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Drying of clay slabs: Experimental determination and prediction by two-dimensional diffusion models

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Abstract

Experiments on convective drying of clay slabs with an initial moisture content of 0.11 (dry basis, db) were performed at 50 and 90 °C. A two-dimensional numerical solution of the diffusion equation with a boundary condition of the third kind was proposed to describe the process using a constant (model 1) and variable (model 2) effective mass diffusivity value. The solution was coupled with an optimizer to determine the process parameters at each temperature using experimental datasets. The analyses of the results indicated good agreement for model 2 between each experimental dataset and the corresponding simulation.

Keywords: Effective mass diffusivity; Two-dimensional domain; Numerical simulation; Optimization

1. Introduction

The brick and roof tile industry is important in virtually every country in the world. Clay is the basic component in fabricating bricks and tiles. To manufacture these products, clay is dried, de-agglomerated and sieved. Afterward, the powder is homogenized in water, and the obtained mass is kept standing for a given amount of time. A wet product is obtained by extrusion, which is later molded into the desired shape and size. After this stage and before the sintering process, the excess water in the product is removed. As noted by Su [1], without a drying stage, the heat emanating from the sintering process will turn the water into steam inside the clay slab, which will severely damage the product. Thus, most of the water found in the product should be removed through a drying process that must be performed prior to burning.

According to Musielak and Mierzwa [2], the drying process usually influences the quality of the resulting product. It is well known that high temperatures and long drying times can significantly decrease the quality of the dried materials (change of color, permanent change in shape, inner structure damage, surface hardening, chemical changes, etc.). During drying, temperature and moisture gradients can produce stresses that generate deformations and/or cracks [1,3–6]. Consequently, a detailed description of this process is important in providing the necessary information required to produce a final item of good quality at minimal waste [7]. To describe the drying process, a mathematical model is usually used, and this model provides information that enables determining the stresses within the product [1,8,9]. Generally, water removal occurs at constant and falling rate periods [5,6,8,10]. However, depending on the value of the initial moisture content and/or the clay mineralogical content, the drying process can occur within an extremely short time period at a constant rate or only at a falling rate [7,10]. In such cases, a diffusion model can be used to describe either the entire drying process or a significant part of this process [6,7,10–12].

The definition of a diffusion model should include the following conditions: the solution is analytical [7,9,10] or numerical [6,12]; the boundary condition is of the first [9,12] or third [6,7,10] kind; and the geometry is one- [7,9,10], two- [7] or three-dimensional [6,7,12]. Recently, Silva et al. [6] described

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Nomenclature

A, B, a, b	coefficients of the discretized diffusion equation or fitting parameters
C	length of slabs
D	effective mass diffusivity (m^2 s^{-1})
h	convective mass transfer coefficient (m s^{-1})
H	height of rectangle (m)
L	thickness of rectangle (m)
M	local moisture content at time instant t (db, kg kg^{-1})
$\overline{M}$	average moisture content at time instant t (db, kg kg^{-1})
M_0	initial moisture content (db, kg kg^{-1})
M_{eq}	equilibrium moisture content (db, kg kg^{-1})
$\overline{M}_i^{exp}$	measured value of the moisture content for experimental point i (db, kg kg^{-1})
$\overline{M}_i^{sim}$	simulated moisture content for experimental point i (db, kg kg^{-1})
M_P^0	moisture content in control volume P at the beginning of a time step (db, kg kg^{-1})
N_p	number of experimental points (dimensionless)
N	number of control volumes (dimensionless)
R^2	coefficient of determination (dimensionless)
S	area (m^2)
t	drying time (s)
T	temperature (°C)
x,y	cartesian coordinates (m)
σ_i	standard deviation of experimental point i (db, kg kg^{-1})
χ^2	chi-square or objective function (dimensionless)

convective drying of clay slabs at air temperatures of 50, 60, 70, 80 and 90 °C. The initial moisture content of the product was 0.23 (db), and according to the authors, the process consisted of two periods: a constant and a falling rate. For the falling rate period, the model chosen by the authors to describe the process was a diffusive model using a three-dimensional numerical solution. The reason given by the authors for the choice of this model was that it would avoid the following simplifications: (1) the imposition of a constant value for the effective mass diffusivity (and volume) and (2) a one-dimensional representation of the clay slabs. The chosen model enabled a rigorous description of the drying process and can predict the moisture content at any position within the slab at a given instant of time. However, determining the process parameters using an optimization technique requires long time. Therefore, it seems appropriate to investigate whether a two-dimensional numerical solution of the diffusion equation can describe the process faster than the typical three-dimensional numerical solution.

The main objective of this paper is to propose a two-dimensional numerical solution for the diffusion equation in Cartesian coordinates using the finite volume method and to use the solution to describe the drying process of clay slabs.

2. Material and methods

2.1. Two-dimensional diffusion equation

The diffusion equation applied to a water migration process within a porous medium is generically written as

$$\frac{\partial M}{\partial t} = \nabla(D\,\nabla M), \tag{1}$$

where M is the moisture content (kg$_{water}$ kg$^{-1}_{dry\ matter}$, dry basis, db), t is time (s) and D is the effective mass diffusivity (m^2 s^{-1}). Depending on the geometry of the medium, a specific coordinate system should be chosen to solve Eq. (1). For example, for slabs, the appropriate system is Cartesian coordinates.

Many times in a diffusion process, the dimensions of the parallelepiped that represents a slab allow one to disregard the fluxes at the two smaller surfaces. In this case, to describe the process, the two-dimensional diffusion equation can be used. If there is symmetry, to save processing time and computational memory, only a quarter of the rectangle that represents the domain is studied, as shown in Fig. 1.

Observing Fig. 1, it can be seen that the mass flux in the z-direction can be disregarded when compared with the mass fluxes in the x- and y-directions. For a quarter of the rectangle, it can also be observed that due to the symmetry, the mass fluxes at the west and south boundaries are zero. In this figure, h_n and h_e represent the convective mass transfer coefficient at the north and east boundaries, respectively, and M_{eqn} and M_{eqe} represent the equilibrium moisture content at the same boundaries.

For the physical situation described above, the diffusion equation in Cartesian coordinates is given by

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D\frac{\partial M}{\partial x}\right) + \frac{\partial}{\partial y}\left(D\frac{\partial M}{\partial y}\right), \tag{2}$$

where x and y are the position coordinates (m).

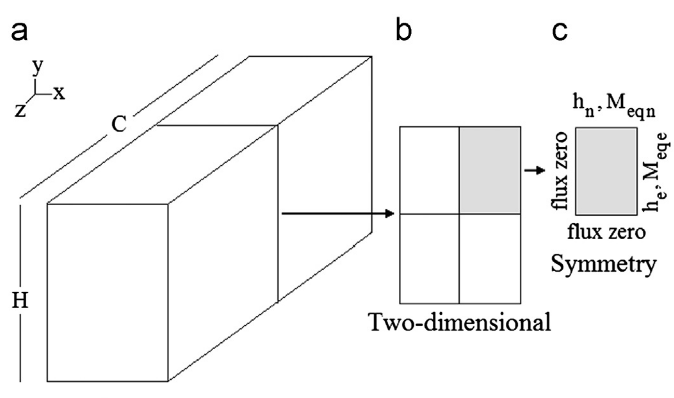

Fig. 1. (a) Parallelepiped; (b) two-dimensional slab domain and (c) symmetrical quarter of the rectangle.