given in the form

$$M_{\mathrm{e}} = M_{\mathrm{mo}} \frac{cH}{1+cH} \left[\frac{1 - aH^{n} - (1-a)H^{p}}{1-H} \right]. \tag{17}$$

In wool fibre, the absorption of moisture changes considerably with temperature. The equation expressing the equilibrium amount of moisture absorbed as a function of the relative humidity and temperature is given elsewhere [20].

The regain difference is the driving force for the mass transfer between wool fibre and steam which is expressed as follows:

$$\Gamma_{\mathrm{gs}} = h_{\mathrm{m}} a_{\mathrm{s}} \gamma_{\mathrm{gs}} (M_{\mathrm{e}} - M_{\mathrm{s}}) \tag{18}$$

where γ_{gs} is the proportionality constant for the absorption of water vapour in wool fibre. It may be linked to the diffusion coefficient of moisture in fibre by equating the mass flux through the vapour–fibre interface with that calculated from the steady-state diffusion within the fibre [21]:

$$\gamma_{\mathrm{gs}} = \frac{8D_{\mathrm{f}}\langle\rho_{\mathrm{f}}\rangle^{\mathrm{f}}}{h_{\mathrm{m}} a_{\mathrm{s}} d^{2}}. \tag{19}$$

2.5. *The physical relations*

The equation of state for the gases and the equation expressing the saturated vapour pressure as a function of the steam temperature can be found in most physics books or in ref. [21]. Equations expressing the differential heat of absorption, heat capacity and density of wool fibre as functions of the regain and temperature can be found in ref. [21]. The dependence of these properties on temperature and regain causes the system of differential equations balancing the heat and mass transfer to be highly non-linear and it is difficult to obtain the analytical solutions. A numerical method was therefore used to solve them.

3. SOLUTION METHOD AND EXPERIMENTAL VERIFICATION

3.1. *Solution method*

The explicit backward finite difference scheme was used to solve the differential equations (3)–(5), (10) and (11) for numerical solutions. The computation is greatly simplified by the use of the rate equations (12), (13), (15), (16) and (18). For the initial conditions, it is assumed that the textile assembly is uniform in temperature and moisture content and in equilibrium with the moist air surrounding it:

$$\varepsilon_{\mathrm{l}}|_{x}^{t=0} = 0 \quad \langle T_{\mathrm{s}}\rangle^{\mathrm{s}}|_{x}^{t=0} = \langle T_{\mathrm{g}}\rangle^{\mathrm{g}}|_{x}^{t=0} = T_{\mathrm{s,0}}$$

$$\langle P_{\mathrm{v}}\rangle^{\mathrm{g}}|_{x}^{t=0} = \langle P_{\mathrm{v}}\rangle^{\mathrm{s}}|_{x}^{t=0} = P_{\mathrm{s,0}} = F[M_{0}, T_{\mathrm{s,0}}]. \tag{20}$$

The boundary conditions on the entrance and the exit sides of the packed bed are

$$\langle T_{\mathrm{g}}\rangle^{\mathrm{g}}|_{x=0}^{t} = T_{\mathrm{g}}^{\mathrm{in}} \quad H_{\mathrm{g}}|_{x=0}^{t} = H_{\mathrm{g}}^{\mathrm{in}}$$

$$\langle P_{\mathrm{g}}\rangle^{\mathrm{g}}|_{x=0}^{t} = P_{\mathrm{g}}^{\mathrm{in}} \quad \langle P_{\mathrm{g}}\rangle^{\mathrm{g}}|_{x=\mathrm{L}}^{t} = P_{\mathrm{g}}^{\mathrm{out}}. \tag{21}$$

Given the initial and boundary conditions, the condensation/evaporation rates and the heat and mass transfer rates at the interface are calculated. The amounts of energy transferred, which relate to the latent heat of condensation and the differential heat of absorption coupled with the mass transfer, are then computed. Changes in the temperatures of the gas phase and fibre are calculated by equations (4) and (11). The fibre regain at the next grid point is evaluated by equation (3), the liquid volume fraction by equation (5), the vapour density by equation (10). The vapour pressure and relative humidity in the gas phase are then obtained and the equilibrium regain related to that condition in the gas phase calculated by equation (17). The partial pressure of air is calculated from equation (6), and, with the equation of state, the phase average density can be calculated. The condensation/evaporation rates are then calculated by equations (13)–(15), and the absorption/desorption rates by equations (16)–(19). At every grid point the volume fraction of the solid phase is calculated by equation (2) and the fabric permeability by equations (7)–(9), and, from these values, the average flow velocity is evaluated by equation (6). The numerical values of the various physical parameters are given in Table 1.

