Journal of Food Engineering 179 (2016) 55–67

Contents lists available at ScienceDirect

Journal of Food Engineering

journal homepage: www.elsevier.com/locate/jfoodeng

A conjugate fluid-porous approach to convective heat and mass transfer with application to produce drying

Furqan Ahmad Khan*, Anthony Gerald Straatman

Department of Mechanical & Materials Engineering, Western University, London, Ontario, N6A 5B9, Canada

ARTICLE INFO

Article history:
Received 31 July 2015
Received in revised form
25 January 2016
Accepted 31 January 2016
Available online 3 February 2016

Keywords:
Computational fluid dynamics (CFD)
Heat transfer
Mass transfer
Convective drying
Porous material
Conjugate modeling

ABSTRACT

A computational model capable of simulating heat and mass transfer in conjugate fluid-porous domains is utilized to simulate forced convective drying. The material to be dried is considered as the porous region, which is coupled through interfaces to the surrounding pure fluid region. The computational model solves transport equations for mass and momentum, energy, and moisture in all regions simultaneously. The model includes non-equilibrium heat and moisture transport in the porous region such that the fluid and solid constituents, and the exchanges between them, are captured. The interfacial moisture transfer condition between phases in the porous region, and between the porous and pure fluid regions, is developed to show the level of detail required for modeling. The study considers the drying of apple flesh to validate the developed drying model against available experimental data. The results show accurate prediction of moisture content as a function of drying time for different airflow velocities, and correctly capture the influences of temperature, relative humidity and initial moisture content on the drying rate. Thus, the model is considered viable for taking steps towards implicit dynamic coupling of the constituents in the porous region.

1. Introduction

Convective drying of porous materials is of interest due to its applicability in engineering applications such as building materials production, processing and dehydration of foods, paper production, among others (Defraeye et al., 2012a). The porous materials to be dried in such applications range from bricks, concrete and wood to fruits, vegetables, and grains. Such materials can be classified based on their hygroscopic nature. For example, potato, carrot, wood, etc. are hygroscopic materials (Srikiatden and Roberts, 2005; Stanish et al., 1986), while, sand, ceramic, etc. are considered to be non-hygroscopic (Stanish et al., 1986).

In convective drying of porous materials, air with low relative humidity is forced across (and through) a wet porous media. Because of its capacity to hold fluids in their vapour state, the air absorbs moisture as it flows across the porous material, which results in drying or dehydration. The capacity of the airstream to take on moisture increases with increasing temperature (and vice-versa), and has its upper threshold for a given temperature at the dew-point, which is defined by 100% relative humidity. The porous material to be dried consists of a solid structure (or solid matrix), water, and void space (Sereno et al., 2007). The moist air – comprised of dry air and water vapour – occupies the void space (Sereno et al., 2007), and the liquid water can be considered to be held inside the microstructure of the solid component of the porous material. As such, moisture transport in the form of water vapour and liquid water occurs inside the porous materials (Defraeye et al., 2012b; Murugesan et al., 2001; Suresh et al., 2001; Younsi et al., 2008). Thus, complete modeling of a drying process requires the consideration of (moist) air passing across the material to be dried with dynamic coupling between the constituents to enable exchanges of heat and moisture to evolve based on local conditions (i.e. temperature, water activity, etc.)

Numerical modeling has been widely used to simulate convective drying. Previous numerical models can be broadly classified into categories based on their level of sophistication. In this respect, the most basic are drying curve models (see, for example Akpinar et al., 2003; Demir et al., 2007; Menges and Ertekin, 2006; Seiiedlou et al., 2010), which utilize a single moisture equation to evaluate moisture loss from a porous material as a function of temperature and other parameters. These models provide overall drying rates, however, they are not capable of accounting for the

* Corresponding author.
E-mail address: fkhan72@uwo.ca (F.A. Khan).

http://dx.doi.org/10.1016/j.jfoodeng.2016.01.029
0260-8774/

local variations of different quantities inside the porous domain.

The next category of models use differential energy and moisture transport equations to model the drying process inside the porous domain (see, for example Barati and Esfahani, 2011a, 2011b, 2013; Golestani et al., 2013; Kumar et al., 2012; Perussello et al., 2014; Srikiatden and Roberts, 2008; Younsi et al., 2006). As a result, these models predict the local variations of temperature and moisture content inside the drying material by solving a single equation for each of energy and moisture transport. The transport equations employed, in general, contain only unsteady and diffusion terms, and Fourier and Fick's Laws are used to model diffusion in the energy and moisture equations, respectively. In such models, convective boundary conditions are imposed at the surface of the material to be dried. In this respect, convective heat and mass transfer coefficients are evaluated using empirical correlations based on $Nu = f(Re,Pr)$ and $Sh = f(Re,Sc)$, which means that the simulation results are dependent upon the empirical correlations used.

