HEAT FLUX AND HEAT GENERATION CHARACTERISATION IN A WET-LAMINAR BODY IN MICROWAVE-ASSISTED DRYING: AN APPLICATION TO MICROWAVE DRYING OF LEATHER

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ABSTRACT

Heat fluxes through a laminar body have been modelled from a parabolic temperature distribution assumption when the material is irradiated with microwaves and immersed in a convective air flow. The heat equation has been analysed and a relationship between thermal conductivity, temperatures and net heat flux through the material surface has been established. This study has been successfully applied to leather hides when they are dried in a combined microwave-hot air oven. With regard to the development of this work, dielectric and temperature measurements have been demonstrated to be of the utmost importance.

Introduction

Microwave heat generation has been widely studied and employed for various industrial materials and applications [1,2]. However, in view of the wide-ranging effects involved in the understanding of the behaviour of materials irradiated with microwaves, such us electromagnetic heat generation, superficial and internal evaporation, heat conduction, internal pressure, etc… [3], it is not common to find a specific experimental study of the energy fluxes taking place in such processes. The knowledge of heat fluxes through the surface when a material is being dried is very relevant, especially in temperature sensitive materials, since the exchange of heat with the surrounding environment may greatly influence the evolution of the material's temperature [4].

Microwave drying of leather has been scarcely reported and no previous works consider the subject from a thermophysical point of view. In some previously reported experiments, the study of drying of leather with microwaves under atmospheric pressure and vacuum conditions has demonstrated the capacity of this technique to accelerate drying rates by obtaining a better moisture distribution [5]. Statistical relationships have also been used to model these drying curves [6]. However, in most cases these statistical models are not able to explain drying mechanisms. Recently, the characteristics of microwave drying of leather, such as drying rates and curve modelling, temperature evolution and surface shrinkage, have been presented in [7]. In that paper, heat generation with electromagnetic energy was shown to be a very efficient alternative to conventional methods since microwave heat generation does not depend on the poor thermal conductivity of the hides [8,9] and, consequently, drying rates can be accelerated without damaging leather tissues.

In this paper, an enhanced method for the calculation of net heat flux through the surface of a laminar body, when microwaves are introduced into the conventional drying process, is presented based on temperature measurements at the centre and on the surface of the hide. With this method, the net heat generated inside the body and the internal evaporation due to the microwave heat generation can also be evaluated.

Theoretical analysis

Drying is usually described as a coupled process of heat and mass transfer. Temperature distributions inside a laminar body irradiated by microwave fields and immersed in an air flow can be mathematically expressed by the so-called heat equation and a boundary condition that governs the temperatures in the interface air-solid [1,7-10]. These relationships can be written as:

$$\frac{\partial T}{\partial t} = \frac{k_T}{\rho \cdot c_P} \nabla^2 T + \frac{Q_{gen_{net}}}{\rho \cdot c_P} \tag{1}$$

$$-k_T \cdot \left.\frac{\partial T}{\partial x}\right|_{sur} = h_{T_{TOTAL}} \cdot (T_{SUR} - T_{AIR}) \tag{2}$$

when $Q_{gen_{net}}$ is the microwave heat generated inside the body minus the loss of energy due to the internal evaporation, and $h_{T_{TOTAL}}$ is the global heat transference coefficient through the surface, thus quantifying the heat lost by the superficial evaporation and that gained or lost by convection. Assuming symmetrical boundary conditions in a laminar body, symmetrical temperature and moisture content distributions can be considered inside the sample with the symmetry axis being placed at the centre of the body. A function that can comply with these symmetrical boundary conditions is a polynomial of second order [10]. Furthermore, in the case of boundary conditions being asymmetrical, the parabolic distribution could be maintained albeit with the centre displaced to the edge of the hide characterised by a lower heat transfer coefficient. This can be observed in figure 1.

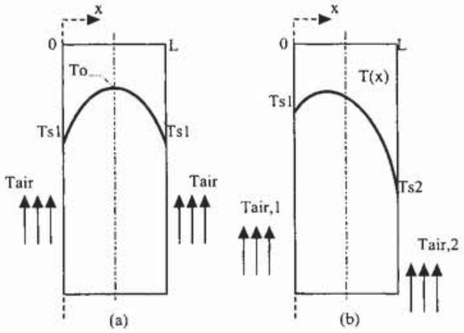

FIG 1.
Temperature distribution with microwave generation
and symmetrical (a) or asymmetrical (b) boundary conditions.

Thus, the temperature in the sheet can be approximated by:

$$T(x) = a_T + b_T \cdot x + c_T \cdot x^2 \tag{3}$$

where x is the distance to the centre of the sheet (as depicted in figure 1) and a_T, b_T y c_T are the coefficients that best adjust that function to the experimental data for each time interval.

The symmetric condition implies that the maximum temperature is located at the centre of the laminar sample, at x=L/2, L being the thickness of the sheet:

$$\left.\frac{\partial T}{\partial x}\right|_{x=L/2} = 0 \tag{4}$$

Therefore, from these equations a relationship between the net heat flux through the surface and the conductivity can be found by only measuring the two temperatures, one corresponding to the centre and the other to the surface of the body (see nomenclature for key to symbols):

$$\frac{k_T}{h_{T_{TOTAL}}} = \frac{\mathrm{T}_{SUR} - T_{AIR}}{-\frac{4}{L}\left(T_{SUR} - T_{CENTRE}\right)} \tag{5}$$

This heat flux is usually divided into two contributions: the flux due to convection and the flux due to surface evaporation as described in equation (6):

$$h_{T_{TOTAL}}\left(T_{SUR} - T_{AIRE}\right) = h_{T_{CONV}}\left(T_{SUR} - T_{AIRE}\right) - \frac{\Delta H_{ev} \cdot m_d \cdot \frac{\partial X}{\partial t}}{Area} \cdot e_S \tag{6}$$

As can be seen from equation (6), while $h_{T_{TOTAL}}(T_{SUR} - T_{AIRE})$ is a continuos function, $h_{T_{TOTAL}}$ is not as the magnitude $T_{SUR} - T_{AIRE}$ can be zero when the body is being heated with microwaves. This discontinuity can be avoided using the net heat flux instead of the total convective heat transfer coefficient. Net volumetric heat generation, which takes into account the heat generated with microwave fields and the heat lost by internal evaporation, can be extracted from equations (1, 3, 4) as:

$$Q_{gen_{NETO}} = \rho c_P \frac{\partial T_{CENTRE}}{\partial t} - 2K_T \frac{4}{L^2}\left(T_{SUP} - T_{CENTRO}\right) \tag{7}$$

On the other hand, microwave volumetric heat generation is calculated using the Lambert law as outlined in [5,6]. Although, in this case, the equation has been modified for the first stage of the drying process with an exponential factor in accordance with the experimental behaviour of this magnitude, thus, microwave heat generation can be calculated as:

$$Q_{gen} = 2\alpha \cdot \frac{\eta \cdot Po}{2\left(L_1L_2 + L_2L_3 + L_3L_1\right)} \cdot [e^{-2\alpha x} + e^{-2\alpha(L_1 - x)}] \tag{8}$$

$$\eta(t) = a \cdot e^{-b \cdot t} + 1 \tag{9}$$

$$\alpha = \frac{2\pi}{\lambda}\sqrt{\left[\varepsilon'\left(1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2\right)^{0.5} - 1\right] \cdot \frac{1}{2}} \tag{10}$$

These equations imply a plane wave assumption [1] and not the exact resolution of Maxwell equations, although this approximation provides good results as will be demonstrated in next sections. From equations (7, 8) the internal evaporation coefficient is

$$e_V = \frac{Q_{gen_{NETO}} - Q_{gen}}{\rho \Delta H_{ev} \frac{\partial X}{\partial t}} \tag{11}$$

Considering all the relationships and parameters described above, temperature evolution has been simulated for leather samples by using the finite difference method, assuming symmetric boundary conditions and via the modelling of the experimental behaviour of the net heat flux through the surface.

Experimental Procedure

A diagram of the experimental equipment used to carry out all drying tests is shown in figure 2. Microwaves were supplied by a computer-controlled 2.45 GHz power source, characterised by an output range from 0 to 920 watts. Air flow was generated by a fan with variable velocity. This flow was confined in a rectangular region to improve its intensity and to minimise turbulence over the samples . For this purpose, a PTFE sheet was placed inside the oven as can be observed in figure 2. Metallic and mobile walls were placed inside the rectangular applicator. These mobile walls facilitate the appearance of different and time-changing electric field configurations allowing an average constant field distribution near leather samples which justifies the plane wave assumption used in equation (8).To avoid external radiation from the oven, two metallic grids were positioned at the extremes of the microwave cavity as the air was flowing. The air temperature was varied from 30ºC to 63ºC by means of electrical resistances. This range was selected to elude possible damages to the leather tissues. To measure temperatures at the centre of the hide and on its surface, an optical fibre thermometer (Luxtron 790) was employed. The use of optical fibres, instead of thermocouples, was preferred so as not to perturb the electric fields within the oven and in order to minimise the interferences of the electric field on the measurements. Symmetrical conditions were obtained due to the use of a grill made with PTFE strings which allowed air contact on both sides of the laminar samples. A high precision scale (Ohaus 110) measured the weight losses during drying. Likewise, the air temperature and its relative humidity were monitored by means of two sensors (Rotronic HVAC, series FTCA15) placed at the air flow inlet and outlet.

The leather samples consisted of chrome tanned hides of Nubuck ND and Gras Dossets types. The average initial mass of the samples was approximately 200 gr., while its average dry mass was almost 100 gr. The hides had an area of 35×35 cm^2 and a thickness of around 2 mm. In order to obtain the dielectric properties of leather, various samples with different moisture contents were measured using a slotted waveguide (WR340) with a network analyser (HP 8720B) as shown in figure 3. With this configuration, the transmission and reflection coefficients of the structure were measured using the procedure described in [11], and the relative dielectric constant and the loss factor of leather were expressed as a function of moisture content.

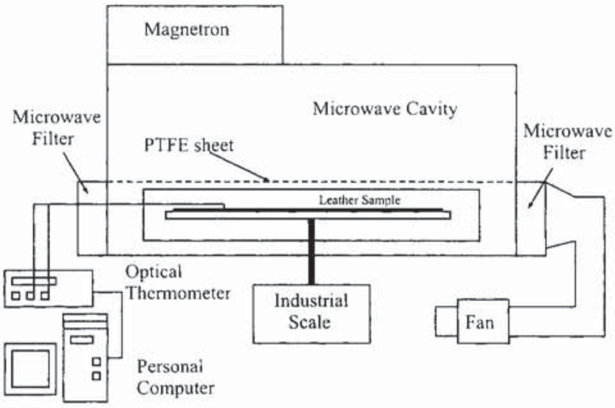

FIG. 2.
Diagram of the experimental set-up used for the drying tests

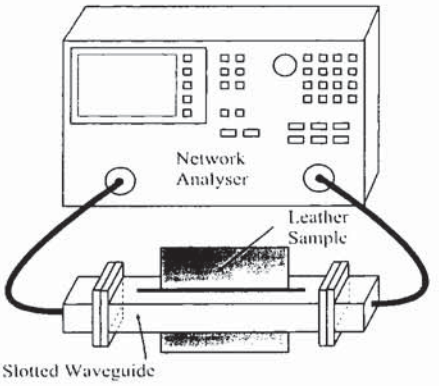

FIG. 3.
Network analyser configuration.

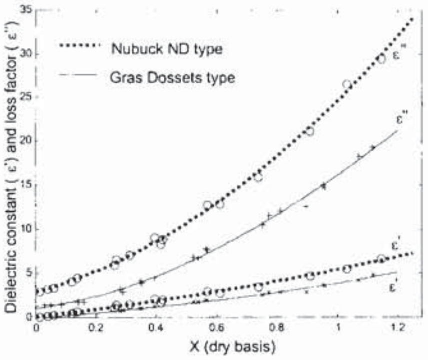

FIG. 4.
Dielectric properties of various leather samples

Results and Conclusions

Figure 4 shows the dielectric properties of leather samples as a function of the moisture content. It can be observed that both measured values ε' and ε'' follow a typical parabolic function, increasing their values with the moisture content. From these values, the attenuation factor (α), described in equation (10), follows a quasi-linear relation versus moisture content in the leather. Hence, the highest heat generation rate is always present in the initial stage of the drying process, in the so-called heating up period [1].

In the drying process evolution, when the hide starts to lose moisture, the dielectric properties, and consequently, the attenuation factor of the samples decrease which produces, as a result, lower heat generation rates in accordance with equation (8). Figures 5 and 6 show the differences between the net heat fluxes through the surface in the convective and the microwave-assisted drying. In the traditional process, shown in figure 5, it can be observed that the net heat flux is almost at zero. This means that all the energy absorbed in the material by convection is expended in evaporating the superficial water. It can also be observed that when the sample increases its sensible temperature, the absorbed heat level falls. However, when microwave fields are applied, the behaviour of the material is completely different. Since the hide may reach higher temperatures on its surface than in its surrounding area, due to the internal heat generation, the sample does not gain heat through its surface. Therefore, the flux now adopts the opposite sign with respect to the traditional process. Figure 6 shows this effect, where the opposite behaviour of the net heat flux produced when leather is irradiated with microwaves is observed.