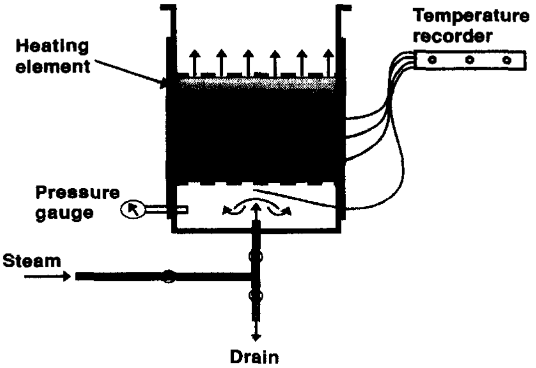

Fig. 1. Sketch of the experimental set-up for the steaming of wool fabric.

3.2. *Experimental set-up*

The sketch of the experimental apparatus is given in Fig. 1. The steaming chamber is a vertical cylinder sealed at the bottom and open to atmospheric pressure at the top. The side wall of the chamber is wrapped by a heating element to pre-heat it to the steam temperature, in order to prevent condensation. The fabric is stacked one layer after another vertically on top of a perforated plate. Another perforated plate is placed on top of the fabric bed to constrain the bed volume. The steam flows in through a regulating valve, excess water being drained off before it enters the chamber to ensure its dryness. A cone is placed above the steam inlet to disperse the flow of steam.

The pressure in the lower compartment and the temperatures at various positions into the bed are monitored. The temperatures sensed by the copper–constantan thermocouples were recorded by a data logger at 1-s intervals and ±0.1°C resolution. The moisture content of various layers of the bed was determined for a number of steaming times by interrupting the steaming process and withdrawing pieces of fabric from the bed. Ten layers of fabric at a time were grasped by a hand placed in a plastic bag, which was quickly pulled inside out to enclose the fabric. The weight increase was determined from the initial weight and expressed as the regain increase.

4. RESULTS AND DISCUSSION

4.1. *Steaming a dry wool fabric bed*

The first case studied was that of a comparatively dry wool fabric bed in order to investigate a situation in which a large amount of heat of absorption is released. The computation was carried out for a wool fabric bed initially of 2% regain, 0.65 porosity and 30°C in temperature. At the inlet side of the bed, the condition of steam chosen was temperature 100.9°C, pressure 104 kPa and relative humidity 100%. The outlet side of the bed is open to atmospheric air at 101 kPa. Because of the nature of the problem, which involves very rapid heat and mass transfer through condensation, a very fine grid of 0.05 s in time and 0.2 mm in space was employed to ensure the stability of the computations.

The early stage of the steaming process is marked by a very distinctive front which sweeps through the bed. It is called the heat transfer front because with the front the bed temperature is brought up to the steam temperature. With steam, the heat transfer front is very notable due to the simultaneous condensation and absorption which releases a large amount of energy and quickly raises the fabric temperature.

Figure 2(a) gives a picture of the evolution of the condensate volume fraction. It shows that the condensed water forms and rapidly disappears, as it is absorbed into the fibre and/or evaporated back into the gas phase, soon after the heat transfer front has passed through.

Figure 2(b) shows the evolution of the fabric temperature across the bed. It takes about 50 s for the front to move through a 5 cm bed. At this stage the bed temperature is higher than the entry steam temperature and varies across the bed. This is due to the varying level of heat released as the dry wool absorbs moisture.

The regain profiles given in Fig. 2(c) show that the fabric regain across the bed quickly increases by about 5% as the heat transfer front moves through. A state is reached where, except for a few layers at the steam inlet side where the regain is rising, a uniform regain exists across the bed for up to 30 min before the slow mass transfer front starts to advance. This phenomenon is of interest in various industrial processes of steam setting wool fabric. Ideally the fabric bed should be brought to a uniform regain during steaming so that a consistent degree of set can be imparted to the fabric throughout the bed.

Figure 3 presents the profiles of a number of interesting variables across the bed, after 25 s of elapsed steaming time. For the case under consideration the frontal changes in the various variables occur in the following order: steam temperature, fabric temperature, mass flow of water vapour, and absorbate volume. The condensate accumulation is small compared to the absorbate volume. This is due to the high absorption rate of the dry fabric used in this case.

