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Modelling of convective and convective-infrared drying of Tunisian Bovine leather: a comparative study

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Abstract : Drying is an essential operation in various industrial applications such as food, pharmaceutical and leather. Leather drying is crucial stage in transformation process of the bovine skin into leather. Convective drying of leather is of a low energy efficiency and has long drying time during the falling drying rate period because of the low thermal conductivity of the product. To avoid this problem and achieve fast and effective thermal processing has resulted in the increase of the use of other drying methods such as infrared (IR) drying and convective-infrared drying.

This work gives a mathematical formulation of the different transfer phenomena (heat, mass and momentum) which describe the process. The model tries to be relatively simple but sufficiently complete in order to predict and analyse the distribution of the temperature, the moisture, the strain and the stress during the convective and combined convective-infrared drying. The model is solved numerically by using finite elements method based on Arbitrary Lagrangian-Eulerian description.

The numerical results reveal that infrared drying reduces drying time comparing to convective drying.

Key words: drying, leather, convective, infrared.

1. Introduction

Drying is one of the most energy-intensive processes used in many production and treatment in wet processing such as leather industries.

Due to the low thermal conductivity of most moist materials such as leather, heat transfer within the product during falling drying rate period during conventional heating is limited. From the other hand, the high energy consumption of the convective drying and the importance of the quality of the final product have directed interest toward the use of different innovative technologies as a potential method for obtaining high quality of leather and reducing leather shrinkage and drying time. The use of alternative technologies in leather domain such as infrared radiation (IR) [1], [2] and convective-infrared drying [3] provide a faster and more efficient heat transfer for drying than the commonly used convection technology. The energy transfer to the medium is direct and permits to attain rapidly suitable levels of temperature, which activates the fundamental drying mechanisms.

The drying process can be conducted by using various sources of electromagnetic radiation with wide range of wavelengths. Radiation can be used to heat the material volumetrically, thus reducing internal resistance to heat transfer. IR heating offers many advantages over conventional drying under similar drying conditions. In fact, the energy transfer to the product is direct and allows to attain rapidly proper temperature levels, activating the drying mechanisms. Because of its performance, IR and combined convective/infrared (CV/IR) drying present currently a strong development and hve been investigated as potential methods for obtaining a high quality of dried product.

The use of simulative tools opens new ideas without incurring the usual high research costs linked to pilot investigations. Thus, it is desirable to formulate an adequate transport model accounting for the simultaneous transfers of heat and mass within the product in order to optimize drying process.

Numerous studies have been carried out on combined drying methods such as convective/infrared[3], [4], convective microwave [3], [5] and other methods.
Monzó Cabrera study drying kinetics of combined microwave and hot air drying of leather [6] He also proposes an enhanced method for calculation of net heat flux through the surface of a laminar body of combined microwave and hot air drying of leather [7] However, few works has been reported on combined convective-infrared drying of leather.

The aim of this paper is to assess to a comparative study of two drying methods: a convective drying and a combined convective/infrared drying. This paper may be useful to the leather industry in optimizing the drying process and thus reducing leather manufacturing costs and obtaining an enhanced final quality for this material.

2. Material and methods

2.1. Modelling approach

The physical model chosen is a parallelepiped Bovine leather sample (8mmx8mmx2mm). All surfaces of the sample are exposed to hot air flow in which the temperature, the velocity and the relative humidity were controlled. The product was considered as a deformable porous product composed of two phases: solid and liquid phase (water).

Our study can be limited to quarter of the Bovine leather sample (1mmx4mm) due to the length of the sample and the symmetry of the problem. It is bounded by two exchange surfaces and two symmetric surfaces.

To simplify more the problem, the following hypotheses have been made:

1. Initial temperature and moisture are considered to be uniform;
2. The product is assumed to be homogeneous, isotropic;
3. Local thermal equilibrium exists between two phases through the product;
4. Heat and mass transfers generated within the product are governed by diffusion and those developed between the material and the environment is governed by convection.

