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Modeling of the packed bed drying of paddy rice using the local volume averaging (LVA) approach

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Abstract

A transient heat and mass transfer model was developed for the packed bed drying of paddy rice using the local volume averaging method in this research. The required conditions for the application of the local volume averaging were evaluated including appropriate length, time, and temperature scales and justified for fixed bed paddy rice drying. Taking local thermal equilibrium in each representative elementary volume, transient mass and heat transfer governing equations were derived. The transport mechanisms considered were conduction and diffusion as well as convection heat and mass transfer. In the model, the transport coefficients were functions of moisture content and temperature, thus they changed during drying process. The governing heat and mass transfer equations were simultaneously solved using an implicit numerical method. The simulation results were compared to available experimental data from literatures. Although the physical properties were from different independent research and independent of the experimental data used for model validation, predicted results showed a reasonable agreement with the measured data.

Keywords: Heat and mass transfer; Porous media; Packed bed; Local volume averaging approach; Paddy rice drying

1. Introduction

Rice is one of the most important cereals in the world. Harvested paddy rice has an initial moisture content around 18–26% by mass wet basis. The management of highly moist paddy during the harvesting period is a great challenge. If the paddy is not dried properly, the remained water can encourage mold growth and high respiration rate from the grains. Consequently, the dry matter of grain is degraded and heat from its respiration and biological activities may accelerate rice yellowing. To obtain high quality paddy and prevent all the problems above, paddy rice moisture content must be reduced to 12–14% (wet basis) (Soponronarit & Nathakaranakul, 1990). To ensure a high head rice yield and a high germination rate of rice, drying temperatures lower than 43 °C are recommended (Soponronnarit & Preechakul, 1990). Conventional paddy rice dryers are divided into batch dryers and continuous dryers. In conventional drying, paddy rice requires exposure to a drying air, relative humidity of which is lower than equilibrium value at the surface of the paddy.

Paddy drying is a complex process, which involves simultaneous heat, mass, and momentum transfer through porous media. Nowadays mathematical modeling and computer simulation are widely used in bioprocess engineering research. Mathematical modeling and computer simulation of paddy drying minimize cost and time for numerous experimentations and allow one to understand the physical phenomena associated with the complicated process. The results of the numerical simulation can also lead to the design and testing of new drying processes. Many researchers have developed mathematical models

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Nomenclature

A_0	specific surface (m^2/m^3 bed)
C_1	constant of Eq. (5)
C_2	constant of Eq. (6)
C_p	specific heat (J/kg °C)
D	diffusivity (m^2/s)
Da	Darcy number
d	diameter (m)
ΔH	latent heat of vaporization (J/kg)
K	permeability (m^2)
k	thermal conductivity (W/m K)
L	the height of the bed (m)
l	linear dimension of representative elementary volume (m)
M	average moisture content of rice kernel (kg H_2O/kg wet paddy)
$\mathring{m}$	drying rate per unit volume of the bed (kg/m^3 s)
N	the last node of the top of the bed
Nu	Nusselt number (dimensionless)
P	pressure (Pa)
Pr	Prandtl number (dimensionless)
Re	Reynolds number (dimensionless)
T	temperature (°C)
t	time (s)
$\langle T \rangle$	local averaged temperature (°C)
U	velocity (m/s)
v	superficial velocity (m/s)
$\langle X \rangle$	local volume averaged moisture content of paddy rice (kg H_2O/kg dry paddy)

Greek letters

α	thermal diffusivity (m^2/s)
ε	porosity (m^3/m^3 bed)
ρ	density (kg/m^3)
μ	viscosity (kg/m s)

Subscripts

a	air
D	Darcy
eff	effective
eq	equivalent
f	fluid
i	node number
p	particle
S	solid phase
v	vapor
0	initial
∞	input air

Superscript

t	time step

for paddy rice drying using different approaches and assumptions.

Prachayawarakorn and Soponronnarit (1993) developed a mathematical model for batch-fluidized bed drying, including the drying kinetic equation. They also investigated optimum operating parameters for the process. Queiroz, Couto, and Haghighi (2000) developed a model using the finite element method to simulate moisture diffusion inside a rice particle during rough rice drying. Their model could predict the temperatures of the drying air and the grain and moisture movement inside the rough rice kernel. Soponronnarit, Wetchacama, Trutassanawin, and Jariyatontivait (2001) designed, constructed and tested a prototype vibro-fluidized bed paddy dryer with a capacity of 2.5–5.0 ton/h. They developed a mathematical model for the process to determine optimum operating parameters. Comparison between the experimental and simulated results showed that the mathematical model could predict fairly well. Izadifar and Mowla (2003) developed a mathematical model to simulate the drying of moist paddy in a cross-flow continuous fluidized bed dryer. Experimental data at a drying air temperature of 60 °C were used to validate the prediction of the model. The predictions of the model showed a good agreement with the experimental results.

Regarding fixed bed drying, Palancz (1985) studied heat and mass transfer between gas phase and solid particles in a deep bed dryer, however no axial dispersion was considered in the bed. Srivastava and John (2002) used thin layer semi-empirical equations for predicting the air humidity, air temperature, and grain temperature with different heights of a fixed bed of grains in unsteady state. Rumsey and Rovedo (2001) applied a dynamic model to cross-flow drying of rice. They determined the effects of inlet moisture content of product, drying air temperature, and grain flow on rice drying. They solved the model using a predictor-corrector method. Simulated data of inlet and outlet moisture contents of rice agreed the experimental data satisfactorily. Wu, Yang, and Jia (2004) developed a three-dimensional theoretical model describing coupled heat and mass transfer inside a single rice kernel during drying. Using the body-fitted coordinate system they characterized 3-D shape of a single rice kernel and applied the finite volume method to solve the governing equations. The simulated average kernel moisture contents compared favourably with the thin-layer drying data.

In this study, unlike the previous research, the local volume averaging method was applied to see its adequacy in modeling and simulation of transient heat and mass transfer through a packed bed of paddy rice, a porous medium. Considering local thermal equilibrium in each representative elementary volume of the bed, transient mass and heat transfer governing equations were derived