Under the conditions considered, it would take more than 10 h for the mass transfer front to propagate through the fabric bed. After the mass front has passed through, no further change will take place as the fabric bed will then be in equilibrium with the steam penetrating it. As can be seen in Fig. 2(c), the mass transfer front is noticeable some 10 min after steaming has started, marked by the rise in the regain at the steam inlet side. As this happens the fabric temperature [Fig. 2(b)] gradually drops to the temperature of the entering steam.

4.2. *Comparison with experimental results*

A twill woven fabric made from R56/2 tex yarns and 24-μm-diameter pure wool fibres and having an aerial density of 260 g m^{-2} was used in the experiment.

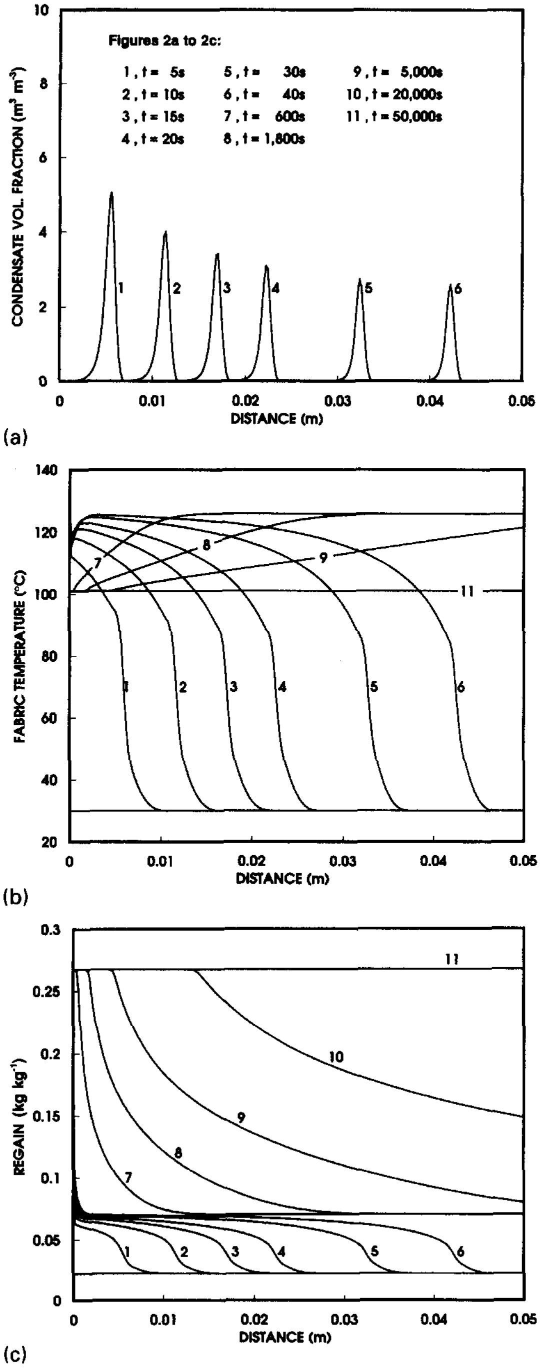

Fig. 2. Evolution of field variables during steaming of an initially dry wool fabric assembly.

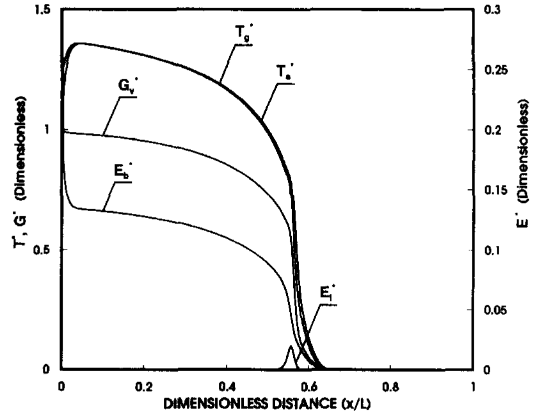

Fig. 3. Variations of the field variables across a dry wool fabric bed in association with the mass transfer front.

The fabric was dried in an oven to 2% regain, then packed into the steaming cylinder to a porosity of 0.65. Three copper–constantan thermocouples of 0.2 mm diameter were placed in the fabric bed at distances of 0.8, 2.2 and 4.8 cm from the inlet side to record the temperature during steaming. The fabric temperature was at 37°C when the steaming started. The supplied steam was at 130 kPa gauge pressure and 125°C temperature, measured in the pipe. When steam was released into the chamber, the pressure dropped to 3 kPa (gauge pressure) and the temperature was recorded at 104°C. The steam was then taken to a condition of about 100°C and 100% rh by allowing it to flow through a thick pad of polyester fabric [21], prior to entering the wool fabric bed.