Considering these assumptions, the macroscopic equations governing heat and mass transfers in the porous leather sample are summarized below:

2.1.1. Mass balance equation

Assuming that the liquid flux is diffusive [8], [9] and using mass conservation equations for the solid phase (denoted by subscript s) and liquid phase (denoted by subscript l) [10] and Fick's law, the liquid transport equation is written as:

$$\rho_s \frac{\delta w}{\delta t} + \rho_s \overrightarrow{v_s}.\nabla(w) + \nabla(-\rho.\frac{D_{eff}}{(1+w)}\nabla(w)) = 0 \quad (1)$$

$$w = \frac{\rho_l}{\rho_s} \quad (2)$$

2.1.2. Energy balance equation

The temperature of saturated Bovine leather during drying is obtained by solving the heat transport equation. Assuming that the phase transition of liquid into vapour occurs only at the surface of the sample during drying, and using the Fourier's law for the internal heat transfer, the energy conservation equation is given by equation (3):

$$\rho.C_p.\frac{\delta T}{\delta t} + \rho.C_p\left[\overrightarrow{v_s} - \frac{c_p^l}{c_p}.\frac{D_{eff}}{(1+w)}.\nabla(w)\right].\nabla(T) = \nabla(\lambda_{eff}.\nabla(T)) \quad (3)$$

The equation includes a term corresponding to the enthalpy transported for each phase and a term of conduction heat.

2.1.3. Initial and boundary conditions

t =0s $w(t=0)=w_0$ and $T(t=0)=T_0$ (4)

t>0s $\nabla(w).\vec{n}=0$ and $\nabla(T).\vec{n}=0$ on symmetric surfaces

Convection, conduction and infraredheating act only on the surface stage.Thus, mass and heat fluxes on exchange surfaces are described as follows:

$$\dot{m}=-(\rho_s.D_{eff}.\nabla(w)).\vec{n} \quad (5)$$

$$h.(T_a-T_{surf})+Q_{abs}-\dot{m}.L_v=\lambda_{eff}.\nabla(T) \quad (6)$$

Where, the infrared flux density absorbed at the surface is:

$$Q_{abs}=\alpha_r Q_0 \quad (7)$$

$\dot{m}$ is the rate of moisture vaporization at the surface (kg.m^{-2}.s^{-1}) [9] defined as:

$$\dot{m}=k_m.\frac{18.10^{-3}}{8,314}\left[\frac{a_w.P_{vsat}(T)}{T}-\frac{a_w.P_{vsat}(T_a)}{T_a}\right] \quad (8)$$

2.1.4. Momentum balance equation

The mechanical behaviour is developed under the following assumptions:

- A quasi-steady state assumption is involved;
- The gravity term is neglected.

The local mechanical equilibrium equation, in terms of total stress, is defined as:

$$\nabla(\overline{\overline{\sigma}})=0 \quad (9)$$

Where $\overline{\overline{\sigma}}$ is the second order total stress tensor.

In the case of elastic behaviour, applying the Hooke's law; the stress tensor σ could be expressed as follows:

$$\overline{\overline{\sigma}}=\lambda\ \mathrm{tr}\left(\underline{\underline{\varepsilon}}^{m}\right).\underline{\underline{I}}+2\mu\underline{\underline{\varepsilon}}^{m} \quad ; \quad \underline{\underline{\varepsilon}}=\underline{\underline{\varepsilon}}^{r}+\underline{\underline{\varepsilon}}^{m} \quad (10)$$

$$\overline{\overline{\sigma}}=\lambda.tr(\varepsilon)+2.\mu.\varepsilon-3.K(\alpha(T-T_0)+\beta(w-w_0)) \quad (11)$$

2.1.5. Initial and boundary conditions

Exchange surfaces	$(\sigma.\vec{n}).\vec{n}=\vec{0}$	(12)
Symmetry surfaces	$\vec{u}.\vec{n}=0$	(13)

2.2. Numerical resolution

Equations (1), (3) and (11), associated with boundary conditions (4, 5, 6, 12 and 13) are implemented in a finite element solver. The physical and mechanical properties of Bovine leather used in the model are summarized in Table 1.

Specific heat of solid (Cps), solid density (ρs), effective thermal conductivity (λ_{eff}) and young's modulus (E) were determined experimentally. For effective diffusion coefficient (D_{eff}), it was estimated using Crank's equation. The equilibrium moisture content (w_{eq}) was obtained by applying GAB model on sorption isotherms. Otherwise, h, α and β used in the model were estimated value.

Table 1 : Expression of the model properties

Property	Expression
Heat transfer coefficient: h ($W.m^{-2}.K^{-1}$)	20
Latent heat of water evaporation: L_v[11] ($J.kg^{-1}$)	$\frac{5.2053\times10^{7}}{18}(1-\frac{T_a}{647.13})^{\left(0.3199-0.212\frac{T_a}{647.13}+0.25795(\frac{T_a}{647.13})^{2}\right)}$
Specific heat of solid: Cp_s($J.kg^{-1}.K^{-1}$)	$Cp_s = 1178.07 + 4.21 \times T$
Effective diffusion coefficient: D_{eff} ($m^2.s^{-1}$)	$D_{eff}(w,T)=3.87\times10^{-7}w^{-1,33}e^{\frac{-0.41}{w}}e^{\frac{-2.32*10^{3}}{T}}$
Effective thermal conductivity: λ_{eff} ($W/(m.K)$)	0.04
Equilibrium moisture content($Kg.kg^{-1}$ *d.b.*)	$w_{eq}=\frac{C\times k\times w_m\times w}{\left((1-k\times w)(1-k\times w+C\times k\times w)\right)}$ C=50.55 k= 0.7836 w_m= 0.0968
Mass transfer coefficient: k_m ($m.s^{-1}$)	$k_m=\frac{h}{(\frac{1004\times219.375}{300}\times(0.62069+0.007))}$
Thermal expansion coefficient: α	3.10^{-8}
Hydric expansion coefficient: β	0.1
Young's modulus E (*MPa*)	$E=\frac{1}{0.0123+0.00989\times w^{2.5629}}$
Solid density (Kg/m^3)	$\rho_s=\frac{1000}{(1.0039\times w+0.8252)}$
infrared absorbing coefficient α_r	0.7

3. Results and discussions

3.1. Variation of the average moisture content and temperature

The variations of the average moisture content and temperature of the studied material for the two investigated drying modes are shown in Fig.1 and Fig.2. We can notice that the curve describing the time evolution of the average moisture content obtained by combined CV/IR drying show the drying reduction times if combined drying process was applied than that obtained with convective drying. The infrared, as a way of superficial drying, may lead to important grandients of moisture content and hence it increases the drying rate and boost the time of drying.The average moisture content attained 0.2 kg/kg d.b after 42min of CV/IR drying, while, it attained the same moisture content after 72min of convective drying.

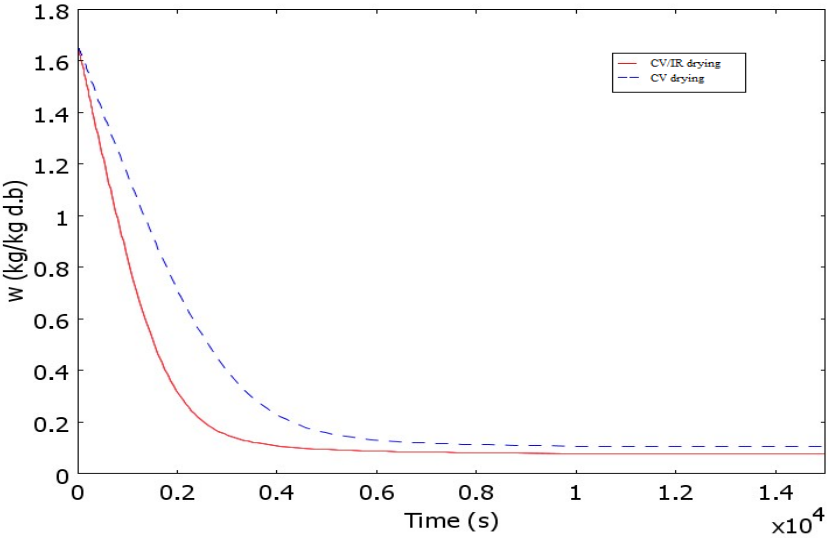

Figure 1 : Average moisture content variations versus time (Ta =60 °C, RH=23 %, P_{IR}=800W/m^2)

