J Biochem Tech (2019) Special Issue (2): 92-97
ISSN: 0974-2328

Large Evaporation Rates in Porous Media

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Received: 29 September 2018 / Received in revised form: 14March 2019, Accepted: 17 March 2019, Published online: 25 May © Biochemical Technology Society 2014-2019
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Abstract

Evaporation is often known as the removal of moisture from the soil or capillary porous media. Evaporation in porous media is an important process in food and paper industry among others. Many physical effects must be considered: fluid flow, heat transfer and transport of participating fluids and gases. All of these effects are strongly coupled and predefined interfaces can be used to model these effects with COMSOL Multiphysics. Considering an unsaturated porous medium requires adjustments of the predefined equations. In this study, the changing water saturation inside the porous medium is computed. In contrast to the situation with a stationary liquid phase where the interfaces provided by COMSOL can be used as they are, the implementation of a multiphase flow requires some changes. This model and the instructions are based on the corresponding model and focus on the additional steps required to implement multiphase flow in porous media together with evaporation from liquid to gaseous phase.

Key words: Porous Media, Evaporation Rate, COMSOL, Multiphase Flow, Phase Change.

Introduction

Evaporation is a process in which liquid water is transferred from land and water masses into the atmosphere (Veissman et al. 1989). At the surface of the porous medium where the water gets vaporized into water vapor and the pores within the soil get replaced with ambient air, the evaporation phenomenon occurs. Evaporation is the largest component of hydrological cycle (Linsley et al., 1982) and also plays an important role in plant transpiration and organisms living beneath the soil surface.

Evaporation is caused by factors such as convection of air, relative humidity, air temperature and infrared radiation. After the water from the surface turns into vapor it gets either replaced with ambient air that fills the soil pores or the soil draws the water from layers below the surface. This phenomenon is caused by the capillary flow inside the porous media where the water flows through hydraulic paths (Lehmann and Or, 2009) in the saturated zone of the sample. The high evaporation rate is caused by the capillary action that transports the water up to the evaporating surface from hydraulically connected drying front (Shokri and Or, 2013).

One of the reasons that the capillary action is possible is due to the bonds between the water particles; this means that as long as the surface tension of water is strong enough the capillary flow will occur. Gravitational force acts opposite to the capillary flow meaning that the water not only has to sustain the water surface tension but also conquer the gravitational forces acting upon it. Gravitational forces make it more difficult for the water to travel vertically thus slowing down the evaporation phenomena. Other variables that can affect the rate of evaporation are temperature (Davarzani et al., 2014), humidity (Mahfuf and Moilhan 1991), wind velocity (Davarzani et al., 2014 and Shahraeeni et al., 2012), the surface water content (Griend and Owe, 1994) the distribution of pores on the drying surface (Haghighi et al., 2013), saturation level (Ghosh et al., 2008) and even pressure and soil conditions (fine, coarse and/or mix sands). All of these effects are strongly coupled and predefined interfaces can be used to model these effects with COMSOL Multiphysics In this study, the changing water saturation inside the porous medium is computed by COMSOL.

Model Definition

This model describes a laminar dry air flow through a porous medium containing water vapor and liquid water. The geometry and principle is shown in **Fig 1.**

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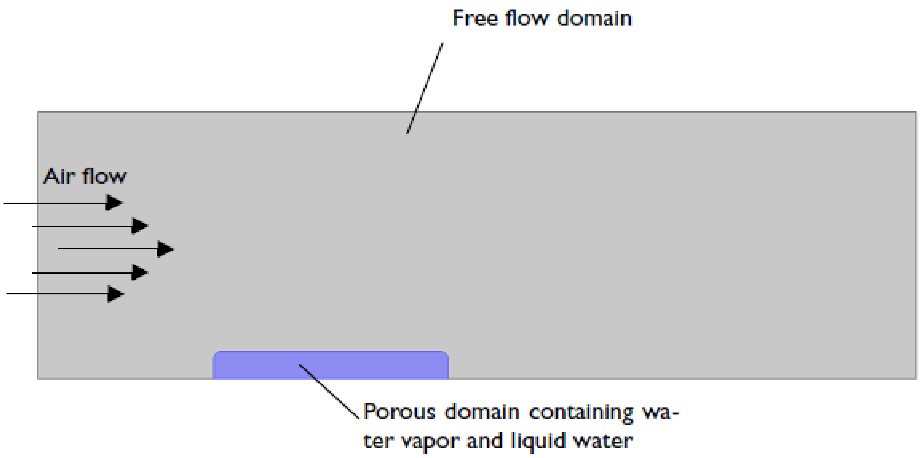