Figure 4 shows the fabric temperatures recorded at the positions mentioned. The theoretical fabric temperatures are given for comparison. In computing the theoretical values, it was found that good agreement with the experimental values is obtained by choosing appropriate values for the heat transfer coefficient and diffusion coefficient of moisture in fibre. Both experimental and calculated results show that, after the heat transfer front has moved through the bed, a ceiling temperature is attained across the bed that lasts until the mass transfer front arrives.

Figure 5 shows the fabric regains measured experimentally at various distances into the bed after 30 s and 3, 10 and 30 min steaming. The calculated results are shown for comparison. These results confirm that, except for the position near the steam entry side, there

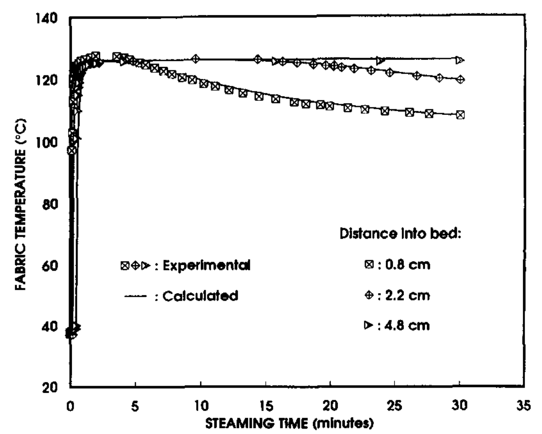

Fig. 4. Fabric temperature measured during steaming of a dry wool fabric bed, shown in comparison with values calculated from the model.

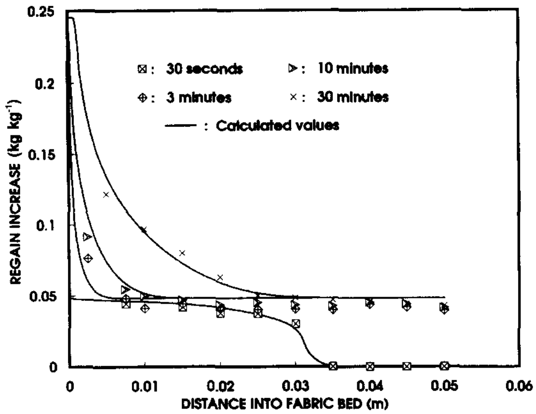

Fig. 5. Fabric regain across the fabric bed measured after an elapsed time of steaming of a dry wool fabric bed, shown in comparison with values calculated from the model.

is a quite uniform increase of about 5% in fabric regain across the bed and that this regain level is maintained for some time after the heat transfer front has moved through.

The values for the diffusion coefficient of water in wool fibre reported from the literature are often scattered [22]. This is because the diffusion coefficient varies with temperature and also increases by as much as three orders of magnitude from dry to a high regain level in wool fibre [23]. For simplicity the computation in this work assumes a constant value for the diffusion coefficient. This is a value (given in the Appendix) chosen within the range of the values reported in the literature which gives good agreement with our own experimental data.

There is no previous work reporting values for the heat transfer coefficient of textile fibres with steam or moist air. Theoretical calculation of this value for a given bed structure involves some geometrical factors which need to be determined experimentally. With the lack of a direct measurement, a value for the heat transfer coefficient was chosen which, when incorporated into the current model, gives a good simulation of the measured temperature curves. This value of heat transfer coefficient was also found appropriate when applied to other textile fibre assemblies such as cotton, nylon and polyester [21].

4.3. *Steaming a wool fabric bed of high initial regain*

To obtain a high degree of permanent set, a wool fabric should have sufficient moisture content to facilitate, under the action of heat, the breaking and reforming of chemical bonds within the fibre. To achieve this, in certain fabric finishing practices the fabric has moisture added to obtain a higher regain prior to steaming. Wool fabric at high regain absorbs less moisture and, for the same amount of moisture absorbed, releases less heat. This will have an effect on the heat and mass transfer, and in particular on the variations in temperature, condensation and absorption/desorption in the system. Excessive condensation at the steam entry side can cause fabric dimensional change and undesirable effects on fabric properties.