The third category of models enables improvement in the evaluation of convective heat and mass transfer inside the porous domain. Such models (see, for example Ateeque et al., 2014; Esfahani et al., 2014; Kaya et al., 2006; Mohan and Talukdar, 2010; Tzempelikos et al., 2015) solve single energy and moisture transport equations inside the drying material, but also consider the fluid region surrounding the material, although not in a direct-coupled, conjugate manner. The surrounding airflow is first resolved by solving the mass and momentum transport equations along with the transport equation of energy to calculate the heat transfer coefficient at the surface of the material. The thermal and concentration boundary layer analogy is then used to compute the surface mass transfer coefficient. The evaluated coefficients are then utilized to impose convective boundary conditions at the material's surface to obtain a solution inside the drying material. The term “non-conjugate approach” is often used to refer to this category of models (Defraeye et al., 2012a).

While the non-conjugate approach considers one domain at a time, a conjugate approach involves simultaneous modeling of both the drying material and the surrounding airflow region. These models introduce mathematical conditions to enforce continuity of heat and mass transfer at the fluid-porous interface, which eliminates the requirement for imposing convective heat and mass transfer coefficients between regions of the domain. The conjugate models proposed by Lamnatou et al. (2010) and Sabarez (2012) use single energy and moisture transport equations for each region to model energy and mass transfer. In this respect, it is the effective heat and moisture transport that is solved for, and the temperature and mass fraction characterize the local conditions. This approach is suitable for predicting temperature and moisture distributions in the porous region, but local transport between the phases of the porous media are not provided.

When the material subjected to drying is comprised of a micro-porous solid structure and void space, which is generally the case for biologically derived systems, moisture transport occurs mainly due to capillary forces, pressure gradients, and temperature gradients (Suresh et al., 2001; Younsi et al., 2008). In such cases, it becomes important to account for both the vapour and liquid transport inside the porous material. In this respect, several studies (Defraeye et al., 2012b; Erriguible et al., 2006; Murugesan et al., 2001; Steeman et al., 2009; Suresh et al., 2001; Younsi et al., 2008) focused on convective drying of porous materials using a conjugate approach, except that moisture transfer inside the drying material was modeled by combining the vapour and water transport into a single moisture transport equation. The work of De Bonis and Ruocco (2008) took a non-equilibrium approach to mass transport by employing separate vapour and water transport equations inside the drying material, but they did not consider advection or thermal non-equilibrium inside the porous material. Defraeye et al. (2012b), Younsi et al. (2008), Erriguible et al. (2006), and Perré and Turner (1999) have utilized volume-averaged energy and moisture transport equations. In addition, Erriguible et al. (2006), and Perré and Turner (1999) considered the advection term in the energy and moisture transport equations, and used Darcy's Law to calculate the flow velocity inside porous material.

The literature survey reveals that a majority of the most advanced prior work models heat and mass transport inside the porous materials or porous solids (Defraeye et al., 2012b; Murugesan et al., 2001; Suresh et al., 2001; Younsi et al., 2008) using single energy and moisture transport equations. In other words, the fluid and solid-constituents in a given cell inside the porous media are generally characterized using single temperature and fluid mass-fraction values. This approach is found to provide reasonable results for temperature and moisture distributions and for overall drying times, provided the effective transport coefficients for heat and mass are carefully calibrated. However, such an approach is not capable of predicting local exchanges of energy and moisture between constituents inside a cell. The main objective of the present work is to demonstrate the capability of the proposed formulation to accurately simulate the convective drying process of porous materials. Moreover, the proposed framework is generic and can be applied to wide range of porous materials. In this respect, the present work utilizes a conjugate domain approach, wherein mass, momentum, energy, and moisture transport equations are solved in the fluid and porous region. The model also accounts for thermal and mass non-equilibrium in the porous region such that both the vapour and water exchanges between the constituents are considered. In this respect, we further demonstrate that a conjugate, non-equilibrium model can provide information necessary to make the next important step towards direct, dynamic coupling of the phases.

Modeling of the porous material at this level of detail requires thermophysical properties of both the fluid and solid constituents, as well as quantification of the key geometric parameters of the porous material. To the best of authors' knowledge, no study, as yet, has provided such a level of detail of the porous material even though such characterization is essential for modeling the different mechanisms of heat and moisture transport inside the porous region and at the fluid-porous interface. The present study models the interfacial moisture transfer using a circuit analogy, which accounts for all interfacial exchanges, and additional parameters required to achieve the physical moisture thresholds observed in the convective drying process. The performance of the complete model is assessed by application to the drying of apple flesh. In this respect, the results of Velić et al. (2004) are used as a reference.

2. Formulation

As described earlier, the airflow surrounding the porous material plays a crucial role in the convective drying process. From the numerical modeling perspective, moist air can be considered as a mixture of dry air (comprised of all the gaseous components) and water vapour. The vapour content of the moist airflow is evaluated by solving a transport equation in the form of vapour mass fraction (Y_v). The moist air is then treated as a mixture of dry air and water vapour, and its flow is evaluated by solving the conventional mass-momentum transport equations. The moist air density (ρ_f) used in the transport equations is continuously updated to account for the moisture gain/loss of the air by the expression