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Research Article

Three Dimensional Simulation of Heat and Mass Transfer During Facing Brick Drying#

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Abstract: This work is devoted to presenting a 3-D drying of facing brick from two perspectives: theory and industrial practice. A Three-dimensional unstructured Control Volume Finite Element Method (CVFEM) is developed in order to simulate unsteady coupled heat and mass transfer phenomena that arise during convective drying of unsaturated porous media. In order to simulate 3-D complex geometries, as application here the drying of facing brick, we used the free mesh generator Gmsh. Several simulation results are presented that depict the new possibilities offered by such a tool. In particular, the simulation of a whole facing brick at the industrial scale.
This simulation proves that only three spatial dimensions are able to explain the heat and mass transfer during drying process. Indeed, thanks to this 3-D tool and unlike 2-D model we can observe for the first time unexpected thermal field, liquid saturation and pressure distributions for whole facing brick at the industrial scale and hence evaluating the correct drying rate under the real conditions.

1. Introduction

Drying which is a classical problem of transport in porous media is one of the most energy intensive industrial processes with applications in a wide variety of industries but its scientific understanding requires considerable efforts. Consequently, considerable researches have been conducted to numerically simulate the drying process. Drying is a process involves a coupled heat and mass transfer in a multi-phase flow in porous media. Based on the theory proposed by drying Luikov [1] and later by Whitaker [2], several mathematical models for drying porous materials have been developed. The first digital studies began on simple geometry and easy to discretize in regular and Cartesian grid. In this context some methods have been developed. In addition, the finite difference method has been widely used in the numerical simulation of mass and heat transfer in porous media. Moreover, this method may causes numerical dispersion and grid orientation problems [3]. It also gives rise to difficulties in the treatment of complicated geometry and boundary conditions. To overcome these deficiencies, the intrinsic grid flexibility of the finite element method has been utilized [4], but this method does not conserve mass locally. Recently, the Control Volume Finite Element Method (CVFEM) has been developed to enforce such a conservation property [5].
Thus, this work presents a contribution to the establishment by MVCEF of a digital three-dimensional simulation of heat and mass transfer during drying of unsaturated porous media with complex geometries.

2. Mathematical model

The proposed problem, which is described by Figure 1, is an industrial problem treating the drying of whole facing brick.

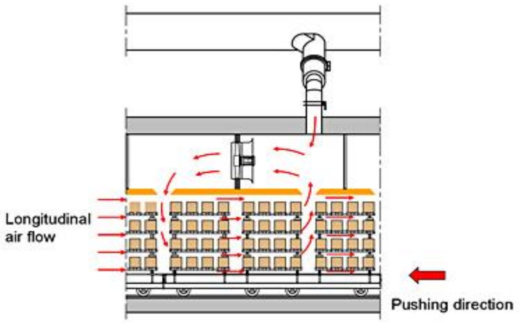

Figure 1. *Industrial dryer of facing bricks.*

The system considered in this work is a facing brick (Figure 2) which is composed of:

- An inert and rigid solid phase (brick matrix).

- A liquid phase (pure water).

- A gaseous phase which contains both air and water vapor.

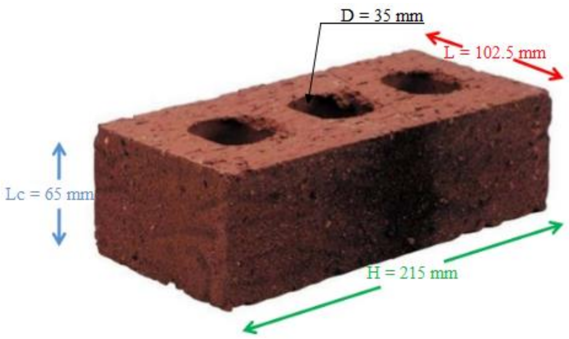

Figure 2. *Facing brick dimensions.*

2.1. Governing equations

Inspiring by Whitaker theory [2], a mathematical model governing heat and mass transfer is established for the unsaturated porous media.
In order to obtain a closed set of governing macroscopic equations, the following assumptions are made:

- The porous layer is homogenous and isotropic.
- The solid, liquid and gas phases are in local thermodynamic equilibrium.
- The compression-work and viscous dissipation are negligible.
- The gas-phase is ideal in the thermodynamic sense.
- The dispersion and tortuosity terms are interpreted as diffusion term.
- The radiative heat transfer is negligible.