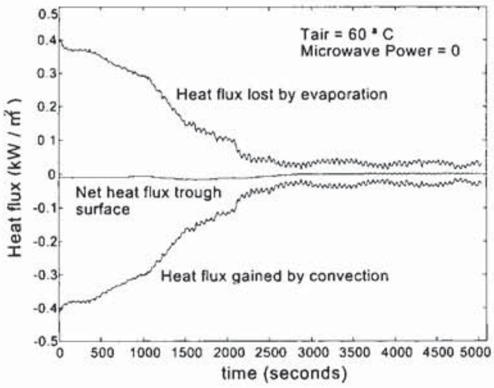

FIG. 5.
Experimental heat fluxes through the surface in convective drying .

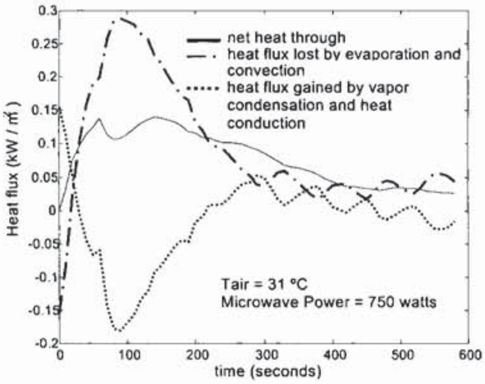

FIG. 6.
Experimental heat fluxes through the surface in microwave- assisted drying.

When the irradiated microwave power is increased, the heat generation inside the hide acts in the same way and, coupled with this effect, the net heat flux lost by leather increases, as depicted in figure 7. It must be pointed out that in the final stages of the drying process, heat fluxes tend to have the same value, despite the different irradiated microwave power. This can be explained by the fact that in this final period the samples have a very low loss factor, and the heat generated by microwaves is negligible. On the other hand, the surface is already dried in the falling rate period [10] so superficial evaporation is also insignificant. With these conditions, the dominating process at the surface is convection. If air temperature is increased, the heat flux lost by convection is reduced, as can be perceived in figure 8. In the case that the room temperature is very high, as represented in figure 9, heat fluxes can even oscillate between positive and negative values due to the fact that air and superficial temperatures are almost equal. In figure 10, the temperature evolution for the tests is plotted. It must be pointed out that the higher the air temperature, the more levelled the temperature distributions are. It is also interesting to emphasise the fact that a point in time is reached at which temperatures at the centre of the sample decrease. This may be associated with internal evaporation which causes a reduction in the net internal heat generation.

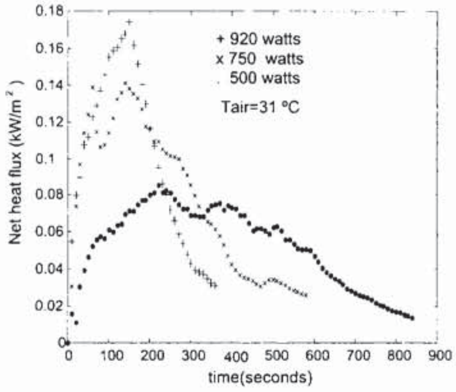

FIG. 7.
Experimental heat fluxes vs. Irradiated microwave power at a constant air temperature

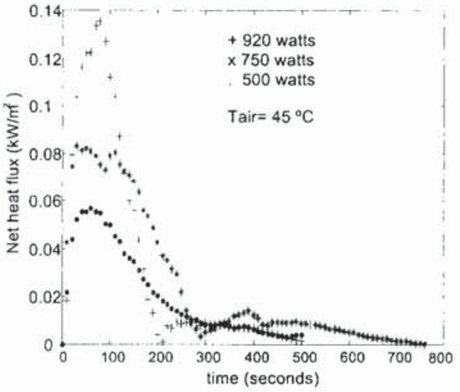

FIG. 8.
Experimental heat fluxes vs. irradiated microwave power at a constant air temperature

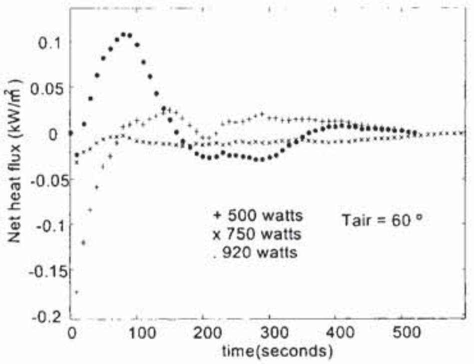

FIG. 9.
Experimental heat fluxes vs. irradiated microwave power at a constant air temperature

