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Comparative numerical study of kaolin clay with three drying methods: Convective, convective–microwave and convective infrared modes

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A B S T R A C T

A mathematical model is developed to simulate the response of a kaolin clay sample when subjected to convective, convective–microwave and convective–infrared mode. This model is proposed to describe heat, mass, and momentum transfers applied to a viscoelastic medium described by a Maxwell model with two branches. The combined drying methods were investigated to examine whether these types of drying may minimize cracking that can be generated in the product and to know whether the best enhancement is developed by the use of infra-red or microwave radiation. The numerical code allowed us to determine, and thus, compare the effect of the drying mode on drying rate, temperature, moisture content and mechanical stress evolutions during drying. The numerical results show that the combined drying decrease the intensity of stresses developed during drying and that convective–microwave drying is the best method that gives a good quality of dried product.

1. Introduction

Drying is an essential operation in many sectors such as food and building materials. For food sector drying is used as a method of preservation. The vaporizing of water provokes a cracking of building materials during burning at temperatures up to 1000 °C. So the water used for forming must imperatively evacuated before burning, so the necessity of the drying operation.

The effectiveness of the drying technique is measured at two levels: operation cost and final product quality. In many cases, the drying time becomes important because of the production rate. Otherwise, time is less important but the quality of products: appearance and biological values in the case of food and pharmaceuticals products or good mechanical resistance in the case of wood and ceramics is relevant. Several types of dryers have been developed in an aim to respond to the requirements of quality and energy efficiency. With respect to thermal drying, there are several types of dryers in which technology is related to the mode of energy transfer. The conventional drying which is widely used but this method is not without drawbacks, since it requires considerable amount of energy and long drying times [1]. Among the disadvantage of such mode, it may be noted that convective heating achieves a lower rate of heat transfer than other heating methods. It also requires increased product exposure time and has as slower start-up/cool down than other heating methods. In addition the airflow in convective dryers can disturb or contaminate the product [2]. Therefore innovative drying methods have been recently developed. Radiative drying (infrared or microwave) was introduced. Radiant technologies are particularly advantageous for a drying operation compared to convective drying. They allow immediate and significant energy input to the product. The high power density applied to the product can significantly decrease the drying time but can also damage the material and modify its surface properties. To simultaneously minimize the drying time and the consumption of energy as well as to improve the quality of dried products, we must look for special methods of drying including hybrid drying in which two drying techniques are mixed [3].

Combined drying methods such as convective/infra-red (Conv/IR), convective/microwave (Conv/MW) and other methods are proposed by many authors [4–8]. Jaturonglumlert and Kiatsiriroat [9] studied heat and mass transfers in combined convective and far-infrared drying of fruit leather and found that the combined convective and far-infrared drying gives shorter drying time due to the higher heat and mass transfer coefficients compared with the hot air drying. Kocabiyik [10] studied infrared heating for food and agricultural processing and shows that since the temperature of the product is kept relatively low during the combined Conv/IR drying, thermal degradation of products can be retained considerably than by convective hot air drying [10]. Combined IR irradiation and hot-air drying has been reported to conserve energy and to improve quality for various products [11,12].

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Nomenclature

a_w	water activity
c	electrical conductivity of kaolin clay (S m^{-1})
c_p^s	specific heat capacity of the solid phase (J kg^{-1} K^{-1})
c_p^l	specific heat capacity of the liquid phase (J kg^{-1} K^{-1})
c_p	effective specific heat capacity (J kg^{-1} K^{-1})
D_{eff}	effective diffusion coefficient (m^2 s^{-1})
$\mathbf{e}$	mechanical deviatory strain
$\underline{E}$	electrical field vector (V m^{-1})
$E(t)$	relaxation function (Pa)
E_i	elastic modulus of branch i
G	shear modulus (MPa)
h	heat transfer coefficient (W m^{-2} K^{-1})
h_l	liquid specific enthalpy (J kg^{-1})
h_s	solid specific enthalpy (J kg^{-1})
$J_{D,l}$	diffusion flux vector of liquid phase (kg m^{-2} s^{-1})
K	bulk modulus (MPa)
k_{eff}	thermal conductivity (W m^{-1} K^{-1})
h_m	mass transfer coefficient between the product and air (m s^{-1})
L_v	latent heat of water evaporation (J kg^{-1})
$\dot{m}$	rate of moisture vaporization (kg m^{-2} s^{-1})
M_v	molecular weight of water (kg kmol^{-1})
Nu	Nusselt number (–)
n	outward oriented unit surface normal
Pr	Prandtl number (–)
P_{vsat}	equilibrium vapor pressure of pressure (Pa)
$\dot{Q}$	microwave volumetric heating (W m^{-3})
q	heat flux density (W m^{-2})
R	universal gas constant (J kmol^{-1} K^{-1})
Re	Reynolds number (–)
RH	Relative Humidity (%)
t	time (s)
T	temperature (°C, K)
u	displacement (m)
v	velocity (m s^{-1})
V	volume (m^3)
x	spatial coordinate (m)
w	moisture content (kg kg^{-1} d.b.)