Considering these assumptions, macroscopic equations governing heat and mass transfer in the porous medium are:

- Mass conservation equations:

For liquid phase:

$$\frac{\partial \varepsilon_l}{\partial t} + \nabla(\overline{V_l}) = -\frac{\dot{m}_v}{\overline{\rho}_l} \quad (1)$$

For Vapor phase:

$$\frac{d\overline{\rho_v}}{dt} + \nabla\left(\overline{\rho_v}^g\, \overline{V_v}\right) = \dot{m}_v \quad (2)$$

$$\overline{\rho_v}^g\, \overline{V}_v = \overline{\rho_v}^g\, \overline{V}_g - \overline{\rho}_g^g D_{eff} \nabla\left(\frac{\overline{\rho_v}}{\overline{\rho_g}^g}\right) \quad (3)$$

- Energy conservation equation:

$$\frac{\partial}{\partial t}\left(\overline{\rho C_p}\,\overline{T}\right) + div\left[\left(\overline{\rho}_l^l C_{pl} \overline{V}_l + \sum_{k=a,v} \overline{\rho}_k^g C_{pk} \overline{V}_k\right)\overline{T}\right] = \nabla\left(\lambda_{eff}.\nabla\overline{T}\right) - \Delta H_{vap}.\dot{m}_v \quad (4)$$

2.2. Boundary and initial conditions

Initially, the temperature, the gas pressure and liquid saturation are uniform in the brick, as shown in Figure 3.
Thermal energy brought by air convection is necessary for water evaporation and to the heat conduction in porous medium. This energy is function of temperature and heat transfer coefficient.

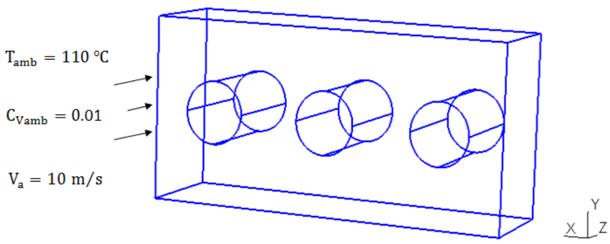

Figure 3. *Operating conditions of drying process.*

3. Solution method

The equations set, with initial and boundary conditions has been solved numerically using the Control Volume Finite Element Method (CVFEM). For the mesh generation (Figure 4), we use the free mesh generator "**Gmsh**".

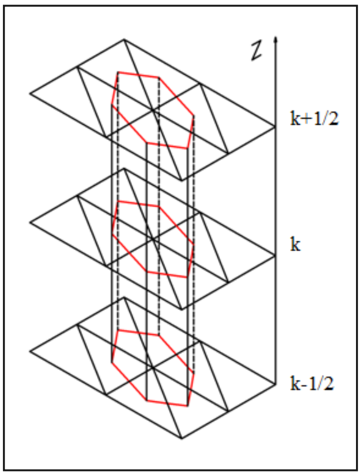

Figure 4. *Control volume and sub-volume.*

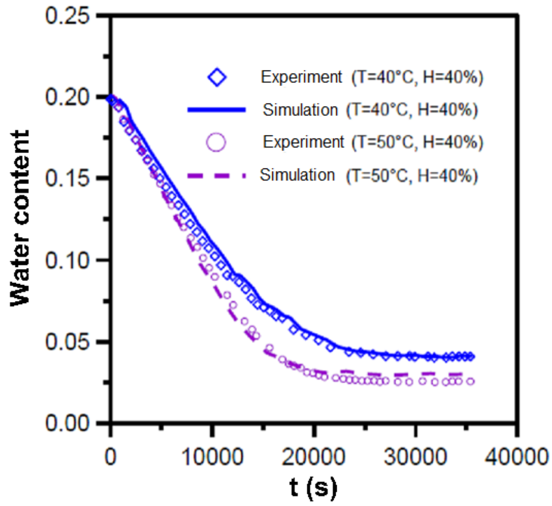

Figure 5. *Comparison of numerical and experimental of average water content.*

4. Experimental validation

The coupled heat and mass transfer model is validated by means of a convective drying experiment developed by Saber CHEMKHI [6].
The experiment was conducted on a rectangular plate size (15x12x1.5 cm^3).
The operating conditions used are presented in Table 1.

