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THERMAL ANALYSIS OF DRYING PROCESS
A theoretical approach

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Abstract

In this paper, the mathematical relations are reviewed and then they are developed which may be used to describe the drying behaviour of carpet in a combined microwave and convective environment. The effect of important parameters during drying process are discussed and their influence are examined in detail using the model.

Keywords: heat and mass transport, microwave assisted drying, theoretical approach, wet body drying behaviour

Introduction

Although through drying of carpet is an old and well established process, it is largely controlled by rule of thumb. This is not so much due to a lack of understanding of the basic physical principles involved as due to a lack of knowledge of the rates of various transfer mechanisms and how they interact. The type of information required for the application of modern control techniques to the drying process of carpet is still largely unknown. The present study is part of a more general attempt to analyze heat and mass transfer in carpet in terms of basic transfer mechanisms in order that a mathematical description of the overall process can be established. In the meantime, the complexity of the problem makes it doubtful that it will ever be possible, or indeed economic, to find a complete solution. However, an analysis like the present one can contribute some useful general principles which may help to develop leather drying technology.

Among the many processes that are performed in the carpet industry, drying has an essential role: by this means, carpet can aquire their final texture, consistency and flexibility. Carpet fabrication has become an important industrial development worldwide, similar to other technologically advanced process industries. However, some of the unit operations involved in this industry, especially the drying process, are still based on empiricism and tradition, with very little use of scientific principles. Widespread methods of carpet drying all over the world are mostly convective meth-

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ods requiring a lot of energy. Specific heat energy consumption increases, especially in the last period of the drying process, when the moisture content of the carpet approaches the value at which the product is storable.

The cost of drying carpets, which is done toward the end of manufacturing process, is quite high. A very common method of removing water from carpet is convective drying. Hot air is used as the heat transfer medium and is exhausted to remove vaporized water. Considerable thermal energy, about 30% of the total energy used, is required to heat make-up air as the hot air is exhausted. Thus, reducing the amount of exhaust is clearly a way to conserve energy, but there is little in the literature that can be used as guidelines for optimizing dryer exhaust flow. In this case the effect of humidity on the drying rates of carpet tile should studied.

When the water is deep within the carpet, combined microwave and convective drying, which have faster heat and mass transfer, may be a better choice. To fully understand the heat and mass transfer phenomenon occurring within the carpet during combined microwave and convective drying, it is required to analyse the moisture, temperature, and pressure distributions generated throughout the process. The water remaining in the carpet is 50–60% times the mass of carpet after mechanical removal is in its thermodynamically favorable position, largely because the low viscosity of the water and connectivity of the pores insure rapid equilibration. It is approximated the pores as essentially cylindrical, with their axis vertical to the carpet backing. The amount of porosity, i.e., the volume fraction of voids within the carpet, determines the capacity of a carpet to hold water; the greater the porosity, the more water the carpet can hold. The carpet is able to absorb 6 times its mass in water. When the water content is reduced to roughly 50–60% by mechanical extraction, free water is probably situated in pores with an effective capillary diameter of up to 200 μm. The occupied pores are distributed throughout the carpet pile thickness and largely within the yarns.

The flow of air through carpet dryers is very complex, and neither simple concurrent or countercurrent flow of air and material takes place. Usually there are a set of well mixed zones, throughout which the drying conditions are effectively uniform. The commonest strategy for regulating a dryer’s behaviour is feedback control, in which the controlled variables (such as the moisture content of the material) is compared with the desired set point. The difference signal, suitably processed by the controller, is then used to modulate the input parameter being used as the control variable. An ideal three-term controller incorporates proportional, integral and derivative action. The proportional term gives a rapid response to an error signal, but the controlled variable is permanently offset from its desired value. The integral function compensates for the steady-state error. Derivative action is rarely used, except with well defined signals, because noise in the signal can confuse the controller, resulting in a hunting action about some mean value. The difficulties in obtaining online measures of a material’s moisture content has led to the use of environmental control of the humidity or temperature within the drying chamber. This strategy, however, can lead to inadequate control, as the wet-bulb depression is the driving force for drying. Use of the dry-bulb temperature or relative humidity of the bulk air as the control variable will only be satisfactory as long as the surface conditions of the material remain constant. The difference in temperature between the surface and the bulk air will give a measure of the surface moisture content, provided the material is hygroscopic and all unbound moisture has been driven off.

Background

In general, drying means to make free or relatively free from a liquid. We define it more narrowly in this paper as the vaporization and removal of water from a material. The typical drying curve begins with a warm-up period, where the material is heated and the drying rate is usually low. The drying rate can be negative in the warm-up period if the gas stream is humid enough. As the material heats up, the rate of drying increases to peak rate that is maintained for a period of time known as the constant rate period. Eventually, the moisture content of the material drops to a level, known as the critical moisture content, where the high rate of evaporation cannot be maintained. This is the beginning of the falling rate period. During the falling rate period, the moisture flow to the surface is insufficient to maintain saturation at the surface. This period can be divided into the first and second falling rate periods. The first falling rate period is a transition between the constant rate period and the second falling rate period. In the constant rate period, external variables such as gas stream humidity, temperature, and flow rate dominate. In the second falling rate period, internal factors such as moisture and energy transport in the carpet dominate.

