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Evaluation of a simulation model in predicting the drying parameters for deep-bed paddy drying

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ABSTRACT

A simulation model for deep-bed batch drying of paddy was developed to predict the profiles of grain moisture content, grain temperature, air temperature and air humidity during the drying process. In order to evaluate the validity of this model, a laboratory-scale deep-bed batch dryer was designed and fabricated. Comprehensive drying experiments were carried out in three replications under different drying conditions with two independent drying variables, namely, drying air temperature (at two levels of 45 and 50 °C) and air mass flow rate (at three levels of 0.1, 0.16 and 0.22 kg m^{-2} s^{-1}). Good agreement was found between the simulation results and the experimental data. After validation of the model, the dryer performance was optimized by minimizing specific energy consumption under identical moisture removal using the simulation model. Based on this criterion, the treatment with mass flow rate of 0.03 kg m^{-2} s^{-1} and air temperature of 35 °C was found to be the optimal drying condition.

1. Introduction

Rice is a major staple food source in the world. Improper drying can cause conspicuous losses to this product. Losses may be reduced through appropriate controlling of the drying process. Extensive characterization of grain drying process using experimental approaches is tedious and complicated and sometimes even impossible due to the large number of variables involved. Drying behaviour can be affected by a large variety of factors including drying temperature, air velocity and relative humidity. It is also affected by grain properties such as grain density, permeability, and porosity. On the other hand, the drying of moist porous materials is a complicated process involving simultaneous coupled heat and mass transfer phenomena (Chua et al., 2002). Since computer simulation is a reasonable and powerful tool for providing a view into physics of drying process it can be applied for predicting of drying parameters including grain temperature, grain moisture content, air humidity and temperature. By predicting these parameters we are able to design new high efficient dryer or improve existing grain drying system. The computer simulation of grain drying can be applied for optimizing and controlling of grain drying systems and processes. A process simulation model is an essential element of a feedforward–feedback automatic grain dryer control system. In a properly designed feedforward–feedback control system, most of the control is performed by the feedforward controller which is done by process model (Pabis et al., 1998).

Deep-bed dryers, also known as fixed bed dryers, are one of the most common types of agricultural dryers, designed for heterogeneous drying of grain in a deep layer (more than 20 cm deep) where drying is faster at the inlet end of the dryer than that at the exhaust end (Lopez et al., 1998). Deep-bed models for grain drying simulation can be classified as logarithmic, heat and mass balance and partial differential equation (PDE) (Tang et al., 2004; Pabis et al., 1998). The PDE model is more detailed, accurate and valid for cereal drying, while the others are less accurate owing to more assumptions being made during model derivations (Tang et al., 2004; Parry, 1985). Various simulation models have been developed for thin layer drying of paddy (Abe and Afzal, 1997; Agrawal and Singh, 1977; Chen, 1998; Chen and Shei, 1996; Islam and Jindal, 1981; Jindal and Siebenmorgen, 1994). However, only limited simulation models have been presented for describing paddy drying in deep-batch dryer which are not based on PDE models (Noomhorn and Verma, 1986; Sitompul et al., 2001). In this study, a comprehensive evaluation of the PDE model for drying of paddy in a deep-bed batch dryer was conducted and as far as we know, no study has been reported on this subject in the literature.

For evaluating the simulation model a laboratory-scale dryer was fabricated and several tests were conducted in three replications for different combinations of drying air temperatures and air mass flow rates. Once a grain drying model is validated, computer simulation can be used for practical applications. One of the most interesting applications of drying simulation is optimization of dryer performance from view points of energy consumption,

