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Three dimensional modeling on airflow, heat and mass transfer in partially impermeable enclosure containing agricultural produce during natural convective cooling

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Abstract

A three dimensional model was developed to simulate the transport phenomena in heat and mass generating porous medium cooled under natural convective environment. Unlike the previous works on this aspect, the present model was aimed for bulk stored agricultural produce contained in a permeable package placed on a hard surface. This situation made the bottom of the package impermeable to fluid flow as well as moisture transfer and adiabatic to heat transfer. The velocity vectors, isotherms and contours of rate of moisture loss were presented during transient cooling as well as at steady state using the commercially available computational fluid dynamics (CFD) code based on the finite volume technique. The CFD model was validated using the experimental data on the time–temperature history as well as weight loss obtained from a bag of potatoes kept in a cold store. The simulated and experimental values on temperature and moisture loss of the product were found to be in good agreement.

Keywords: Air flow; Heat mass transfer; Porous medium; Partially impermeable; Natural convection

1. Introduction

Many important applications make use of fluid flow as well as heat and mass transfer in porous media. Bulk storage of agricultural produce, where both heat and mass transfer take place simultaneously is one such application [1]. Analysis of transport phenomena in packed agricultural produce is important to designers of storage facilities of the commodities. Some of the agricultural produce, like potato, onion, etc. are packed in gunny bags for long term storage in cold stores. The gunny bag is made of woven jute threads and allows the exchange of air and moisture rather than heat between the surrounding air and the bulk of the product. However, when such bags are placed on a floor or any other hard surface, the bottom of the bag becomes impermeable. The impermeable bottom may affect the dynamics of the transport phenomena in the product kept in the bag.

A lot of literature is available to model the transport phenomena during cooling and storage of various bulk stored agricultural produce. Both forced and natural convective cooling with permeable or impermeable container surfaces have been taken into account in these literatures. In most of the mathematical models for forced convection cooling, the bulk stored mass of agricultural produce was considered as a deep bed system. To use this approach, Bakker-Arkema et al. [2] presented a set of simultaneous partial differential equations to simulate cooling of a deep bed of biological products. Huzayyin et al. [3] developed a model to predict the temperature and moisture content of a fixed bed of shelled corn aerated with cold air. A typical application of deep bed theory was found in a model to simulate the cooling of bulk stored potato as well [4]. At low air velocities, the effect of natural convection rather than forced air cooling was included, and a two dimen-

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Nomenclature

a_p	specific surface area ($m^2\ m^{-3}$)
a_w	water activity (dimensionless)
C_2	internal resistance factor (m^{-1})
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
d	effective diameter (m)
D_{AB}	diffusion coefficient ($m^2\ s^{-1}$)
E	energy ($J\ kg^{-1}$)
$\vec{F}$	external body force ($N\ m^{-3}$)
$\vec{g}$	gravity vector ($m\ s^{-2}$)
h_i	enthalpy of species 'i' ($J\ kg^{-1}$)
J_i	diffusion flux of species 'i' ($kg\ m^{-2}\ s^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_m	overall mass transfer coefficient ($kg\ s^{-1}\ m^{-2}\ Pa^{-1}$)
p	pressure (Pa)
RH	relative humidity (%)
S_f^h	enthalpy source term ($W\ m^{-3}$)
S_i	source term for generation of species 'i' ($kg\ m^{-3}\ s^{-1}$)
S_j	resistance of porous medium ($Pa\ m^{-1}$)
S_M	source term for mass generation ($kg\ m^{-3}\ s^{-1}$)
t	time (s)
T	temperature (K)
$\vec{v}$	velocity vector ($m\ s^{-1}$)
v_j	velocity components in x, y, and z directions ($m\ s^{-1}$)
v_{mag}	fluid velocity ($m\ s^{-1}$)
x	direction along depth of bag
y	direction along height of bag
Y	mass fraction (dimensionless)
z	direction along width of bag

Greek symbols

α	permeability of porous medium (m^2)
ε	porosity in bag (dimensionless)
μ	dynamic viscosity (Pa s)
ρ	density ($kg\ m^{-3}$)

Subscripts

eff	porous medium
f	air–vapor mixture (fluid)
i	species (water vapor)
int	at time zero
o	surrounding air
p	product
sat	saturation

sional, two phase model was developed to predict the temperature and moisture distribution during cooling and storage of the agricultural produce [5]. Alvarez and Trystram [6] developed a heat and mass transfer model to describe the refrigeration process between the air and the product for a situation wherein the agricultural produce was packed in bins piled on a pallet. A mathematical model to describe the heat and mass transfer processes under different storage conditions arising during the cooling and storage of fruits and vegetables in cold storage was presented by Ref. [7].

When agricultural products are stored in bulk mass with no provision for mechanical ventilation, the behavior of the heat and mass transfer processes depends mainly on the intensity of natural convection. The degree of safety with which the product can be stored in bulk depends on the extent of heat generation by respiration, the means through which this heat is dissipated, the extent to which it causes a risk in the increase in temperature of the product, container dimensions etc. [8]. Beukema et al. [9] developed a model for natural convection in a confined porous medium with internal heat generation to simulate natural convective cooling of agricultural produce. The studies described above for natural convective cooling process did not consider the mass transfer phenomenon, though a knowledge of temperature and moisture distribution was equally important for safe storage of agricultural produce. Keeping the importance of coupled heat and mass transfer in mind, Singh et al. [10] formulated a three dimensional model to describe the behavior of the convection and diffusion processes that occurred in bulk stored grains. Subsequently, a few more models were developed to simulate the heat and mass transfer in stored grains [11–13].

Concentrating on potato storage, some literature is available on the aspect of heat and mass transfer in a bulk stored mass of potatoes. Marchant et al. [14] modeled the heat and mass transfer in a potato cold store considering the potato in arbitrary layers with plug air flow between them. Chourasia et al. [15] modeled the heat transfer in a packed bag of potato and investigated the effect of operating and geometric parameters on cool down time and product temperature, wherein the surfaces of the bag were considered as impermeable to air flow. A lattice Boltzmann scheme was used to optimize the vent hole design of the seed potato container in order to avoid condensation during transportation [16]. A simulation model of the interdependent heat and mass transfer was offered in a mound of stored potato in view of the centers of spontaneous heating [17].

The studies described above did not model a situation representative of natural convective cooling of a partially impermeable enclosure containing agricultural produce. As a preliminary work, Chourasia and Goswami [18] investigated the effect of different boundary conditions on the steady state airflow pattern and temperature profile in a rectangular enclosure containing heat generating porous medium. It was found that the enclosure having an impermeable bottom surface showed an entirely different air flow pattern and temperature profile in comparison to a