Although much of the water is removed in the constant rate period of drying, the time required to reduce the moisture in the product to desired value can depend on the falling rate period. If the target moisture content is significantly lower than critical moisture content, the drying rates in the falling rate period become important.

It has been recognized that microwave could perform a useful function in carpet drying in the leveling out of moisture profiles across a wet sample. This is not surprising because water is more reactive than any other material to dielectric heating so that water removal is accelerated.

Many investigators have attempted to explain the effect of humidity drying rates and the existence of inversion temperatures [1–9]. The explanations are usually based on changes that occur in convective heat transfer, radiative heat transfer, and mass transfer as the humidity and temperature of the gas stream change. We will briefly discuss these explanations.

At a given gas stream temperature, convective heat transfer rate can change as the humidity in the gas stream is varied, because product temperature and fluid properties vary with humidity. These effects can be explained using the following relationship for the convective heat transfer rate:

$$\frac{q}{A}=h(T_{\infty}-T_{\mathrm{S}})=h\Delta T$$

where q/A – convective heat transfer per unit surface area A, h – heat transfer coefficient, T_{∞} – free stream temperature of the drying medium, T_{S} – surface temperature of material being dried.

Since product temperature is dependent on humidity, clearly ΔT is also dependent. Further, the heat transfer coefficient h is a function of both product temperature and fluid properties. Thus, the convective heat transfer rate changes with humidity, as does the drying rate of a material. However, drying in air will always have an advantage over drying in steam because ΔT is larger for drying in air; this is a consequence of T_S being very nearly the wet bulb temperature. The wet bulb temperature is lowest for dry air, increases with increasing humidity, and reaches the saturation temperature of water for a pure steam environment. Thus, ΔT_{AIR} will be larger than ΔT_{STEAM}, but $\Delta T_{AIR}/\Delta T_{STEAM}$ decreases with increasing T_∞. Further, the heat transfer coefficient increases with humidity. Apparently, the net effect of the changes in h and ΔT is that the convective heat transfer rate increases faster for steam than for air with increasing temperature.

King and Cassie [10] conducted an experimental study on the rate of absorption of water vapor by wool fibers. They observed that, if a textile is immersed in a humid atmosphere, the time required for the fibers to come to equilibrium with this atmosphere is negligible compared with the time required for the dissipation of heat generated or absorbed when the regain changes. McMahon and Watt [11] investigated the effects of heat of sorption in the wool-water sorption system. They observed that the equilibrium value of the water content was directly determined by the humidity but that the rate of absorption and desorption decreased as the heat-transfer efficiency decreased. Heat transfer was influenced by the mass of the sample, the packing density of the fiber assembly, and the geometry of the constituent fibers. Crank [12] pointed out that the water-vapor-uptake rate of wool is reduced by a rise in temperature that is due to the heat of sorption.

The dynamic-water-vapor-sorption behavior of fabrics in the transient state will therefore not be the same as that of single fibers owing to the heat of sorption and the process to dissipate the heat released or absorbed.

Henry [13, 14] was who the first started theoretical investigation of this phenomenon. He proposed a system of differential equations to describe the coupled heat and moisture diffusion into bales of cotton. Two of the equations involve the conservation of mass and energy, and the third relates fiber moisture content with the moisture in the adjacent air. Since these equations are non-linear, Henry made a number of simplifying assumptions to derive an analytical solution.

In order to model the two-stage sorption process of wool fibers, David and Nordon [15] proposed three empirical expressions for a description of the dynamic relationship between fiber moisture content and the surrounding relative humidity. By incorporating several features omitted by Henry [13] into the three equations, David and Nordon [15] were able to solve the model numerically. Since their sorption mechanisms (i.e. sorption kinetics) of fibers were neglected, the constants in their sorption-rate equations had to be determined by comparing theoretical predictions with experimental results.

Farnworth [16] reported a numerical model describing the combined heat and water-vapor transport through fibers. The assumptions in the model did not allow for the complexity of the moisture-sorption isotherm and the sorption kinetics of fibers. Wehner *et al*. [17] presented two mechanical models to simulate the interaction between moisture sorption by fibers and moisture flux through the void spaces of a fabric. In the first model, diffusion within the fiber was considered to be so rapid that the fiber moisture content was always in equilibrium with the adjacent air. In the second model, the sorption kinetics of the fiber were assumed to follow Fickian diffusion. In these models, the effect of heat of sorption and the complicated sorption behavior of the fibers were neglected.

Li and Holcombe [18] developed a two-stage model, which takes into account water-vapor-sorption kinetics of wool fibers and can be used to describe the coupled heat and moisture transfer in wool fabrics. The predictions from the model showed good agreement with experimental observations obtained from a sorption-cell experiment. More recently, Li and Luo [19] further improved the method of mathematical simulation of the coupled diffusion of the moisture and heat in wool fabric by using a direct numerical solution of the moisture-diffusion equation in the fibers with two sets of variable diffusion coefficients. These research publications were focused on fabrics made from one type of fiber. The features and differences in the physical mechanisms of coupled moisture and heat diffusion into fabrics made from different fibers have not been systematically investigated.