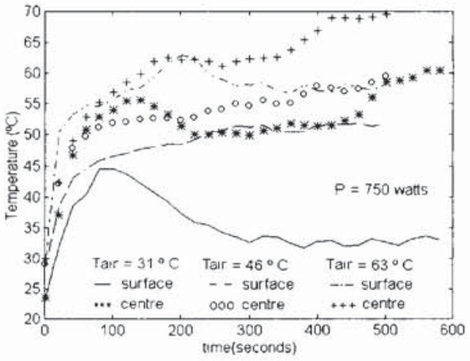

FIG. 10.
Temperature evolution for several drying tests at constant microwave power

In figure 11 the net heat generation rate (evaluated from equation 7) and the microwave generation rate (estimated from equation 8) are depicted versus the moisture content. It can be observed that both quantities present a good agreement, despite having been calculated from different sources. It can also be deduced from this figure that, for the conditions of the test, also plotted in the figure, internal evaporation can be considered negligible since the net heat generation rate is very similar that generated by microwaves. The temperature evolution inside leather has been also simulated using the developed finite differences code described in previous section, and the values obtained with the experimental modelling of the net heat flux through the surface. In Figure 12, the simulated temperature distribution at the surface and centre of the material is illustrated by comparing these results to the previous experiments. The agreement between empirical and simulated data fully confirms the parabolic assumption performed for the temperature distribution used in this work. The precise determination of the dielectric properties of leather have been demonstrated to be also as a fundamental parameter in order to correctly simulate the dielectric heating process.

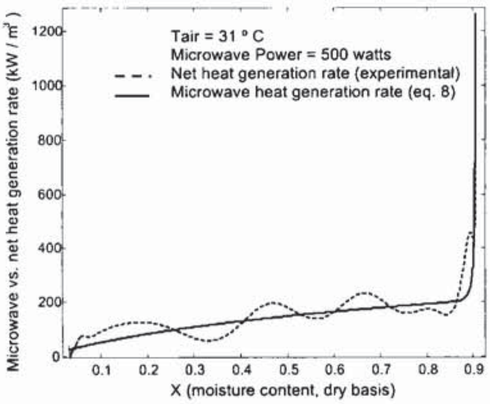

FIG. 11.
Microwave vs. net heat generation rate

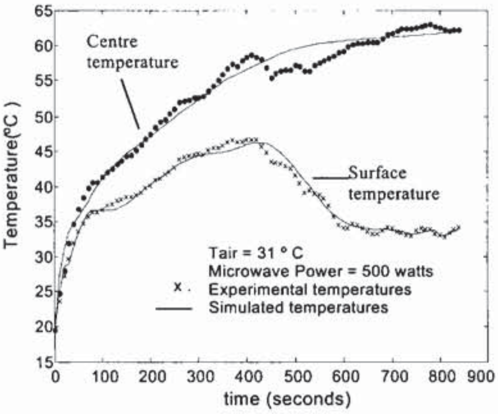

FIG. 12.
Experimental temperature evolution vs. Simulated values.

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Nomenclature

$A, Area$	Total area of the sample (m^2)
c_P	Specific heat (kW / kg ° C)
e_V	Phase conversion factor (dimensionless)
e_S	Local evaporation ratio (local evaporation rate vs. average evaporation rate)
D	Diffusive coefficient (m^2 / s)
h_t, $h_{TCONVECTIVE}$	Convective heat transfer coefficient (kW / m^2 ° C)
h_{TTOTAL}	Global heat transfer coefficient (kW / m^2 ° C)
k_T	Thermal conductivity (kW / m ° C)
L, L_1, L_2	Thickness and surface dimensions of samples (m)
P_O	Incident microwave power upon leather surface (kW)
Q_{gen}	Volumetric heat (kW/m^3)
T	Temperature (° C)
T_{SUR}	Surface temperature of the sample (° C)
T_{AIR}	Air temperature in the microwave cavity (° C)
T_{CENTRE}	Temperature in the centre of leather hide (° C)
t	time (s)
x	x coordinate value (m)
α	Attenuation coefficient (dimensionless)
ΔH_{ev}	Latent heat of evaporation (kJ / kg)
ε'	Dielectric constant (dimensionless)
ε''	Dielectric loss factor (dimensionless)
λ	Wavelength of microwave fields (m)
ρ	Density of leather samples (kg / m^3)

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