Fig. 1: Geometry and principle of the model.

- *Two Phase Flow in Porous Media*

The basic principle of modeling two phase flow in porous media is similar for many applications. First, to account for different phases, saturation variables are used that fulfill the following constraint:

$$S_g + S_l = 1 \qquad (1)$$

Where the index g is used for the gaseous phase (which in this model is moist air) and the index l is used for the liquid phase (which in this model is water).

Single-phase flow in porous media is described by the Brinkman Equations. With an additional liquid phase, capillary effects also arise and the liquid flow is driven by a pressure gradient and capillary pressure$p_c = p_g - p_l$. How to deal with the latter one depends on the application: sometimes the capillary pressure can be neglected, sometimes it is the driving effect and different approaches exist.

The formulation used in this model follows (Datta, 2007 part II), where capillary effects are treated by an additional diffusion term in the transport equation. The Brinkman Equation is used to calculate the flow field u_g and pressure distribution p_g of moist air in the porous medium. Therefore, the porosity ε must take into account that only a fraction of the void space is occupied by the gas phase.

The liquid phase velocity is small compared to the moist air velocity and such Darcy's Law is defined in terms of the gas phase pressure gradient to calculate the water velocity u_l according to

$$u_l = -\frac{k_l}{\mu_l} \nabla p_g \qquad (2)$$

Where k_l and μ_l are the permeability and viscosity of the liquid phase. It is not necessary to define a second Darcy's law equation, but an additional transport equation for the liquid phase is required.

The boundary conditions for the flow equations and their coupling is the same as in the corresponding model.

- *Liquid Phase Transport in Porous Media*

COMSOL provides the Transport of Diluted Species interface, which solves for a concentration in the very general form:

$$\frac{\partial c}{\partial t} + \nabla \cdot N = R \qquad (3)$$

This interface is used to describe the transport of the liquid phase inside the porous domain, following the ideas about mechanistic formulations from (Datta, 2007 part I). In this paper and the references given there the transport of water vapor, liquid water and dry air by convection and diffusion is expressed by flux variables.

It is assumed that no liquid water can leave the porous domain. From now on the index w is used to indicate that the properties are water properties and not a general liquid phase anymore.

The concentration c_w describes the water concentration and is rather an auxiliary variable, since the saturation is crucial for this process. The correlation for water concentration c_w and liquid phase saturation S_l is:

$$S_l = \frac{c_w M_w}{\rho_w \varepsilon}$$

Where M_w and ρ_w are the molar mass and density of water and ε is the porosity.

The velocity field in Equation 2 must take into account that the pore space is not fully saturated with water. Additionally, the permeability for the liquid phase k_l depends on the overall permeability of the porous matrix k and a relative permeabilityk_{rl}, thus:

$$u_l = -\frac{k k_{rl}}{S_l \varepsilon \mu_w} \nabla p_g$$

The pressure gradient ∇p_g is solved with the Brinkman Equation and μ_w is the viscosity of water. The capillary effect is introduced as the diffusion coefficient D_{cap} which depends on the moisture content (Data, 2007 part II):