The mathematical model describing the coupled heat and moisture diffusion in textiles was first proposed by Henry [13, 14] and then further developed by David and Nordon [15] and Li and Holcombe [20]. The conservation of heat and moisture can be expressed by the following equations:

$$\varepsilon\frac{\partial C_{\mathrm{a}}}{\partial t}+(1-\varepsilon)\frac{\partial C_{\mathrm{t}}}{\partial t}=\frac{D_{\mathrm{a}}\varepsilon}{\tau'}\frac{\partial^2 C_{\mathrm{a}}}{\partial x^2} \tag{1}$$

$$C_{\mathrm{v}}\frac{\partial T}{\partial t}-\lambda\frac{\partial C_{\mathrm{t}}}{\partial t}=K'\frac{\partial^2 T}{\partial x^2} \tag{2}$$

In the equations, both C_{v} and λ are functions of the concentration of moisture absorbed by the fibers. Most textile fibers are of very small diameter and have a very large surface/volume ratio. The assumption in the second equation of instantaneous thermal equilibrium between the fibers and the inter-fiber space does not therefore lead to appreciable error. The two equations in the model are not linear and contain the three unknowns, C_{p}, T and C_{a}. A third equation is needed to solve the equations.

Henry [13, 14] derived a third equation to obtain an analytical solution by assuming that C_{f} is linearly dependent on T and C_{s} and that fibers reach moisture equilibrium with the adjacent air instantaneously. Downes and Mackay [21] found experimentally that the sorption of water vapor by wool is a two-stage process, the first stage obeys Fick's law of diffusion with a concentration-dependent diffusion coefficient. The second-stage, which involves structural changes within fibers, is much slower than the first. To simulate the two stage-sorption process, David and Nordon [15] proposed an exponential function to describe the rate of change of fiber water content, which needed to be adjusted according to the measured fabric moisture content. Li and Holcombe [20] developed a two-stage sorption-rate equation to describe the moisture sorption of wool. The first stage is represented by a Fickian diffusion with a constant coefficient. The diffusion equation was solved by using Crank's truncated solution [12]. The second stage is described by an exponential relationship, which also needs to be adjusted according to the experimental measurements. The relative contributions of the two stages to the total moisture sorption are function of the sorption time and the initial regain of the fibers.

Li and Luo [19] improved the sorption rate equation by assuming that the moisture sorption of wool fiber can be generally described by a uniform-diffusion equation for both stages of sorption:

$$\frac{\partial C_{\mathrm{t}}}{\partial t}=\frac{1}{r}\frac{\partial}{\partial r}\left\{RD_{\mathrm{t}}(x,t)\frac{\partial C_{\mathrm{f}}}{\partial r}\right\} \tag{3}$$

where $D_{\mathrm{f}}(x,t)$ are the diffusion coefficients that have different values at different stages of moisture sorption. In a wool fiber, $D_{\mathrm{f}}(x,t)$ is a function of water content of the fibers, which is dependent on the time of sorption and the location of the fiber.

In the first-stage, the diffusion coefficient is concentration-dependent and is assumed to be quadratic function of water content when the sorption is less than 540 s, as given in Eq. (4a).

In the second-stage, in which the moisture sorption is much slower than in the first, the diffusion coefficient of moisture in a wool fiber is attenuated along with the time of sorption when $t \geq 540$ s as shown in Eq. (4b).

$$D_{\mathrm{t}}\{W_{\mathrm{c}}(t)\}=\{1.04+68.204W_{\mathrm{c}}(t)-1342.5924W_{\mathrm{c}}(t)^2\}10^{14},\ t\leq 540\ \mathrm{s} \tag{4a}$$

$$D_{\mathrm{t}}\{W_{\mathrm{c}}(t)\}=1.616405[1-\exp\{-18.16323\exp(-28.0W_{\mathrm{c}}(t))\}]10^{-14},\ t\geq 540\ \mathrm{s} \tag{4b}$$

The second formula for D_{f} in Eq. (4b) shows that the rate of moisture diffusion into a wool fiber (when $t\geq 540$ s) attenuates in the form of double-exponential function, which may indicate that the attenuating feature of the moisture sorption of wool is due to its microstructural changes and the decreasing number of available polar groups.

Now, we assume that the sorption process for all the fibers can be described by a uniform diffusion equation from Eq. (2.3), with diffusion-coefficient functions to describe the moisture-sorption kinetics. Through a large number of computational experiments in comparison with the measured water-content changes and temperature changes of various fibers, we try to identify whether the moisture-sorption process needs to be described by a two-stage process or a single Fickian-diffusion process. The diffusion-coefficient functions identified for carpets made from wool, cotton, porous acrylic fiber, and polypropylene fiber which is reported by Li and Planete [22] are listed in the appendix.

