Journal of Stored Products Research 61 (2015) 76–84

Contents lists available at ScienceDirect

Journal of Stored Products Research

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

Application of simulation in determining suitable operating parameters for industrial scale fluidized bed dryer during drying of high impurity moist paddy

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ARTICLE INFO

Article history:
Received 8 May 2013
Received in revised form
15 August 2014
Accepted 12 December 2014
Available online 26 December 2014

Keywords:
Industrial fluidized bed dryer
Simulation
Operating parameters
Dryer performance
Moisture removal
Specific energy consumption

ABSTRACT

A systematic approach has been developed for selecting the suitable drying parameters to be used for drying of high moisture and high impurity paddy with an industrial fluidized bed paddy dryer (10–20 t h^{-1} capacity) based on targeted specific air flow rate and residence time during two typical paddy drying seasons. A mathematical model was developed by modifying an existing model and was simulated and validated with observed industrial drying data as well as data reported in the literature. Comparison between the observed and simulated results showed that the mathematical model is capable of predicting outlet paddy moisture content and air temperature well. Suitable operating parameters were determined for reducing any initial paddy moisture content (mc) down to 24–25% dry basis (db), the safe mc level after fluidized bed drying to maintain rice quality, to achieve maximum possible throughput capacity of the dryer with corresponding energy consumption. Based on these criteria, bed thickness at 10 cm, specific air flow rate of 0.05 kg kg^{-1} s^{-1} (for corresponding bed air velocity of 2.3 m s^{-1}), air temperature of 150 °C and residence time of 1.0 min were found to be suitable drying conditions for reducing paddy mc from 30 to 24.30% (db) in one season while the maximum throughput capacity of 15.7 tonne per hour (t h^{-1}) might be achieved. The specific electrical and thermal energy were 0.48 and 6.15 MJ kg^{-1} water evaporated, respectively. On the other hand, the dryer capacity was found to be limited to 7.4 t h^{-1} during drying paddy of higher initial mc (35% db). This approach might provide easy and comprehensive guidelines for selecting suitable sets of operating parameters for any industrial fluidized bed dryer at its possible maximum throughput capacity for drying of freshly harvested high moist paddy with a high level of impurities.

1. Introduction

Quick and efficient drying of the influx of freshly harvested high moisture paddy to ensure acceptable final quality is of great concern for rice industry. Computer simulation is a cheap and time-saving method to predict drying parameters for designing and optimizing a dryer. Tumambing and Driscoll (1991) modelled the performance of fluidized bed drying of paddy and found experimentally that the drying rate of paddy was affected by drying air temperature and bed thickness. They used drying air temperatures of 40–100 °C, bed thickness of 5–20 cm and air velocity of 1.5–2.5 m s^{-1} in their experiments. Mathematical modelling for a batch-fluidized bed dryer including drying kinetic equation and optimum operating parameters were investigated by Prachayawarakorn and Soponronnarit (1993). Feasibility of paddy drying by fluidization technique was studied through experimentation and simulation and the maximum drying temperature was suggested as 115 °C to reduce moisture to 24–25% (db) for ensuring rice quality (Soponronnarit and Prachayawarakorn, 1994). The industrial scale continuous cross flow fluidized bed dryer with capacity of 5–10 t h^{-1} was studied and developed using mathematical simulation and experimental results by Wetchacama et al. (1997). Modelling, simulation and experimental works on fluidized bed paddy drying have also been reported by Prachayawarakorn et al. (2005a, 2005b) and Poomsa-ad et al. (2005) for different types,

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http://dx.doi.org/10.1016/j.jspr.2014.12.004
0022-474X/

sizes and capacities of dryers. Prachayawarakorn et al. (2005b) studied commercial pulsed fluidized bed drying and reported that the drying temperature should be less than 145 °C for initial paddy moisture content of 28% (db) to maintain rice quality. Prachayawarakorn et al. (2005a; 2005b) reported both experimental and simulation results on fluidized bed paddy drying using laboratory scale and commercial scale dryers.

