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Modelling of the shape effect on the drying shrinkage of wet granular materials

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ABSTRACT

The objective of this work is to suggest an analytical model that describes the influence of the shape on the drying and shrinkage of a granular matrix. The model was established for the stationary regime of mass transfer, the constant drying flux period, which allows a simply analytical solution of the mass balance. In this specific regime we observe the major part of the shrinkage of a deformable wet granular medium. The model, which integrates explicitly the dependence of the liquid/gas exchange surface by its relation with the product shape, gives the kinetics of average water content, volume deformation, and compactness at the product scale. Several geometries were analyzed: sphere, cylinder, cube, ellipsoid, isosceles tetrahedron, cone torus, and a film. Experimental drying and shrinkage kinetics of two different granular media (kaolin and microcrystalline cellulose) were determined under soft-drying conditions. This confrontation between simulation and experimental data gives the elements of the model validation. It was found that, during the constant drying flux period, the predicted results obtained from the suggested model are found to be in good agreement with the determined kinetics. The model could be used to predict ideal shrinkage and water content evolutions of a medium with a given shape.

1. Introduction

The drying of deformable heterogeneous media (e.g. gel, soils, concrete, pastes, wood, sludge, etc.) is usually accompanied by a mechanical contraction, called shrinkage. This phenomenon is controlled by the physicochemical nature of the compounds, by the initial hydrous state of the media and by the applied process conditions (Jomaa and Puiggali, 1991; Rahman, 2001; Huisheng et al., 2015; Jangam et al., 2016). The shrinkage occurring during a drying process could be the cause of certain modifications in the mechanical properties of the medium. It could be observed for example on soil surface and on porous construction materials due to seasonal climatic variations (Mitchell and Soga, 2005; Gascha et al., 2016). This is the case for concrete where the shrinkage is made up from three different processes: autogenous shrinkage, drying shrinkage and thermal contraction, all of which can have variable magnitudes (Eguchi and Teranishi, 2005; Ye and Radlińska, 2016) and the evolution of the rheological behavior need to be taking into account (Rougelot et al., 2009). Shrinkage results from complex coupling phenomena, and each contribution are not easily to be "deconvolving". This is not an easily controllable phenomenon. It can lead to consolidation which could increase the mechanical strength of the medium, but also to warping, fissuring and cracking which could damage the product and give a degradation of its mechanical characteristics (Kowalski, 1996; Augier et al., 2002). It often takes place during materials shaping by "wet-based processes" such as extrusion (Galland et al., 2003; Song et al., 2007) and agglomeration (Goldszal and Bousquet, 2001; Rondet et al., 2010), in bio-products elaboration such as foodstuffs (Ratti, 1994; Mayor and Sereno, 2004; Madiouli et al., 2012) or other various organic and mineral raw materials (Caquineau et al., 2003; Faure and Coussot, 2010). The added liquid binder mixed with a granular

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Nomenclature

A_{ex}	Area of the liquid/gas exchange surface (m^2)
d_s^*	True density of solid phase (/)
e	Slenderness ratio of a cylinder or eccentricity of an ellipsoid (/)
F	Drying flux (kg of water × $kg^{-1}$of dry solid × m^{-2} s^{-1})
h	Height or thickness (m)
m	Mass (kg)
r,R	Radius (m)
t	Time (s)
V	Volume (m^3)
w	Water content (kg of water × $kg^{-1}$of dry solid)

Greek letters

α	Half angle at the top for a cone (°)
β	Constant of the model in Eq. (5) (s^{-3})
ε	Shrinkage or volume deformation (/)
ϕ	Compactness (/)
γ	Shape factor (/)
κ	Constant of the model in Eq. (14) (s)
ρ	Ratio of the radius if a tore (/)
ρ^*	True density (kg m^{-3})
τ	Constant of the model in Eq. (5) (s)

Subscripts

c	Critical
init	Initial
s	Solid phase
w	Water phase

medium (e.g. powder) aims to promote a plasticity in the medium, which then acquires its shape. The final product is obtained afterwards by the extraction of the liquid binder. The morphogenesis of the desired shape of the product is a result of the combination of formulation, chapping and processing associated with mass and energy transfer conditions. The later morphogenesis is usually observed in the case of certain products processed by pharmaceutical, paper, food, bioproduct, ceramic or chemical industries (Nadeau and Puiggali, 1995). Usually, a drying stage is included in the production process to finalize the formation of the products. The control of the deformations resulting of the drying shrinkage is important in order to control the shape and texture of the products or to stabilize its mechanical characteristics.