Vapor Transport in a Porous Media

The procedure to derive the transport equation for water vapor is similar to the previous section. Starting from the conservation equation (Equation 3) and following the description in (Datta, 2007 part I), one has to implement the flux due to convection whereas the velocity field is already known from the Brinkman equation and needs to be applied to the vapor phase. The second transport mechanism is flux due to binary diffusion of water vapor and dry air in the gaseous phase. A common correlation for an effective diffusivity D_{eff} for two components is the Millington and Quirk equation

$$D_{eff} = D_{va} \varepsilon^{4/3} S_g^{10/3}$$

With the vapor-air diffusivity $D_{va} = 2.6 \cdot 10^{-5} \frac{m^2}{s}$

Both effects provide the velocity field that is applied to the water vapor transport equation:

$$u = \frac{u_g}{S_g \varepsilon} - \frac{M_a D_{eff}}{M_{ma} \rho_{ma}} \nabla \rho_{ma}$$

M_{ma} and ρ_{ma} refer to the moist air molar mass and density.

- *Evaporation*

To calculate the amount of water that evaporates into air and to account for the reducing liquid and increasing moist air proportion, the same correlation as in the Evaporation section from is used:

$$m_{evap} = K(a_w c_{sat} - c)$$

Where K $(\frac{1}{s})$ is the evaporation rate, $c_{sat}$the vapor concentration under saturation conditions and c the current vapor concentration.

Heat Transfer

The free flow domain contains moist air only and the velocity field from the laminar flow equation is used to describe the heat transferred by convection.

Inside the porous domain the overall velocity field for liquid and gaseous phase contributes to the heat convection term. Averaged thermal properties are required:

$$\rho_{tot} = S_g \rho_{ma} + S_l \rho_w$$

$$C_{p.tot} = \frac{S_g \rho_{ma} C_{p.ma} + S_l \rho_w C_{p.w}}{\rho_{tot}} \quad (4)$$

$$k_{tot} = S_g k_{ma} + S_l k_w$$

Then the overall velocity can be expressed as the average of dry air, water vapor, and liquid water velocity, which is:

$$u_{mean} = \frac{n_a C_{p.a} + n_v C_{p.v} + n_w C_{p.w}}{\rho_{tot} C_{p.tot}} \qquad (5)$$

n_a, n_v, and n_w are the flux variables for each component (Datta, 2007 part I). The heat of evaporation is inserted as a source term in the heat transfer equation according to:

$$Q = -\, H_{vap} \cdot m_{vap} \qquad (6)$$

Where H_{vap} $(\frac{j}{mol})$ is the latent heat of evaporation?

Moist Air Properties

The properties of moist air are the same as used in the other model. Inside the porous domain there is the option to define a single fluid type. Implementing a two phase flow means that the fluid type has to be defined in a way that it accounts for liquid and gaseous phases. Therefore, it is necessary to define the moist air properties manually. Also all other material properties are defined manually for sake of simplicity.

- *Permeability*

The permeability of the porous matrix k defines the absolute permeability. When two phases are present, the permeability of each phase depends also on the saturation. This is defined by the relative permeabilities k_{rl} and k_{rg} for liquid and gaseous phase respectively, so that $k_l = kk_{rl}$ and$k_g = kk_{rg}$. The determination of relative permeability curves is often done empirically or experimentally and the form strongly depends on the porous material properties and the liquids themselves. The functions that are used in this model (Datta, 2007 part II) are defined such that they are always positive:

$$k_{rg} = \begin{Bmatrix} 1 - 1.1S_l \ . \ S_l < \dfrac{1}{1.1} \\ eps \ . \ S_l \geq \dfrac{1}{1.1} \end{Bmatrix}$$

$$k_{rl} = \begin{Bmatrix} \left(\dfrac{S_l - S_{li}}{1 - S_{li}}\right)^3 & . \ S_l > S_{li} \\ eps & . \ S_l \leq S_{li} \end{Bmatrix}$$

The variable S_{li} is the irreducible liquid phase saturation, describing the saturation of the liquid phase that will remain inside the porous medium.

Results and Discussion

Using a proper mesh size is important to resolve the steep gradients at the interface boundaries. Therefore, a customized mesh with boundary layers is used. To get good convergence of the time dependent behavior, first solve the stationary flow equations only. This solution will then be used for the time dependent study step. This approximation neglects the evaporation mass source in the fluid flow computation.

The temperature (**Fig. 2**) shows significant cooling in the whole domain.

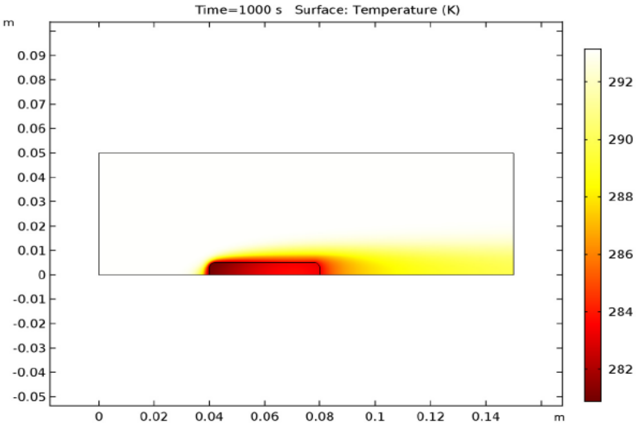

Fig. 2: Temperature field after 1000s.

The default pressure contour plot is shown on **Fig. (3).** Also, it can be seen that inside the porous domain the relative humidity is close to 100% everywhere (**Fig. 4)**.

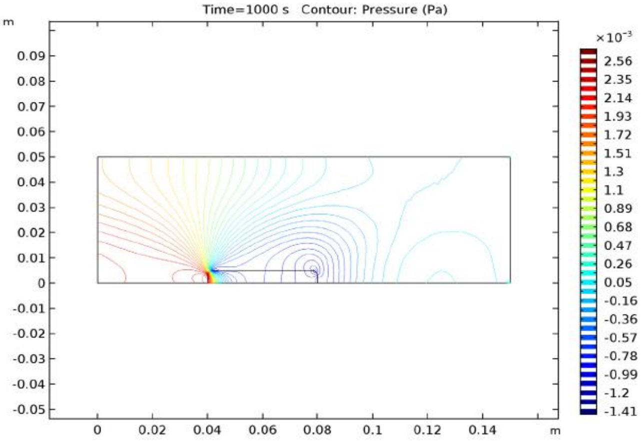

Fig. 3: Pressure distribution.

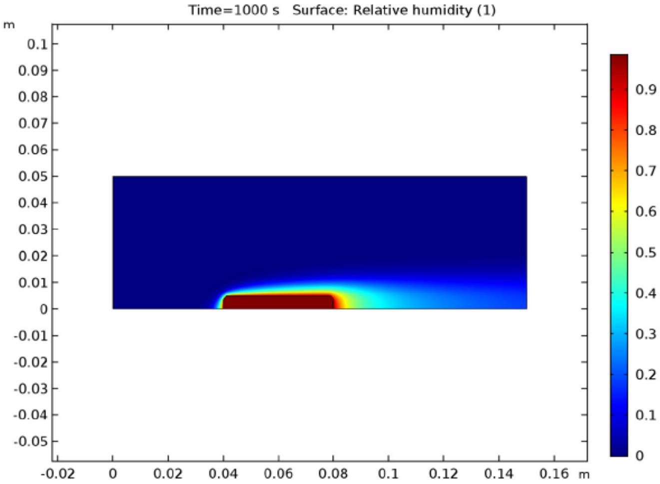

Fig. 4: Relative humidity after 1000 s.

Conclusion

In this study, the changing water saturation inside the porous medium is computed. In contrast to the situation with a stationary liquid phase where the interfaces provided by COMSOL can be used as they are, the implementation of a multiphase flow requires some changes. This model describes a laminar dry air flow through a porous medium containing water vapor and liquid water. The liquid phase velocity is small compared to the moist air velocity and such Darcy's Law is defined in terms of the gas phase pressure gradient to calculate the water velocity. The boundary conditions for the flow equations and their coupling is the same as in the corresponding model.

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