To generate a solution to the above-mentioned equations, we need to specify an initial condition and boundary conditions at the fiber surfaces of the humidity, moisture content, and temperature. Initially, a fiber is equilibrated to a given atmosphere of temperature (T_{a0}) and humidity (C_{a0} and H_{a0}), the temperature and moisture content being uniform throughout the fabric at known values:

$$T_{\mathrm{a}}(x,0)=T_{\mathrm{a0}} \tag{5}$$

$$C_{\mathrm{a}}(x,0)=C_{\mathrm{a0}} \tag{6}$$

$$C_f(x,r,0)=f(H_{a0}, T_0) \tag{7}$$

The fiber then undergoes a step change to a different atmosphere. Its boundaries are exposed to an air stream of a new moisture concentration C_{ab} and temperature T_{ab}. Considering the convective nature of the boundary air layers, the boundary conditions can be described by the following equations:

$$D_a \varepsilon \frac{\partial C_a}{\partial x}\bigg|_{x=0} = h_c (C_a - C_{ab}) \tag{8}$$

$$D_a \varepsilon \frac{\partial C_a}{\partial x}\bigg|_{x=L} = -h_c (C_a - C_{ab}) \tag{9}$$

$$K' \varepsilon \frac{\partial T}{\partial x}\bigg|_{x=0} = h_t (T - T_{ab}) \tag{10}$$

$$K' \varepsilon \frac{\partial T}{\partial x}\bigg|_{x=L} = -h_t (T - T_{ab}) \tag{11}$$

These conditions show that the thermal and moisture fluxes across the boundaries are proportional to the differences in the temperature and moisture concentration between the surrounding medium and the fabric surface, respectively.

Equations (2.1) and (2.2) are solved by a finite-difference method by using the Crank–Nicolson scheme, and Eq. (2.3) is solved by using an implicit-difference scheme, together with specification of the initial condition of Eqs (2.5)–(2.7), the boundary conditions of Eqs (2.8)–(2.11), and the fiber properties. Details of the solution method have been reported previously by Li and Luo [19].

Before carpet is conveyed into drying oven, most of the water is typically vacuum extracted. After vacuum extraction, the moisture regain is about 50–60%, indicating that there is still a significant amount of water inside the carpet. This water is usually removed with heat in industrial manufacturing processes. As a general rule, the water is distributed in larger pores.

It seems reasonable to anticipate that many of these pores are formed within the pile yarns throughout the thickness of the carpet. The location of this water is of interest to people in the carpet industry. The carpet surface characteristics can be studied using topographical parameter measurement.

Formulation of the problem

It was shown by Ilic and Turner (1989) that a theory based on a continuum approach led to the following equations of motion governing the drying of a slab of material:

Total mass:

$$\frac{\partial}{\partial t}(\phi S_g \rho_g + \phi S_W \rho_W) + \nabla(X_g \rho_g V_g + X_w \rho_W V_W) = 0 \tag{12}$$

Total liquid:

$$\frac{\partial}{\partial t}(\phi S_{\mathrm{g}}\rho_{\mathrm{gv}}+\phi S_{\mathrm{W}}\rho_{\mathrm{W}})+\nabla(X_{\mathrm{g}}\rho_{\mathrm{gv}}V_{\mathrm{gv}}+X_{\mathrm{W}}\rho_{\mathrm{W}}V_{\mathrm{W}})=0 \tag{13}$$

Total enthalpy:

$$\begin{aligned}&\frac{\partial}{\partial t}\left(\phi S_{\mathrm{g}}\rho_{\mathrm{gv}}h_{\mathrm{gv}}+\phi S_{\mathrm{g}}\rho_{\mathrm{ga}}h_{\mathrm{ga}}+\phi S_{\mathrm{g}}\rho_{\mathrm{ga}}h_{\mathrm{ga}}+\phi S_{\mathrm{W}}\rho_{\mathrm{W}}h_{\mathrm{W}}+(1-\phi)\rho_{\mathrm{S}}h_{\mathrm{S}}-\phi\rho_{\mathrm{W}}\int_0^{S_{\mathrm{W}}}\Delta h_{\mathrm{W}}(S)\mathrm{d}S\right)+\\&+\nabla(X_{\mathrm{g}}\rho_{\mathrm{gv}}V_{\mathrm{gv}}h_{\mathrm{gv}}+X_{\mathrm{g}}\rho_{\mathrm{ga}}V_{\mathrm{ga}}h_{\mathrm{ga}}+X_{\mathrm{W}}\rho_{\mathrm{W}}V_{\mathrm{W}}h_{\mathrm{W}})\\&=\nabla((K_{\mathrm{g}}X_{\mathrm{g}}+K_{\mathrm{W}}X_{\mathrm{W}}+K_{\mathrm{S}}(1-X))\nabla T+\phi\end{aligned} \tag{14}$$

where ϕ is the internal microwave power dissipated per unit volume. In Eq. (14) the effects of viscous dissipation and compressional work have been omitted.