From a macroscopic point of view, such deformations result from the rheological ability of the medium with the variation of the interstitial liquid volume which is activated by the mass and energy transfers implied by drying (Bird et al., 1960; Nadeau and Puiggali, 1995; Kowalski, 2000; Katekawa and Silva, 2006). Also, if the mechanical aspect of the shrinkage is associated to the description of the solvent (water) and heat transfers, it could be highly recommended to identify the respective influences of the rheological properties of the product and the applied process conditions.

For biphasic materials and porous media, those saturated by an interstitial liquid, the evolutions of the average water content and the volume deformation are usually split in a succession of periods. These periods are identified on the well-known characteristic drying curve where the drying flux was plot versus water content (Fig. 1). After the establishment of a thermal equilibrium between the drying air and the product, drying and shrinkage kinetics usually reach a steady state called the constant drying flux period. During this period, the drying rate is controlled primarily by the characteristics of the aerothermic process conditions at the air-product interface. It is during the drying flux period that the mass transfer is the most intense. The induced mechanical shrinkage seems also considerable and implies a significant densification in the texture of the dried medium. One or several drying periods take place before the water content of the media reaches its equilibrium value, obtained from the sorption isotherm, at the end of the drying. The identification of these periods and the study of the constant flux period, seem essential to control the drying. One could particularly mention a problem related to the identification of the critical water content, which characterizes the transition between the constant flux period and the first decreasing flux period that follows subsequently (Mujumdar, 2015). Moreover, it is essential to assess the coupling between several implied phenomena: mass transfer at the liquid–gas interface, interstitial liquid migration within the porous medium to the gas liquid interface, and the mechanical behavior of the medium (Kowalski, 2000). The drying rate is controlled by one of the later phenomena that could be considered as the limiting phenomena (Prat, 2002). All these transfer, transport, and mechanical phenomena would be modulated according to products shape. An important example is the mass transfer dependence on the extension of the area of the liquid/gas exchange surface which is in relation with the product shape. The mechanical shrinkage impact the volume of the product and would also change the value of area of the liquid/gas exchange surface during drying (May and Perré, 2002). So, in a drying model, it would be important to take into account the geometrical relation between the product shape and its surface, for modelling this effect on the drying rate.

The aim of this work is, first, to propose a drying model, in product scale, which takes into account the mechanical shrinkage associated to the constant flux period, and to the shape factor of the product. Our study is limited to multiphase media, initially biphasic (solid and liquid), deformable, isotropic whose mechanical shrinkage could be supposed to be ideal. Our suggested model integrates the influence of the ideal mechanical shrinkages on the drying rate via the reduction of the liquid/gas exchange surface. Several ideal geometries were considered in our study and the shape factors of these geometries were integrated in our suggested model, considering that the liquid/gas exchange surface is the whole external surface of the product volume. The suggested model has an analytical solution that expresses the kinetics of the average water content of the product, i.e. the drying kinetics.

Our research work also suggests a validation of the suggested model based on a comparison between calculated and experimental data obtained from drying two different granular media under soft drying conditions.

2. Drying model with ideal shrinkage

The analysis of the drying kinetics at the product scale, starting from the characteristic drying curve, makes it possible to identify several distinct drying periods (Nadeau and Puiggali, 1995; Kowalski, 2000). These distinct periods seem to result from the succession of distinct phenomena (Fig. 1). In soft convective drying conditions at low aerothermic velocity and isothermal transfer, the mass transfer kinetic begins (as soon as the product reaches a thermal equilibrium with the drying air) by a constant drying flux period. This steady state period is characterized by a constant value of the drying flux. This

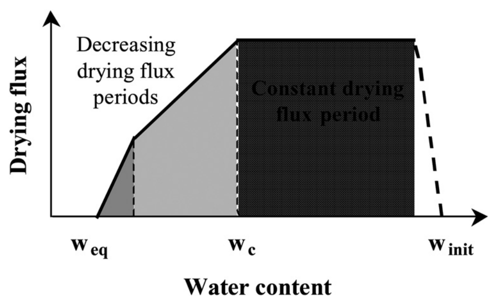

Fig. 1 – Cartoon of a standard drying curve.