In order to study the condensation problem, a case of a wool fabric of high regain was investigated. As previously, the fabric bed was open at one end to the atmosphere and its chosen initial temperature was again 30°C. The initial regain in the fabric was 25%, which, under the same constraint in volume, reduced the bed porosity to 0.61. The steam pressure at the entry side was chosen at 109 kPa (real pressure) to get the same value of the Peclet number as in the previous case. The steam entering the fabric bed was superheated at a chosen 120°C and 53% rh in order to study the drying of the bed after the initial period of condensation.

As would be expected with a less absorbing medium, the condensate volume fraction of a high regain fabric bed increases substantially. Figure 6(a) shows an initial sharp increase in the condensate fraction corresponding to the arrival of the heat transfer front. The condensate fraction then decreases toward a quasi-equilibrium level which remains little changed for an extended period of time until it quickly reduces to zero as the drying front sweeps through. The rise in fabric temperature with the heat transfer front in this case is limited to a value just above 100°C (Fig. 6(b)) for a long period of time before the drying front moves in and raises it to 120°C.

Figure 6(c) shows that the changes in fabric regain associated with the heat transfer front are more diffuse than those associated with the mass transfer (or drying) front. At equilibration, which is after about 90 min of steaming, the moisture regain throughout the bed reduces to 9%, a value which relates to the 53% rh in the steam. It is also seen that, although the initial regain was higher than the equilibrium regain, condensation and subsequent absorption from condensate water increased the regain in the fabric to a saturated value of 27% during the early stage.

Figure 7 presents profiles of the heat transfer front similar to those given in Fig. 3 for the previous case, but taken at the 40th second of the elapsed steaming time. Because of the higher heat capacity of the high regain fabric bed, the heat transfer front moves at a much slower speed even for the same value of the Peclet number. The frontal changes are very sharp: note that the volume fraction of condensate accumulation is much higher than that of the absorbate.

The previous section, on the steaming of a dry fabric bed with saturated steam, shows that, unless the time involved is excessively long, the fabric regain will remain low. Furthermore, in the section just discussed on a fabric bed of high initial regain, an increase in the fabric regain is observed during the initial period of steaming, although the supplied steam is superheated. Wool fabric is normally steamed for less than 5 min in an industrial process. In that case, it is the initial fabric regain, not the steam condition, that governs the fabric regain during steaming.

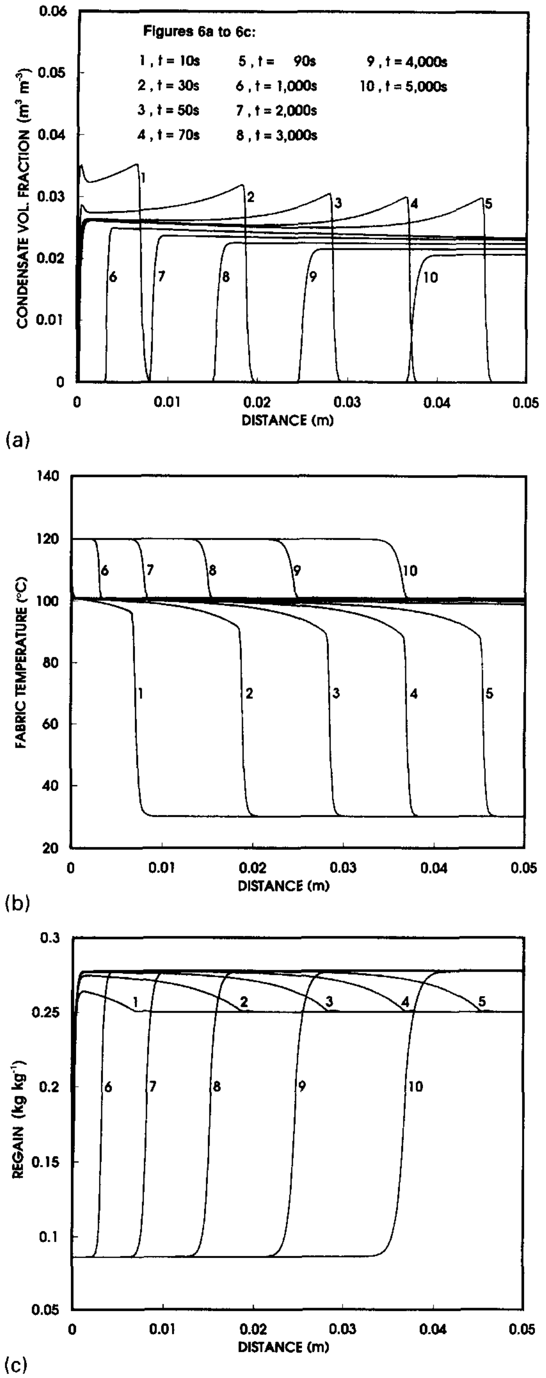

Fig. 6. Evolution of field variables during steaming of an initially high regain wool fabric assembly.