Table 1. *Operating conditions for the validation*

T_{amb} (°C)	40	50
T_{ini} (°C)	25	
Initial water content (kg/kg b.s)	0.1995	
C_{Vamb}	0.01	
P_{amb} (atm)	1	
Relative humidity (%)	40	
Air velocity (m/s)	2	

Referring to Figure 5, which shows the time evolution of the water content, there is overall good agreement between the numerical results and the experimental data.

5. Results and discussions

The operating conditions are takers the same of a typical industrial drying process which are listed in Table 2.

Table 2. *Operating conditions.*

T_{amb} (°C)	T_{ini} (°C)	S_{ini} (%)	C_{Vamb}	P_{amb} (atm)	P_{ini} (atm)
110	20	50	0.01	1	1

From the time evolution of temperature, liquid saturation and gaseous pressure for five nodes aligned along the z axis which are depicted in Figure 6, we can clearly observe the three conventional drying phases:

- The transient heating phase
- The constant drying rate phase
- The decreasing drying rate phase:
  - First decreasing drying rate period
  - Second decreasing drying rate period

In order to better observe the mechanisms of drying, we have shown in Figure 7 the spatiotemporal evolutions of temperature, liquid saturation and gaseous pressure during the drying of facing brick.

Figure 7 represents the distribution of the temperature, the liquid saturation and the gaseous pressure of the drying of facing brick at 5 h of drying.

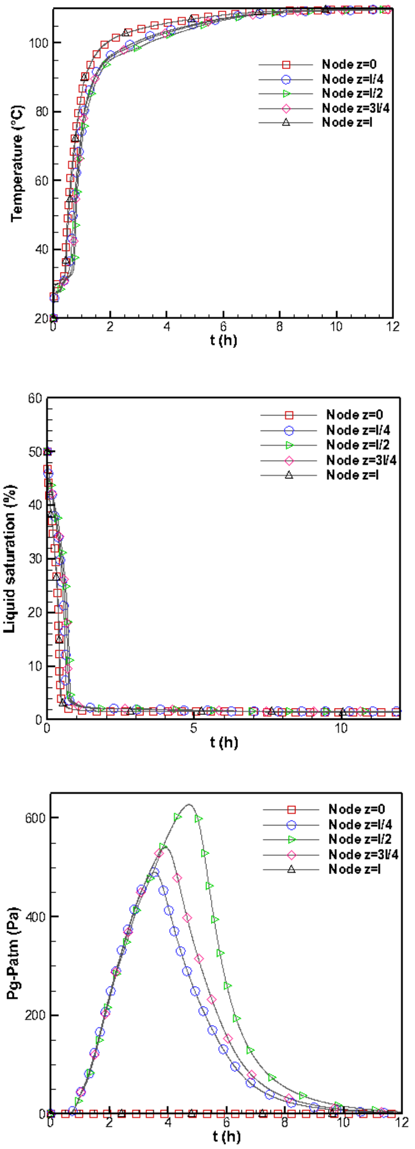

Figure 6. *Evolution of temperature, liquid saturation and pressure for five nodes aligned along the z axis.*