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Nomenclature

A	inlet area of bin (m^2)
a_s	specific surface area ($m^2\,m^{-3}$)
c_a	specific heat capacity of air ($J\,kg^{-1}\,K^{-1}$)
c_v	specific heat capacity of water vapor ($J\,kg^{-1}\,K^{-1}$)
c_w	specific heat capacity of water ($J\,kg^{-1}\,K^{-1}$)
c_d	specific heat capacity of dry mass equal to 1109 for unshelled rice ($J\,kg^{-1}\,K^{-1}$)
c_p	specific heat capacity of paddy ($J\,kg^{-1}\,K^{-1}$)
E_t	total energy supplied for the drying process (J)
FP	power supplied to the fan per unit bin floor area ($W\,m^{-2}$)
G	mass flow rate of air ($kg\,m^{-2}\,s^{-1}$)
h_a	grain bed volumetric heat transfer coefficient ($J\,m^{-3}\,K^{-1}\,s^{-1}$)
h_v	latent heat of vaporization ($J\,kg^{-1}$)
H	absolute humidity of air ($kg\,kg^{-1}$)
HP	heat power required for drying (W)
L	depth of grain bed (m)
m	total number of layers
M	moisture content of grain (dry basis) ($kg\,kg^{-1}$)
M_{ab}	moisture content of a batch at end of drying process (dry basis) ($kg\,kg^{-1}$)
M_e	equilibrium moisture content of grain (dry basis) ($kg\,kg^{-1}$)
M_i	predicted moisture content at ith layer (dry basis) ($kg\,kg^{-1}$)
MRD	mean relative deviation (%)
n	total number of measurements in each experiment
O_f	percentage perforation (decimal)
P	atmospheric pressure (Pa)
P_{vs}	saturated vapour pressure (Pa)
r_0	equivalent particle radius (m)
RH	relative humidity of air (decimal)
RE	relative error at each time step (%)
t	time (s)
T	air temperature (°C)
T_{abs}	absolute air temperature (K)
T_a	ambient air temperature (°C)
T_d	drying air temperature (°C)
V	air velocity ($m\,s^{-1}$)
w_1	thermal–electrical energy weight (decimal)
x	depth in bed from air inlet (m)
Y_j	jth predicted parameter
$\hat{Y}_j$	jth experimental parameter
θ	grain temperature (K)
ρ_p	particle density ($kg\,m^{-3}$)
ε	porosity (decimal)
μ_a	air viscosity ($kg\,m^{-1}\,s^{-1}$)
ΔP_g	pressure drop for clean grain (Pa)
ΔP_f	pressure drop due to perforated floor (Pa)
ΔP_d	pressure drop due to duct system (Pa)
ΔP	total static pressure drop (Pa)
Δt	drying duration (s)
η_f	fan efficiency (decimal)
$\eta_{th-elec}$	conversion efficiency of thermal to electrical energy (decimal)
$\eta_{trans-dist}$	transmission and distribution network efficiency (decimal)

efficiency and moisture removal. Here, the dryer performance is optimized based on specific energy consumption.

2. Materials and methods

2.1. Development of computer simulation model

In deriving the mathematical non-equilibrium PDE model for batch drying of paddy, the following assumptions were made (Mandas and Habte, 2002; Parry, 1985):

1. The volume shrinkage of the bed of grain was negligible during the drying process.
2. The temperature gradients within the individual kernels of grain were negligible.
3. The heat transfer by conduction between kernels of grain was negligible.
4. The bin walls were adiabatic, with negligible heat capacity.
5. During any short time interval, the heat capacity of moist air and grain were constant.
6. ($\partial T/\partial t$) and ($\partial H/\partial t$) were negligible compared with ($\partial T/\partial x$) and ($\partial H/\partial x$), where x was the bed thickness in the direction of air flow.

By conducting the heat and mass balances, similar to Sharp's the following set of partial differential equations can be obtained (Sharp, 1982).

Grain moisture-mass balance:

$$G\frac{\partial H}{\partial x} = -\rho_p\frac{\partial M}{\partial t} - \varepsilon\frac{\partial H}{\partial t} \quad (1)$$

Heat balance (energy) balance of air:

$$G(c_a + c_v H)\frac{\partial T}{\partial x} = \rho_p c_v (T-\theta)\frac{\partial M}{\partial t} - h_a(T-\theta) - \rho_a\varepsilon(c_a + c_v H)\frac{\partial T}{\partial t} \quad (2)$$

Heat transfer equation (energy balance of grain):

$$\rho_p(c_p + c_w M)\frac{\partial \theta}{\partial t} = h_a(T-\theta) + h_v\frac{\partial M}{\partial t}\rho_p \quad (3)$$

There are four unknown drying variables, namely, $M(x, t)$, $\theta(x, t)$, $H(x, t)$ and $T(x, t)$ in the above three equations. To complete the system of equations, an appropriate thin layer equation is normally employed (Pabis et al., 1998). In this study, a modified empirical thin layer drying equation for paddy was used (Wang and Singh, 1978):

$$\frac{\partial M}{\partial t} = [M(t) - M_e]\left(-XY\left(\frac{t}{60}\right)^{Y-1}\right) \quad (4)$$

where

$$X = 0.01579 + 0.0000176T + 0.078867(RH) \quad (4\text{-a})$$

$$Y = 0.6545 + 0.002425T + 0.078867(RH) \quad (4\text{-b})$$

Some additional information about properties of paddy was needed including specific heat capacity of moist grain, the equilibrium moisture content and the volumetric heat transfer coefficient.The specific heat capacity of grain was calculated by the following relationship (Pabis et al., 1998):

$$c_p = c_d + 4186M \quad (5)$$

The equilibrium moisture content (M_e) of paddy is independent of the rice type. It is only a function of air temperature and relative