5. CONCLUSION

The interactive heat and mass transfer between penetrating steam and a wool fabric assembly has been studied both theoretically and experimentally. The local volume average theory was used in formulating a set of differential equations to describe such a system of complex interactive heat and mass transfer. The frontal characteristics of the process were clearly observed in the experiment as well as demonstrated in the calculated results. The work proves that the so-called state of 'transient equilibrium' [23] does exist during the steaming of a fabric bed where the fabric temperature and regain, after an initial sharp change, remain constant for an extended period of time.

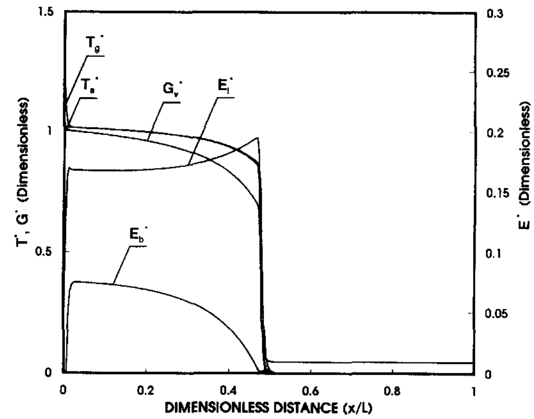

Fig. 7. Variations of the field variables across a high regain wool fabric bed in association with the heat transfer front.

While the model is capable of simulating any steaming process, an accurate quantitative prediction of the behaviour of a certain system requires knowledge about the flow regime and the rates of heat and mass transfer between the various phases. The vapour flow was assumed to be uniform on a macroscopic scale, whereas a detailed treatment should account for the preferential flow of steam around tightly woven yarns. The transfer of heat and mass in the system was characterized by the heat transfer coefficient and the two rate constants representing the fibre surface characteristics and the diffusivity of the absorbate. More work may be needed to account for the variation of the diffusivity of a liquid in an absorbent material with temperature and concentration. However, for applications in the modelling of industrial steaming processes, which often involve short steaming times and rapid heat and moisture transfer, the approach of using a constant transfer rate, employed in this model, was shown to be appropriate.

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APPENDIX: NUMERICAL VALUES

Properties	Units	Dry bed	High regain bed
P_{out}	[kPa]	101	101
P_{in}	[kPa]	104	110
L	[m]	0.064	0.064
$T_{\mathrm{s,0}}$	[K]	303	303
$T_{\mathrm{g,in}}$	[K]	373.9	393
λ_ϕ	[W m^{-1} K^{-1}]	0.038	0.038
D_{a}	[m^2 s^{-1}]	2.5×10^{-5}	2.5×10^{-5}
$D_\phi \approx \varepsilon_{\mathrm{g}} D_{\mathrm{a}}$	[m^2 s^{-1}]	1.6×10^{-5}	1.6×10^{-5}
$\alpha_\phi = \lambda_\phi/(\rho_{\mathrm{v}} C_{\mathrm{p,v}})$	[W m^{-1} K^{-1}]	3.0×10^{-5}	3.0×10^{-5}
Δh_{av}	[J kg^{-1}]	311.6	311.6
R	[J mol^{-1} K^{-1}]	8.31	8.31
$C_{\mathrm{p,a}}$	[J kg^{-1} K^{-1}]	1005	1005
$C_{\mathrm{p,v}}$	[J kg^{-1} K^{-1}]	2010	2010
h	[W m^{-2} K^{-1}]	2.88	2.88
γ_{ls}	[kg m^{-3}]	0.15	0.15
D_{f}	[m^2 s^{-1}	1.5×10^{-13}	1.5×10^{-13}
ε_{g}		0.65	0.61
M_0		0.02	0.25
H_0		1.00	0.55
$Pe = v^* L/\alpha_\phi$		101.3	104.8
$Le = \alpha_\phi/D_\phi$		1.99	1.99
M_{m0}	[kg kg^{-1}]	0.0831	0.0831
a		0.88	0.88
c		8.5	8.5
n		3	3
p		18	18