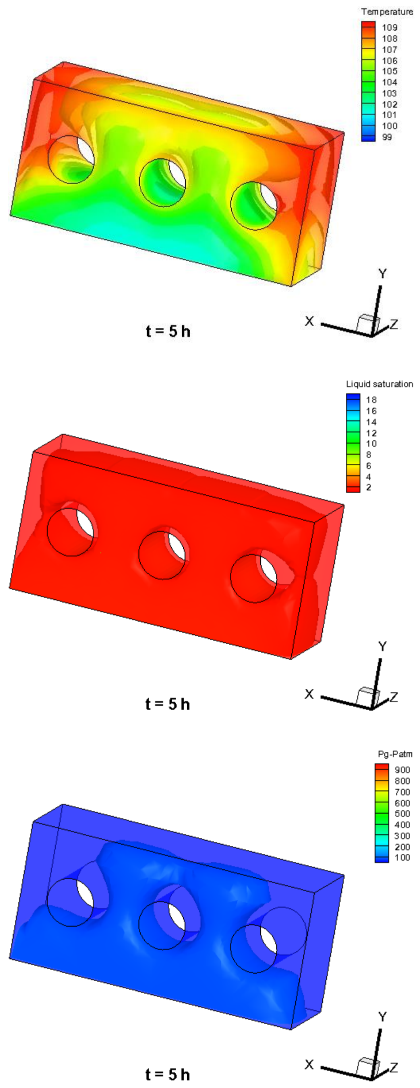

Figure 7. *Distribution of the temperature, the liquid saturation and the gaseous pressure inside facing brick.*

The presence of three orthogonal exchanging faces forces the liquid saturation to be very low at the corners and given the fact of the gravity, it is clear that only the core of facing brick retains a high value of liquid saturation. Moreover, the temperature and pressure fields allow more subtle phenomena to be observed. The temperature gradient is required to supply the energy necessary for the evaporation which occurs rapidly and intensively near the exchanging faces. Also the temperature varies significantly in space only in the region of vapor migration (gaseous Darcy's flow and vapor diffusion). The pressure gradient that exists in this region results from a cross diffusion effect of vapor and air, and in the domain of free water, almost no pressure gradient exists.

6. Conclusions

For the first time, a 3-D drying model that is able to deal with a comprehensive set of macroscopic equations for three-dimensional drying of a whole facing brick at the industrial scale has been established.

From the presented numerical results that highlight the phenomena accompanying the drying of unsaturated porous media (facing brick), we can conclude that:

- The model successfully simulates the appearance and the evolution of the different phases of convective drying.
- The model allows simulating problems of heat and mass transfer for three-dimensional complex geometries.

- The physical analysis presented in this work highlights the ability of this code to be closer to reality than every before.

In the end, the new 3-D version of heat and mass transfer during drying of facing brick appears to be a very promising tool for improving the understanding of the drying process and therefore shows the limitations of the two-dimensional numerical studies to solve this kind of problems.

Nomenclature

C_a specific heat of the air $[kJ/kgK]$
C_p specific heat at constant pressure $[kJ/kgK]$
C_v specific heat of the vapor $[kJ/kgK]$
C_w specific heat of the water $[kJ/kgK]$
$D_{A,B}$ diffusion coefficient [m^2/s]
D holes diameter [m]
g gravitational acceleration [m/s^2]
h_m convective mass transfer coefficient$[W/m^2°C]$
h_t convective heat transfer coefficient$[W/m^2°C]$
K intrinsic permeability [m^2]
L_c characteristic length of brick [m]
M_a molar mass of air [kg/mol]
M_v molar mass of vapour [kg/mol]
$\dot{m}$ evaporation rate [kg/s]
n_i outward normal vector
P pressure [Pa]
Pc capillary pressure [Pa]
P_{Vs} partial pressure of saturated vapour [Pa]
R gas constant $[J/Kmol]$
r characteristic magnitude that represents the average radius of curvature of the menisci if the retention forces of the liquid are of capillary origin
S liquid saturation [%]
T temperature [K]
t time [s]
w_a air velocity $[m/s]$

Greek symbols

ε porosity
ε_l volume fraction of liquid phase
μ dynamic viscosity [kg/ms]
ϑ cinematic viscosity $[m^2/s]$
ρ density [kg/m^3]
λ conductive transfer coefficient $[W/m°C]$
σ surface tension $[N/m]$
ΔH_{vap} vaporisation latent heat [J / Kg]

Subscripts

0 initial condition
A air
eff effective
g gas
l liquid
v vapour

Dimensionless groups

R_e Reynolds number
P_r Prandtl number
S_c Schmidt number

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