Greek letters

α	microwave attenuation coefficient (m^{-1})
β	volume shrinkage coefficient
α_a	infrared absorption coefficient
$\boldsymbol{\varepsilon}$	strain
$\boldsymbol{\sigma}$	stress (Pa)
ρ	density (kg m^{-3})
ϕ	mechanical volumetric strain
v''^{l}	dielectric dissipation factor

Subscripts

surf	surface
0	initial
a	air
s	solid
ray	radiated
abs	absorbed
l	liquid

Numerous authors studied the combined Conv/MW drying. Lee [13] investigated the effects of convective air temperature on the microwave drying characteristics of Korean red pine wood. in this he demonstrated that the air heated the wood surface and the combined convective–microwave drying minimized the heat loss from wood heated by microwave. Itaya et al. [14] analyzed the behavior of drying-induced stresses in a ceramic molded slab by convective drying enhanced with microwave heating, and demonstrated that the drying process had completed successfully without crack formation at a remarkably shorter time than drying by convective heating. Mihoubi and Bellagi [15] examined the effect of combined drying Conv/MW heating on kaolin clay and show that the enhanced drying mode generates lower internal stresses than continuous convective drying.

There are some works studying stresses generated during convective and microwave drying [14–17]. Also, many experimental studies of heat and mass transfers of the drying of kaolin with different techniques (convective, infrared and microwave) have been investigated [6–8,18]. But no theoretical and experimental work has been reported on the drying induces stress with the three cited techniques together.

Therefore, our work deals with a comparative study of three methods of drying: the convective and combined convection/infra-red and the combined convection/microwave. The kaolin is considered as a viscoelastic material and modeled by a two branch Maxwell model. A two dimensional mathematical model is proposed. The drying model considers the coupled transfers of mass, heat and momentum. The developed model was solved numerically in order to evaluate and compare the temperature, the drying rate and time as well as the induced stresses for the three drying methods.

2. Mathematical modeling

The proposed mathematical model describes the mass and heat transfers in product kaolin sample during drying. These two transfers phenomena are associated with a rheological behavior. A parallelepiped shape is used as a physical configuration. The porous medium is a deformable product composed of a solid phase, and a liquid phase (water). The small thickness of the sample and the symmetry of the problem enable us to limit our study as shown in Fig. 1 to a quarter of the sample's section which is bounded by two exchange surfaces and two adiabatic surfaces.

The exchange surfaces are driven by convective flux (Fig. 1(a)), convective and radiative fluxes (Fig. 1(b) and (c)).

2.1. Mass conservation

The mass conservation for the solid and liquid phases are respectively:

$$\frac{\partial \rho_s}{\partial t} + \nabla \cdot (\rho_s \vec{v}_s) = 0 \quad \frac{\partial \rho_l}{\partial t} + \nabla \cdot (\rho_l \vec{v}_l) = 0 \qquad (1)$$

where ρ_i is the apparent density of the phase i, and v_i its velocity; i = 's' and 'l' for solid and liquid, respectively.

The liquid flux is the sum of a diffusive flux and a convective flux [19]

$$\rho_l \vec{v}_l = -\rho D_{eff} \nabla \left(\frac{\rho_l}{\rho} \right) + \rho_l \vec{v} \qquad (2)$$

where v is the barycentric velocity system.

For a product composed exclusively of liquid and solid and undergoing an ideal shrinkage, we can write the following relationship [20]: