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# Sequential modeling of fluidized bed paddy dryer

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ABSTRACT

A sequential method was developed to model a continuous plug flow fluidized bed dryer. The method is based on dividing the dryer into sections in series with ideal mixing for both solid and gas phases in each section. In order to determine the proper number of sections, drying experiments were carried out using paddy at different operating conditions. It was shown that the number of sections can be correlated to Damköhler number, which includes kinetic and hydrodynamic parameters of the process. The model is able to predict the particle's moisture profile along the bed as well as the moisture content of dried product. It was shown that the model fits the experimental data satisfactorily with the correlation coefficient of 0.989. Moreover, the model was tested against available data in the literature at different scales and operating conditions for which an error of less than 4.5% was observed in predicting the paddy moisture content at the outlet.



## 1. Introduction

Numerous types of fluidized bed dryers have been developed in various industries, among which, well-mixed, plug flow, vibrated, agitated and centrifugal fluidized bed dryers are the most important ones (Mujumdar and Devahastin, 2003). Despite this variety, the well-mixed and plug flow fluidized bed dryers are the most common types, which can cover other above-mentioned types of dryers. The major purpose of employing these diverse types of dryers is to enrich the fluidization quality. Considering the fluidization behavior and characteristics of paddy, the plug flow is the most suitable type of fluidized bed dryer for paddy. However, well-mixed fluidized bed dryers have been applied for paddy drying in some researches (Assari et al., 2007; Fyhr and Kemp, 1999; Lai and Chen, 1986; Madhiyanon et al., 2006; Palancz, 1983; Srinivasakannan and Balasubramanian, 2002; Zare and Chen, 2009).

Many efforts were made in research and development of fluidized bed paddy dryers to predict the dryer behavior with a mathematical model (Soponronnarit et al., 1998). For modeling the well-mixed fluidized bed dryer, two general approaches have been developed. In the first approach, only the mass and energy balances for the particles and gas are considered, leading to a set of partial differential equations (Fyhr and Kemp, 1999; Madhiyanon et al., 2006; Zare and Chen, 2009). The other approach is based on the hydrodynamic considerations. This method is categorized into multiphase modeling, when two (Assari et al., 2007; Lai and Chen, 1986; Srinivasakannan and Balasubramanian, 2002) or three (Palancz, 1983) phases are presented. The latter type of modeling is one of the most complex procedures to predict the behavior of a fluidized bed dryer.

Numerous models have been developed for plug flow fluidized bed paddy dryer based on the knowledge of interaction between solid phase and gas phase (Daud, 2008). These models can be classified into two major groups:

- *Differential modeling:* This is based on the mass and energy balances for both solid and gas phases (Daud, 2007; Soponronnarit et al., 1996). In some cases, the momentum balance for each phase is also included (Izadifar and Mowla, 2003). Some researchers (Soponronnarit, 2003; Tirawanichakul et al., 2003, 2005, 2009) considered diffusion through the paddy based on Fick's second law. Obviously, models of this group can provide details about the behavior of fluidized bed dryer but the complexity of this method prevents it from being used easily, practically and extensively.
- *Sequential modeling:* In this method, by employing the axial dispersion theory and/or residence time distribution (RTD), the bed is divided into several mixed sections (Baker et al., 2004, 2006; Fyhr et al., 1999; Wanjari et al., 2006). Each section is considered as a well-mixed fluidized bed dryer. This method provides a reasonable and reliable procedure to model the plug flow fluidized bed dryers with the least complexity. The only problem of this type is the difficulty of specifying the required number of sections (Daud, 2008).

In the present work, a sequential modeling approach was developed by dividing the fluidized bed dryer into several sections. Mixing for both gas and solid phases was considered ideal in each section. It was tried to relate the number of sections to the

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**Nomenclature**

| | |
|---|---|
| $Da$ | Damköhler number (dimensionless), $R_i\varepsilon\rho_p V/FX_i$ |
| $F$ | particle flow rate (kg/s) |
| $K$ | drying rate constant (1/s) |
| $n$ | number of sections |
| $R$ | rate of drying (kg water/kg dry solid s) |
| $R_i$ | initial rate of drying (kg water/kg dry solid s) |
| $RH$ | relative humidity (kg water/kg dry solid) |
| $t$ | time (s) |
| $T_i$ | air inlet temperature (°C) |
| $V$ | dryer volume (m$^3$) |
| $X$ | particle moisture (kg water/kg dry solid) |
| $X_e$ | equilibrium moisture (kg water/kg dry solid) |
| $X_i$ | initial moisture of particle (kg water/kg dry solid) |
| *Greek symbols* | |
| $\varepsilon$ | porosity |
| $\rho_p$ | particle density (kg/m$^3$) |
| $\tau$ | residence time (s) |
| *Subscripts* | |
| $j$ | section index |

operating conditions of the dryer, based on which the moisture of paddy can be evaluated. For this purpose, Damköhler dimensionless number was employed which is the ratio of reaction rate to the convective mass transfer rate (Fogler, 2006). The present work, the drying rate was used and Damköhler number was defined for a drying process as the ratio of drying rate to the covective rate of moisture removal. Fogler (2006) showed that by employing Damköhler dimensionless number, the number of well-mixed sections can be obtained. Simplicity, flexibility for various conditions, and its ability to be used by commercial simulators are the biggest advantages of this modeling. The model was validated using experimental data at various operating conditions.

## 2. Mathematical modeling

### 2.1. Drying kinetics

Different theoretical kinetic models for changes of moisture against time were presented for different materials by Hii et al. (2009) and Srinivasakannan and Balasubramaniam (2006). Some of these models were applied to paddy drying by Das et al. (2004, 2009). According to their study, Page's equation showed the best agreement with the experimental data followed by the exponential model (Newton's function). In the present work, the Newton's function was used for describing the drying kinetics:

$$\text{Moisture ratio} = \frac{X - X_e}{X_i - X_e} = \exp(-Kt) \quad (1)$$

Based on this equation, the drying rate is:

$$R = -\frac{dX}{dt} = K(X - X_e) \quad (2)$$

where $X_e$ represents the equilibrium moisture, which is a function of inlet air temperature and inlet air relative humidity as follows (Atthajariyakul and Leephakpreeda, 2006):

$$X_e = \frac{1}{100}\left(\frac{\ln(1 - RH)}{-4.723 \times 10^{-6}(1.8T_i + 491.7)}\right)^{\frac{1}{1.386}} \quad (3)$$

The constant $K$ in Eq. (1) is sum of two different mass transfer resistances (internal and external) in the process of transferring moisture from paddy to the air and is affected by paddy thermal conductivity and external heat transfer coefficient.

### 2.2. Modeling

Paddy is categorized as type D particles based on Geldart's classification (Geldart, 1973). Fluidization characteristics of these particles are not well known (Brzic et al., 2005). Although, no reliable assumption for the paddy flow regime can be made, an acceptable hypothesis used in this work was complete mixing of solids since high fluidization velocity is necessary to fluidize Geldart D particles. Moreover, the bed height was set in a way to achieve easy fluidization. Nevertheless, to consider the effect of non-ideality; the model was represented by a series of distinct well-mixed cells (Fogler, 2006). This is the hydrodynamic scheme adopted for the paddy dryer in this work, which is illustrated in Fig. 1. Energy and mass balances are the basic equations in modeling a drying process. Temperature affects the equilibrium moisture content and the drying rate. However, the temperature change through the bed is limited (Baker et al., 2004, 2006; Fyhr et al., 1999; Izadifar and Mowla, 2003; Wanjari et al., 2006). In the case of short length of beds, temperature variation is in the range of few degrees Celsius (Daud, 2007). Therefore, the drying considered in this work can be considered as isothermal process, thus, only the mass balance for the moisture of paddy was considered.

Moisture balance for the paddy in a section of the dryer, as shown in Fig. 1, at the steady state condition is:

$$FX_{j-1} - FX_j - R_j\rho_p V_j\varepsilon = 0 \quad (4)$$

Replacing the rate of drying from Eq. (2), moisture content of paddy at the exit of the section can be obtained:

$$X_j = \frac{FX_{j-1} + K_j X_e \rho_p V_j \varepsilon}{F + K_j \rho_p V_j \varepsilon} \quad (5)$$

The residence time of the paddy in each section is defined as:

$$\tau_j = \frac{V_j \varepsilon \rho_p}{F} \quad (6)$$

Therefore, Eq. (5) can be presented as:

$$X_j = \frac{X_{j-1} + K_j X_e \tau_j}{1 + K_j \tau_j} \quad (7)$$

Since all sections in Fig. 1 were assumed to be of equal sizes, there are equal residence times for all sections:

$$\tau_1 = \tau_2 = \cdots = \tau_n \equiv \frac{\tau}{n} \quad (8)$$

Therefore, the moisture of paddy in each section can be obtained from:

$$X_j = \frac{X_{j-1} + K_j X_e \frac{\tau}{n}}{1 + K_j \frac{\tau}{n}} \quad (9)$$

By considering the same drying rate constant at each section, the final outlet moisture can be evaluated from:

$$X = \frac{X_i + \left(K\tau + \left(K\frac{\tau}{n}\right)^n\right) X_e}{\left(1 + K\frac{\tau}{n}\right)^n} \quad (10)$$