



Modelling of heat and mass transfer in a granular medium during high-temperature air drying. Effect of the internal gas pressure



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ABSTRACT

A comprehensive internal heat and water transfer model including the gas pressure effect has been proposed in order to improve the industrial high-temperature air drying of inserts made of agglomerated sand. In this model, the internal gas phase pressure effect was made perfectly explicit, by considering the liquid and vapour transfer by filtration and the liquid expulsion at the surface. Wet sand enclosed in a tight cylindrical glass bottle dried convectively at a high temperature was chosen as an application case. The model was validated on the basis of the experimental average water content and core temperature curves for drying trials at different operating conditions. The simulations of the spatio-temporal distribution of internal gas pressure were performed and interpreted in terms of product potential damage. Based on a compromise between the drying time and the pressure increase, a simple drying cycle was implemented in order to optimize the drying process.

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1. Introduction

The context of this study is the application of high-temperature heating for drying enhancement of agglomerated sand used as container inserts for industrial purposes. The wet agglomerate used as a filling material for containers is composed in general of calibrated sand and of the aqueous solution of a mineral binder. The goal was to predict the spatio-temporal evolution of the moisture content, the temperature and the internal gas pressure within the wet agglomerate sand. The product damage was supposed to be entirely due to the gas phase (vapour and air) overpressure inside the sample [1]. To accelerate the industrial drying of the containers' interiors, it is intended to use intensive drying conditions, like high-temperature convective drying. In this way, the core temperature can quickly reach the water boiling point [2]. In this case, the intense water vaporization induces a strong rise in the pressure of the internal gas phase (vapour and air); such pressure literally pushes the water within and out of the product, which increases very significantly the drying rate [3,4]. However, the internal overpressure that exerts a stress on the material can be a cause of cracking and a compromise must be sought between the drying rate and the pressure raise while defining the operating conditions. The work was carried out in three steps. First, an internal heat and mass transfer model was developed, mainly based on the equations of Constant et al. [5] and Perré and Turner [6]. In this model, the boundary conditions must be adapted in a way that enables liquid water ex-

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List of symbols

C_p^{eq}	Equivalent specific heat capacity of the product..... J/kg/K	P_g	Total pressure of the gas phase within the product..... Pa
C_{pl}	Specific heat capacity of liquid water .. J/kg/K	P_v	Water vapour pressure within the product Pa
D_v^{eq}	Equivalent water vapour diffusivity of the product..... m ² /s	R	Ideal gas constant..... J/mol/K
h	Heat transfer coefficient at the product surface..... W/m ² /K	t	Time..... s
h_m	Mass transfer coefficient at the product surface..... m/s	T	Product temperature..... °C, K
K_g^{eq}	Equivalent gas phase permeability of the product..... m ²	X	Product water content dry basis..... kg/kg
K_l^{eq}	Equivalent liquid phase permeability of the product..... m ²	<i>Greek symbols</i>	
M_a	Air molar mass..... kg/mol	Δh_{des}	Specific differential enthalpy of water desorption..... J/kg
M_v	Water vapour molar mass..... Pa	Δh_{vap}	Specific differential enthalpy of water vaporization..... J/kg
n	Mass flux..... kg/m ² /s	ϕ_0	Dry product total porosity
P_{atm}	Atmospheric pressure..... Pa	λ_{eq}	Equivalent thermal conductivity of the product..... W/m/K
P_c	Capillary pressure within the product..... Pa	ν_l	Kinematic viscosity of liquid water..... m ² /s
		ρ_0	Dry product apparent density..... kg/m ³
		ρ_l	Liquid water density..... kg/m ³

pulsion at the surface. This adaptation is generally omitted or not explicated in the literature and, to our best knowledge, only Constant et al. [5] considered it and give some precisions about its implementation. Second, the model was validated by comparing the experimental and simulated mean water content in the product and the core temperature curves. The application material was wet sand enclosed in a cylindrical glass bottle. The drying trials were realized in a laboratory hot-air drying tunnel. The equations of our model were solved by means of the COMSOL “Multiphysics” software (v. 3.5), but using the open “PDE coefficient form” mode and not the predefined heat and mass transfer modules. Finally, the model was used to simulate the spatio-temporal evolution of the state variables within the material during the drying process. Based on these simulations, an optimized simple drying schedule was implemented.

2. Methods

2.1. Internal transfer model

The mathematical model proposed in this paper for describing the physical phenomena involved in hygroscopic capillary porous medium subjected to high-air-temperature drying was based on the macroscopic approach of Whitaker [7]. This theory has been successfully adapted and applied to several configurations of granular medium drying, including configuration, which generates intense mass transfer due to an important internal overpressure. The internal heat and mass transfer model was based on the equations of Constant et al. [5] and Perré and Turner [6]. A special emphasis will be applied to the boundary conditions because of the ‘water pumping’ phenomenon. The formulation of the boundary conditions is one of the original contributions to this study.

2.1.1. Water transfer

The liquid phase flows by filtration due to the gas phase pressure (P_g) gradient and by capillarity due mainly to the liquid water content (X) gradient (the influence of the temperature gradient on the capillary flow is neglected). The liquid flux is thus given by:

$$n_l = -\frac{K_l^{eq}}{\nu_l} \text{grad } P_g + \frac{K_l^{eq}}{\nu_l} \frac{\partial P_c}{\partial X} \text{grad } X \quad (1)$$

where K_l is the product liquid permeability, ν_l is the liquid viscosity, P_c is the capillary pressure (as a function of the water content X).

The transfer equation is obtained by inserting the above flux expression in the local mass balance equation and is written as follows:

$$\rho_0 \frac{\partial X}{\partial t} = -\text{div}(n_l + n_v) \quad (2)$$

In equation (2), n_v is the flux of water vapour. The vapour is supposed to move by filtration due to the gas phase pressure gradient, by thermo-diffusion due to the temperature gradient and by ordinary diffusion due to the water content gradient. This flux is hence given by:

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