Equations (12)–(14) are augmented with the usual thermodynamic relations and the following relations:

Flux expressions are given as follows:

Gas flux:

$$X_{\mathrm{g}}\rho_{\mathrm{g}}V_{\mathrm{g}}=-\frac{KK_{\mathrm{g}}(S_{\mathrm{W}})\rho_{\mathrm{g}}}{\mu_{\mathrm{g}}(T)}[\nabla P_{\mathrm{g}}-\rho_{\mathrm{g}}g] \tag{14a}$$

Liquid flux:

$$X_{\mathrm{W}}\rho_{\mathrm{W}}V_{\mathrm{W}}=-\frac{KK_{\mathrm{W}}(S_{\mathrm{W}})\rho_{\mathrm{W}}}{\mu_{\mathrm{W}}(T)}[\nabla(P_{\mathrm{g}}-P_{\mathrm{C}}(S_{\mathrm{W}},T)-\rho_{\mathrm{W}}g] \tag{14b}$$

Vapour flux:

$$X_{\mathrm{g}}\rho_{\mathrm{gv}}V_{\mathrm{gv}}=X_{\mathrm{g}}\rho_{\mathrm{gv}}V_{\mathrm{g}}-\frac{X_{\mathrm{g}}\rho_{\mathrm{g}}D(T,P_{\mathrm{g}})M_{\mathrm{a}}M_{\mathrm{v}}}{M^2}\nabla\left(\frac{P_{\mathrm{qv}}}{\mathrm{P_g}}\right) \tag{14c}$$

Air flux:

$$X_{\mathrm{g}}\rho_{\mathrm{ga}}V_{\mathrm{ga}}=X_{\mathrm{g}}\rho_{\mathrm{g}}V_{\mathrm{g}}-X_{\mathrm{g}}\rho_{\mathrm{g}}V_{\mathrm{gv}} \tag{14d}$$

Relative humidity (Kelvin effect):

$$\psi(S_{\mathrm{W}},T)=\frac{P_{\mathrm{gv}}}{P_{\mathrm{gvs}}(T)}=\exp\left(\frac{2\sigma(T)M_{\mathrm{v}}}{r(S_{\mathrm{W}})\rho_{\mathrm{W}}RT}\right)$$

where $P_{\mathrm{gvs}}(T)$ is the saturated vapour pressure given by the Clausius–Clapeyron equation.

Differential heat of sorption:

$$\Delta h_{\mathrm{W}}=R_{\mathrm{v}}T^2\frac{\partial(\ln\psi)}{\partial T}$$

Enthalpy-temperature relations:

$$h_{\mathrm{ga}}=C_{\mathrm{pa}}(T-T_{\mathrm{R}})$$

$$h_{\mathrm{gv}}=h_{\mathrm{vap}}^0+C_{\mathrm{pv}}(T-T_{\mathrm{R}})$$

$$h_W=C_{pW}(T-T_R)$$

$$h_s=C_{ps}(T-T_R)$$

The expressions for K_g, K_W are those given by Turner and Ilic [23], and μ_g, μ_W have had functional fits according to the data by Holman [24]. The diffusivity $D(T,P_g)$ given by Quintard and Puiggali [25] and the latent heat of evaporation given by,

$$h_{vap}(T)=h_{gv}-h_W$$

After some mathematical manipulations, the one-dimensional system of three non-linear coupled partial differential equations which model the drying process in a thermal equilibrium environment are given by:

$$a_{s1}\frac{\partial S_W}{\partial t}+a_{s2}\frac{\partial T}{\partial t}=\frac{\partial}{\partial Z}\left[K_{S1}\frac{\partial S_W}{\partial Z}+K_{T1}\frac{\partial T}{\partial Z}+K_{T1}\frac{\partial T}{\partial Z}+K_{P1}\frac{\partial P_g}{\partial Z}+K_{gr1}\right] \tag{15}$$

$$\begin{aligned}a_{T1}\frac{\partial S_W}{\partial t}+a_{T2}\frac{\partial T}{\partial t}=\frac{\partial}{\partial Z}\left(K_e\frac{\partial T}{\partial Z}\right)-\phi\rho_W h_{vap}\frac{\partial}{\partial Z}\left[K_S\frac{\partial S_W}{\partial Z}+K_T\frac{\partial T}{\partial Z}+K_P\frac{\partial P_g}{\partial Z}K_{gr}\right]+\\+\left[\phi\rho_W C_{pW}\left(K_{S2}\frac{\partial S_W}{\partial Z}+K_{T2}\frac{\partial T}{\partial Z}+K_{P2}\frac{\partial P_g}{\partial Z}+K_{gr2}\right)\right]\frac{\partial T}{\partial Z}+\Phi(S_W,T)\end{aligned} \tag{16}$$

$$a_{P1}\frac{\partial S_W}{\partial T}+a_{P2}\frac{\partial T}{\partial t}+a_{P3}\frac{\partial P_g}{\partial t}=\frac{\partial}{\partial Z}\left[K_S\frac{\partial S_W}{\partial Z}+K_T\frac{\partial T}{\partial Z}+K_{P3}\frac{\partial P_g}{\partial Z}+K_{gr3}\right] \tag{17}$$

The capacity coefficients a_{S1}, a_{T1}, a_{p1} and the kinetic coefficients K_{S1}, K_{T1}, K_{P1}, K_{gr1} all depend on the independent variables: saturation S_W, temperature T and total pressure P_g. The boundary conditions are written in one dimension as:

At z=0 (drying surface):

$$K_{S1}\frac{\partial S_W}{\partial Z}+K_{T1}\frac{\partial T}{\partial Z}+K_{P1}\frac{\partial P_g}{\partial Z}+K_{gr1}=\frac{K_m M_v}{R\phi\rho_W}\left(\frac{P_{gV}}{T}-\frac{P_{gV0}}{T_0}\right) \tag{18a}$$

$$K_e\frac{\partial T}{\partial Z}-\phi\rho_W h_{vap}\left(K_S\frac{\partial S_W}{\partial Z}+K_T\frac{\partial T}{\partial Z}+K_P\frac{\partial P_g}{\partial Z}+K_{gr}\right)=Q(T-T_0) \tag{18b}$$

$$P_g=P_0 \tag{18c}$$

At $z=L$ (impermeable surface):

$$K_{S1}\frac{\partial S_W}{\partial Z}+K_{T1}\frac{\partial T}{\partial Z}+K_{P1}\frac{\partial P_g}{\partial Z}+K_{gr1}=0 \tag{19a}$$

$$K_e\frac{\partial T}{\partial Z}-\phi\rho_W h_{vap}\left(K_S\frac{\partial S_W}{\partial Z}+K_T\frac{\partial T}{\partial Z}+K_P\frac{\partial P_g}{\partial Z}+K_{gr}\right)=0 \tag{19b}$$

$$(K_{S1}-K_S)\frac{\partial S_W}{\partial Z}+(K_{T1}-K_T)\frac{\partial T}{\partial Z}+(K_{P1}-K_{P3})\frac{\partial P_g}{\partial Z}+(K_{gr1}-K_{gr3})=0 \tag{19c}$$

Initially:

$$T(z,0)=T_1 \tag{20a}$$

$$P_g(z,0)=P_0 \tag{20b}$$

$$\frac{\partial P_c}{\partial Z}=-\rho_W g \tag{20c}$$

Results and discussion

The primary parameter monitored during the drying tests was moisture content, which is calculated as a ratio of wet mass minus the final dry mass over the final dry mass. The masses include the mass of the entire sample, tufts, and backing. Mass loss during drying is predominately due to water evaporation. Although other materials such as finish may be driven off during drying, the associated mass loss is insignificant compared to that of water. Thus, the determination of moisture content is simple yet accurate.

For most industrial carpet tile operations, the target moisture content is set so that the mass of moisture on the tiles is approximately 5% of the mass of the face yarns. Considering the mass of the entire sample, as we did for this investigation, the target moisture content in industry is typically about 0.9%. Drying rates below this level are of little concern.

Figure 1 shows a comparison of convective drying with and without microwaves. Whilst for convective drying there are definite constant rate and falling rate periods, when microwaves are added the form of the curves change and the use of the words constant and falling rate may no longer apply.

In hot air drying the constant rate period is the period of drying before the drying front recedes below the outer boundary. During this period the convective heat transfer is used for evaporation only, resulting in a constant surface temperature and drying rate (see horizontal plateau in Fig. 2).

Figure 3 presents the specific moisture extraction rate (SMER), as a function of time for both cases of drying. SMER is defined as the energy required to extract a unit

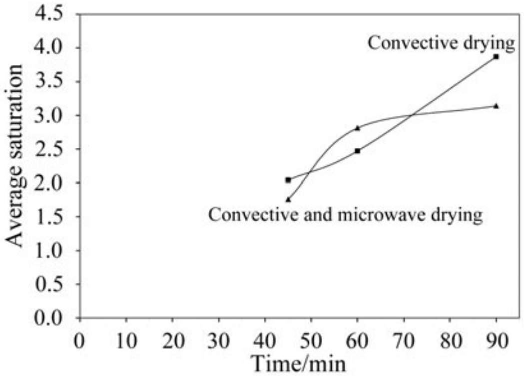

Fig. 1 Average saturation profiles in time for drying

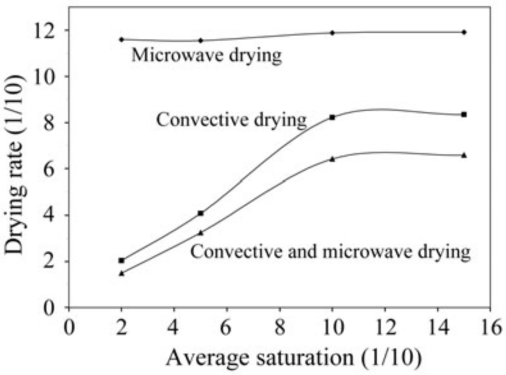

Fig. 2 Drying rate curves corresponding to profiles plotted in Fig. 1

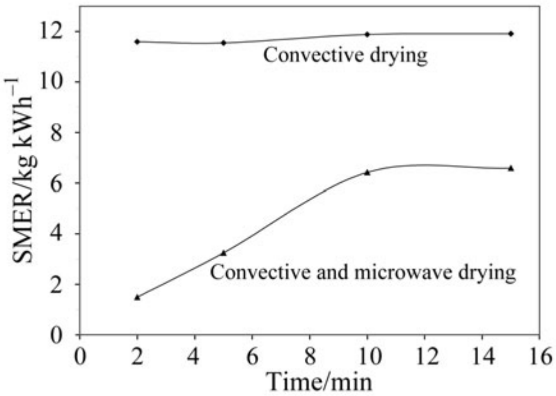

Fig. 3 Specific moisture extraction rate in time for drying

of water from the product. Figure 3 shows the SMER for the microwave case is much lower than the convective case. The liquid flows to the surface initially in a linear fashion (Fig. 4). As the material begins to dry out, there is a liquid flux up to what can confidently be explained as the position of evaporation front and then there is no movement of liquid from that point to the surface. The rate of evaporation for both case of drying is plotted in Fig. 5. The uneven during of carpet in convection ovens is often a problem that lengthens drying times and causes variable moisture distribution.

Conclusions

More than 80% of the water in a completely wetted cut-pile carpet is trapped between the yarns and only a small portion of the water (about 10–15%) is stored inside yarns. In summary, we can conclude that combined microwave and convective drying can provide faster drying time. The results show that the use of combined microwave and convective drying can improve drying time and give higher drying rate.

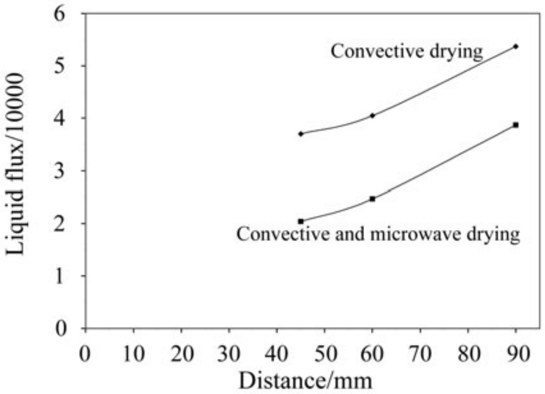

Fig. 4 Liquid flux as a function of distance

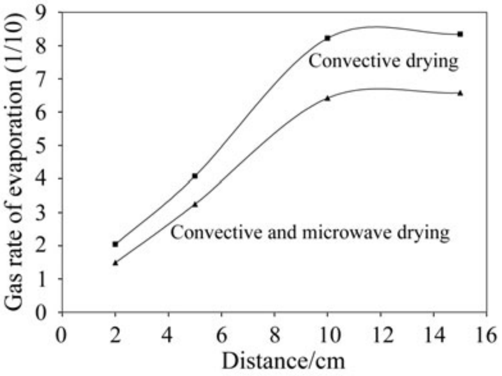

Fig. 5 Rate of evaporation as a function of distance

Nomenclature

C_a	Water-vapor concentration in the air filling the inter-fiber void space/kg m^{-3}
C_f	Water-vapor concentration in the fibers of the fabric/kg m^{-3}
C_P	Specific heat/J kg^{-1} K^{-1}
C_v	Volumetric heat capacity of the fabric/kJ m^{-3} °C^{-1}
D	Diffusivity/m^2 s^{-1}
D_a	Diffusion coefficient of water vapor in the air/m^2 s^{-1}
D_f	Diffusion coefficient of water vapor in the fibers of the fabric/m^2 s^{-1}
g	Gravitational constant/m s^{-2}
h	Intrinsic averaged enthalpy/J kg^{-1}
h_{vap}	Latent heat of evaporation/J kg^{-1}
h_c	Convective-mass-transfer coefficient/m s^{-1}
h_t	Convective-heat-transfer coefficient/kW m^{-2} K^{-1}
Δh_W	Differential heat of sorption/J kg^{-1}
K	Intrinsic permeability/m^{-2}
K'	Thermal conductivity/kW m^{-1} K^{-1}
K_g	Relative permeability of gas

K_m	Mass transfer coefficient/m s^{-1}
K_W	Relative permeability of water
L	Thickness of the fabric/m
M	Molar mass/kg mol^{-1}
P_{abs}	Power absorbed in the material per unit area/W m^{-2}
Q	Heat transfer coefficient/W m^{-2} K^{-1}
R	Universak gas constant/J mol^{-1} K^{-1}
r	Radial co-ordinate of fiber/m
S	Volume saturation
t	Real time from change in conditions/s
T_{ab}	Temperature of the ambient air/°C
T	Temperature of the fabric/°C
v	Averaged velocity/m s^{-1}
W_c	Water content of the fibers in the fabric, $W_c=C_f/\rho$
x, z	Distance/m
λ	Heat of sorption or desorption of water vapor by the fibers/kJ kg^{-1}
θ	Non-dimensional temperature
ρ	Density of the fibers/kg m^{-3}
σ	Surface tension/Nm^{-1}
τ'	Effective porosity of the fabric
τ	Non-dimensional time
ϕ	Porosity/m^3 m^{-3}
χ	Surface porosity/m^2 m^{-2}
Φ	Internal microwave power source/W m^{-3}
Ψ	Relative humidity
μ_g	Dynamic viscosity of gas/kg m^{-1} s^{-1}
μ_W	Dynamic viscosity of water/kg m^{-1} s^{-1}
μ	Permeability of free space/H m^{-1}

Subscripts

a	Air
c	Capacity
g	Gas
v	Vapour
W	Liquid
o	Atmospheric
l	Initial

Appendix A – physical characteristics [22]

Wool:

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–1st stage:

$$D_f=(1.04+68.20W_c-1342.59W_c^2)10^{-14},\ t<540\text{ s} \tag{A1}$$

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–2nd stage:

$$D_f=1.6164\{1-\exp[-18.163\exp(-28.0W_c)]\}10-14,\ t\geq540\ \mathrm{s} \tag{A2}$$

Diffusion coefficient in the air:

$$D_a=2.5e^{-5} \tag{A3}$$

Volumetric heat capacity of fiber/kJ m^{-3} K

$$C_v=373.3+4661.0W_c+4.221T \tag{A4}$$

Thermal conductivity of fiber:

$$K=(38.49-0.720W_c+0.113W_c^2-0.002W_c^3)10^{-3} \tag{A5}$$

Heat of sorption/kJ kg^{-1}

$$\lambda=1602.5\exp(-11.72W_c)+2522.0 \tag{A6}$$

Cotton:

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–1st stage:

$$D_f=(0.8481+50.6W_c-1100W_c^2)10^{-14},\ t<540\ \mathrm{s} \tag{A7}$$

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–2nd stage:

$$D_f=2.5\{1-\exp[-3.5385\exp(-46W_c)]\}10^{-14},\ t\geq540\ \mathrm{s} \tag{A8}$$

Diffusion coefficient in the air:

$$D_a=2.5e^{-5} \tag{A9}$$

Volumetric heat capacity of fiber/kJ m^{-3} K

$$C_v=\frac{(1663.0+4184.0W_c)}{(1+W_c)1610.9} \tag{A10}$$

Thermal conductivity of fiber:

$$K=(44.1+63.0W)10^{-3} \tag{A11}$$

Heat of sorption/kJ kg^{-1}

$$\lambda=1030.9\exp(-22.39W_c)+2522.0 \tag{A12}$$

Porous acrylic fiber:

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–1st stage:

$$D_f=(1.12-410W_c-8200W_c^2)10^{-13},\ t<540\ \mathrm{s} \tag{A13}$$

Diffusion coefficient of water vapor in fiber/m^2 S^{-1}
–2nd stage:

$$D_f=6.23\cdot10^{-13},\ t\geq540\ \mathrm{s} \tag{A14}$$

Diffusion coefficient in the air:

$$D_a=2.5e^{-5} \quad \text{(A15)}$$

Volumetric heat capacity of fiber/kJ m^{-3} K

$$C_v=1610.9 \quad \text{(A16)}$$

Thermal conductivity of fiber:

$$K=28.8\cdot10^{-3}\ \text{kW m}^{-1}\ \text{K}^{-1} \quad \text{(A17)}$$

Heat of sorption/kJ kg^{-1}

$$\lambda=2522\ \text{kJ kg}^{-1} \quad \text{(A18)}$$

Polypropylene fiber:

Diffusion coefficient of water vapor in fiber/m^2 S^{-1} –1st stage:

$$D_f=1.3e^{-13},\ t<540\ \text{s} \quad \text{(A19)}$$

Diffusion coefficient of water vapor in fiber/m^2 S^{-1} –2nd stage:

$$D_f=1.3e^{-13},\ t\geq540\ \text{s} \quad \text{(A20)}$$

Diffusion coefficient in the air:

$$D_a=2.5e^{-5} \quad \text{(A21)}$$

Volumetric heat capacity of fiber/kJ m^{-3} K

$$C_v=1715.0 \quad \text{(A22)}$$

Thermal conductivity of fiber:

$$K=51.80\cdot10^{-3}\ \text{kW m}^{-1}\ \text{K}^{-1} \quad \text{(A23)}$$

Heat of sorption/kJ kg^{-1}

$$\lambda=2522\ \text{kJ kg}^{-1} \quad \text{(A24)}$$

Appendix B - kinetic coefficients

$$K_s=\frac{-KK_W}{\phi\mu_W}\frac{\partial P_c}{\partial S_W},\ K_{S1}=K_S+\frac{(1-S_W)DM_aM_v}{\rho_W MRT}\frac{\partial P_{gV}}{\partial S_W}$$

$$K_{S2}=K_S+\frac{(C_{gV}-C_{pa})(1-S_W)DM_aM_v}{C_{pW}\rho_W MRT}\frac{\partial P_{gV}}{\partial S_W}$$

$$K_T=-\frac{KK_W}{\phi\mu_W}\frac{\partial P_C}{\partial T},\ K_{T1}=K_T+\frac{(1-S_W)DM_aM_v}{\rho_W MRT}\frac{\partial P_{gV}}{\partial T}$$

$$K_{T2}=K_T+\frac{(C_{pV}-C_{pa})(1-S_W)DM_a M_v}{C_{pW}\rho_W MRT}\frac{\partial P_{gV}}{\partial T}$$

$$K_p=\frac{KK_W}{\phi\mu_W},\ K_{p1}=K_p+\frac{KK_g M_v P_{gV}}{\phi\mu_g\rho_W MRT}\frac{\partial P_{gV}}{\partial T}-\frac{(1-S_W)DM_a M_v P_{gV}}{\rho_W RTMP_g}$$

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