As shown in Fig.2, the temperature of the material surface is directly affected by the drying method. For both CVand CV/IR drying, the temperature rises quickly in the beginning of drying. Then, radiative heating is more efficient for higher moisture content values. In fact, the higher values of temperature during conv/IR drying can be explained by the fact that the surface of the sample is fed by two heating fluxes: a convective and a radiative one.

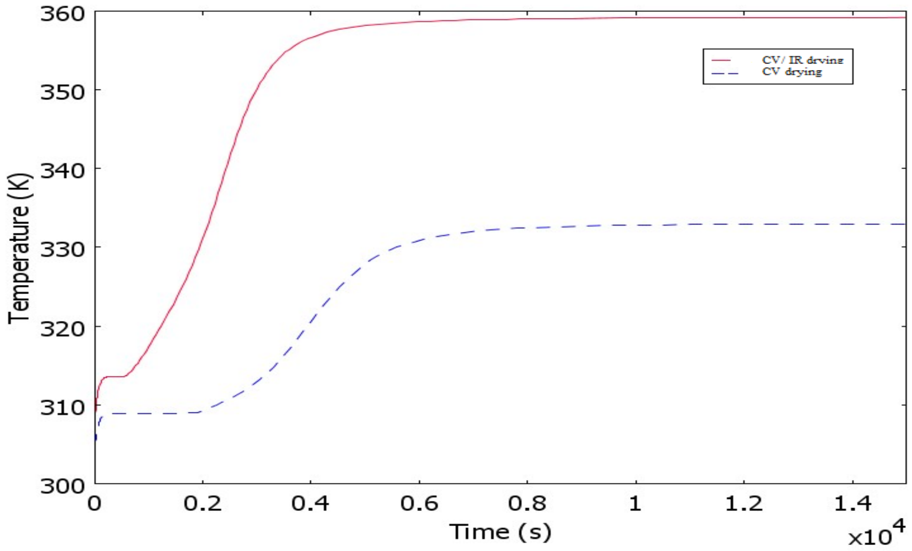

Figure 2 : Temperature distribution at the surface of the Bovine leather

3.2. Stresses profiles

Fig.3, 4 and 5 represent the time evolution of the distribution of the σ_{xx}, σ_{yy} and σ_{xy} stresses in the quarter of the Bovine leather sample simulated for bidirectional configurations for the two drying modes (CV,CV/IR), at air temperature of 60°C, relative humidity of 23% and P_{IR}=800w/m^2.

Fig.3 and 4 show the normal stresses field at different sample positions. At the beginning of drying, the stresses appeared due to the rapidity of the first drying phase as shown in Fig.1. Then, during the constant drying rate period, the stresses increase rapidly. This stresses are tensile in the surface exposed to the drying air and equilibrated by a compressive stress within the product. At the end of this phase the stresses reached her maximum and begin to decrease until the end of the drying. It is easy to notice that the maximum stresses are generated during combined convective infrared drying.

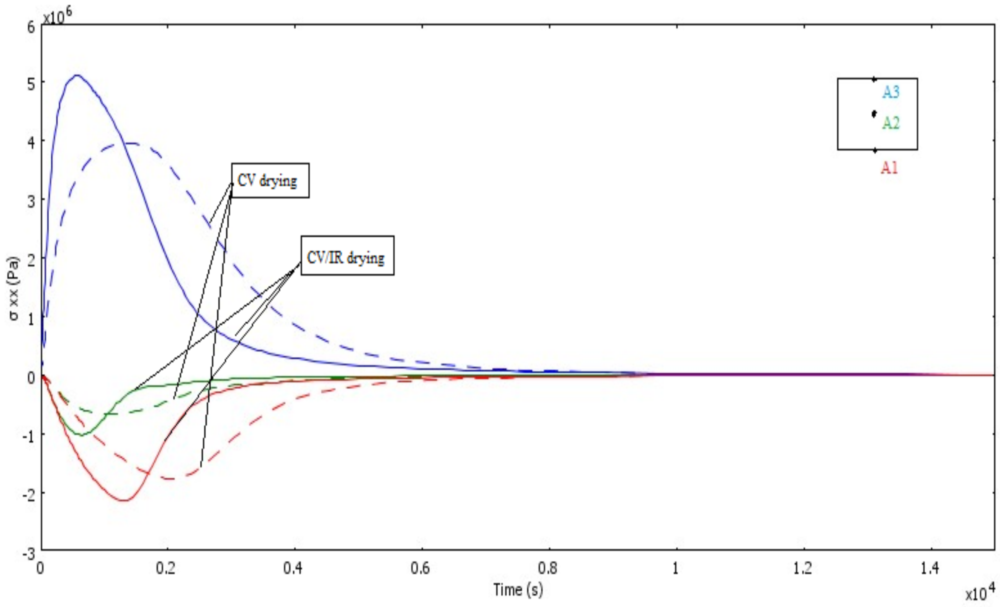

Figure 3 : Variations of stress σ_{xx} versus drying time at different sample positions (Ta =60 °C, RH=23 %, P_{IR} =800W/m^2)

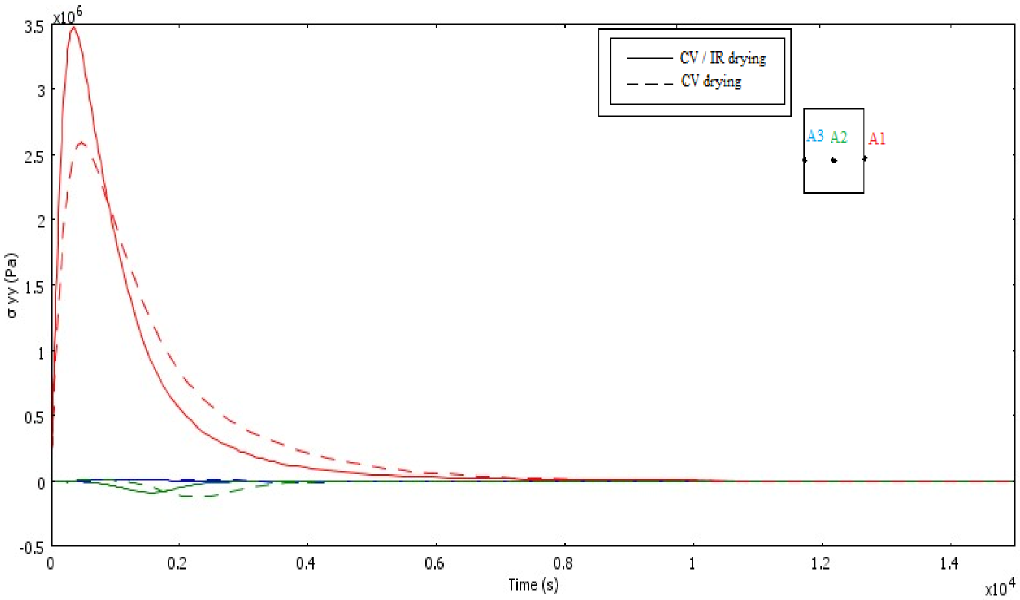

Figure 4 : Variations of stress σ_{yy} versus drying time at different sample positions (Ta =60 °C, RH=23 %, P_{IR} =800W/m^2)

Fig.5 presents the time evolution of shear stresses at different sample positions due to heterogeneous shrinkage occurring in the spatial directions. Their values are not so great as the other stresses (σ_{xx} and σ_{yy}), but shear stresses can destroy the material structure at significantly smaller values. Therefore, the cracks observed inside the dried material are mostly caused by shear stresses. The same as normal stresses, the lowest maximum compressive shear stresses are generated during combined convective infrared drying.