Single and multi-phase models have been used in order to simulate fluidized bed drying by some researchers. In a single-phase model, the fluidized bed is regarded essentially as a continuum. Heat and mass balances are applied over the fluidized bed. It is assumed that particles in the bed are perfectly mixed (Martinez-Vera et al., 1995). A multi-phase model of fluidized bed drying treats the fluidized bed to be composed of a bubble phase (dilute phase) and a suspension phase (dense phase). In some research, the suspension phase itself was assumed to be composed of the particles and intermediate gas phase (Burgschweiger et al., 1999; Zahed et al., 1995). Khanali et al. (2012) examined different drying models and found that the model proposed by Midilli et al. (2002) was the best for describing fluidized bed drying characteristics of rough rice. The incremental model was modified by modelling the cross-flow of the drying medium and removing the need to use the time increment and bed velocity for computing the distance along the dryer (Daud, 2004, 2007). Queiroz et al. (2000) developed a model to simulate the moisture diffusion during the drying process of rough rice by using finite element analysis. Their simulated model could predict the temperature of the air and grain and the moisture movement inside the rough rice kernel. Izadifar and Mowla (2003) developed a mathematical model to simulate the drying of moist paddy in a cross-flow continuous fluidized bed dryer. The model is based on the differential equations, which are obtained by applying the momentum, mass and energy balances to each element of the dryer and also on the drying properties of paddy. The optimum drying parameters have been reported based on energy consumption and drying capacity for achieving acceptable rice quality, while the basis of fixing the operating parameters such as feed rate, air velocity and bed thickness have been rarely mentioned. Soponronnarit et al. (1996b) studied the performance evaluation of commercial fluidized bed dryer with 1–2, 2.5–5.0 and 5–10 t h^{-1} capacity having the provision of recycling the exhaust air while the heat source was from burning diesel or oil fuel. They reported that energy consumption decreased with increasing paddy moisture content and drying temperature. Paddy drying is a highly energy-intensive process and sensitive to the quality of rice (Jittanit et al., 2010). To reduce paddy moisture down to 22% (db) in a single pass, they recommended a maximum drying temperature of 150 °C to achieve acceptable quality of product. Fluidization techniques have been reported to produce increased head rice yield compared to conventional drying methods (Inprasit and Noomhorm, 2001; Tirawanichakul et al., 2004; Prachayawarakorn et al., 2005a). To date, very few published works are available on performance evaluation of large scale industrial fluidized bed paddy drying involving freshly harvested moist paddy with high impurities. Impurities include immature paddy, straw, leaves, stones and other foreign materials. Standardizing the drying process through maximizing capacity and minimizing energy utilization is also important as performance evaluation of a dryer promotes its successful and economic operation. Before starting the operation of any dryer it is very important to fix the possible suitable air velocity, particular air temperature and weir height for a constant feed rate to minimize energy and maximize drying capacity. The use of simulation can help to draw conclusion regarding potential operating conditions of the dryer, which would not otherwise be possible without extensive experimental measurements. This paper attempts to formulate a guideline for solving some of the limitations in the operation of industrial dryer. This might be an easy and comprehensive package in selecting the suitable sets of operating parameters for industrial fluidized bed dryer for drying of freshly harvested high moisture and high impurity paddy.

2. Materials and methods

2.1. Development of computer simulation model

In deriving the mathematical model for the fluidized bed drying of MR219, a common paddy variety in Malaysia, the following assumptions were made following Soponronnarit and Prachayawarakorn (1994), Soponronnarit et al. (1996a) and Prachayawarakorn et al. (2005b).

1. Grain temperature is in thermal equilibrium with outlet-air temperature, implying a high heat transfer rate between air and the grain bed.
2. The air and grain flows are in plug type in order to simplify calculation although grain dispersion may occur while the bed of particles is fluidized.
3. The temperature gradients within the grain kernels are negligible
4. Moisture distribution within grain kernels is especially uniform at the beginning.

To describe the change in moisture content mathematically, the dryer was divided into N small elements (strips) as shown in Fig. 1.

2.1.1. Equation of mean residence time

The following equation of mean residence time of paddy was used.

$$\mathrm{Taw} = \frac{hu}{F} \tag{1}$$

where, Taw is the mean residence time, second (s); hu is hold up (kg), F is feed rate (kg s^{-1}). Again, $hu = \rho_p Ah$, while, ρ_p is the paddy bulk density (kg m^{-3}), A is the bed area (m^2), h is the bed thickness (m)

Paddy bulk density largely varies with paddy moisture content and impurities that affects hold up capacity of dryer. Therefore, bulk density of paddy with various moisture content and impurities was determined. A 40 cm diameter and 25 cm height steel cylinder was used for determining the bulk density. The bulk density of paddy (ρ_b) with various moisture contents and impurities was first calculated using the following common formula while samples were taken from 20 different paddy heaps after passing through the Pre-cleaner.

$$\text{Bulk density} = \frac{\text{weight of paddy}}{\text{cylinder volume}}$$

Finally, by multiple linear regression analysis, the following empirical relationship (between bulk density and paddy moisture content & impurity) was obtained as shown in Eq. (2).

$$\rho_b = a - b_1 \cdot M - b_2 \cdot I \tag{2}$$

where, M is the fraction of paddy moisture content in dry basis, I is the fraction of impurity percentage in paddy. The parameters of Eq. (2) was, $a = 744.24$, $b_1 = 18.59$ and $b_2 = 1065.49$ with the Coefficient of Determination (R^2) value of 0.96.