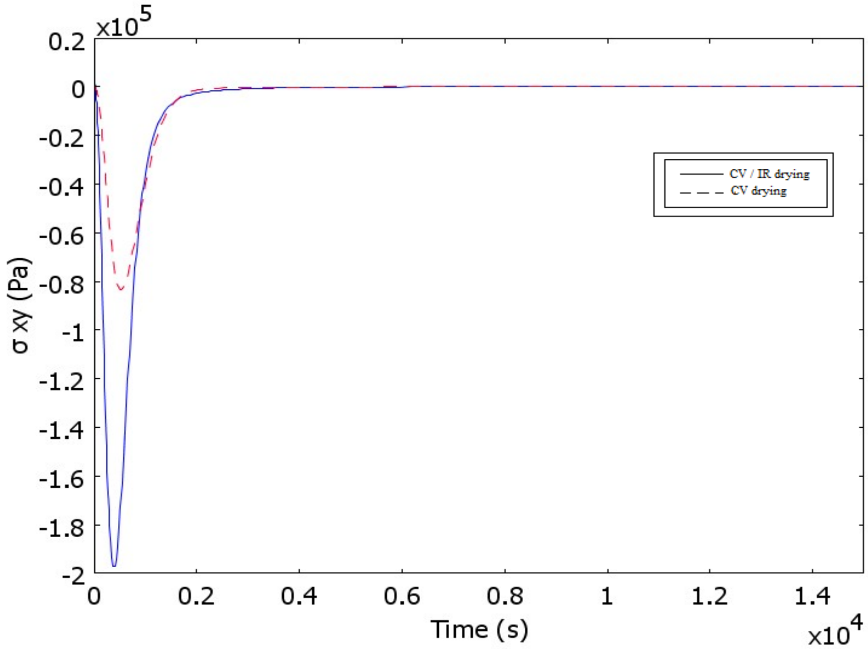

Figure 5 : The variations of stress σ_{xy} versus drying time obtained for convective drying at different sample positions (Ta =60 °C, RH=23 %, P_{IR} =800 W/m^2)

Conclusion

A mathematical model describing heat and mass transfers and the induced drying stresses in bovine leather sample during convective and combined convective-infrared drying was developed. Elastic mechanical behaviour of Bovine leather was considered. The model allows the simulation of distributions of moisture content, temperature, and induced drying stresses for a bovine leather material.

The comparison between the values of the average moisture content for the two drying modes shows that combined CV/IR drying gives faster drying. Moreover, the study shows that the elastic model keeps the stress sign at the end stage of the two drying modes. The generated stresses are more concentrated at the surface than in the inner of the product. The maximum stresses are generated during combined convective infrared drying.

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Nomenclature

Symbol Name, *unit*

Symbol	Name, unit
h	Heat transfer coefficient, *W.m^{-2}.K^{-1}*
L_v	Latent heat of water evaporation, *J.kg^{-1}*
C_p	Specific heat of the product, *kJ.kg^{-1}.K^{-1}*
C_{ps}	Specific heat of solid, *J.kg^{-1}.K^{-1}*
C_{pl}	Heat capacity of water, *J.kg^{-1}.K^{-1}*
D_{eff}	Effective diffusion coefficient, *m^2.s^{-1}*
w	Moisture content, *kg/kg d.b.*
w_{eq}	Equilibrium moisture content, *kg.kg^{-1} d.b.*
k_m	Mass transfer coefficient, *m.s^{-1}*
E	Young's modulus, *MPa*
$\vec{\mathbf{v}}_s$	Solid velocity (m.s^{-1})
Q_0	Power density radiated, *W/m^2*
$\dot{m}$	rate of moisture vaporization at the surface, *kg.m^{-2}.s^{-1}*

Grec symbol

λ_{eff}	Effective thermal conductivity, *W/(m.K)*
α	Thermal expansion coefficient
α_r	infrared absorbing coefficient
β	Hydric expansion coefficient
ρ	density, *Kg/m^3*
$\overline{\overline{\sigma}}$	stress tensor

Superscript, subscript

s	solid
0	initial

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