An Analysis on Modeling of Fluidized Bed Drying of Granular Material

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Abstract
The drying kinetics corresponding to the falling rate period is commonly modeled using Fick’s diffusion equation in fluidized beds. The appropriateness of the use of Fick’s diffusion equation to represent the falling rate drying kinetics is the subject of the present paper. The estimated diffusion coefficient is normally the single kinetic parameter to assess the kinetics of the drying and is often used to compare the drying kinetics in different forms of drying. The dependence of the diffusion coefficient on the temperature and the concentration is well understood from the basic concepts of mass transfer; however, the diffusion coefficient estimated using Fick’s diffusion model is found to vary with additional variables such as the solids holdup. The dependence of the diffusion coefficient on additional parameters is purely empirical and has not been justified in the earlier studies. Towards this, experiments are conducted in fluidization columns of varying diameter in order not to vary the quality of fluidization while varying the solids holdup on a larger scale. The estimated diffusion coefficient is found to vary by orders of magnitude with the variation in the column diameter (solids holdup), necessitating the caution one needs to observe while comparing the kinetics of fluidized beds based on the diffusion coefficient.

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Keywords
Fluidized bed, diffusion coefficient, drying

Nomenclature

\( \text{Bi}_m \) Biot number, \( K R_s / D_{\text{eff}} \)

\( C \) moisture content of ragi grain at any time (kg of moisture/kg of dry solid)

\( C_i \) initial moisture content of ragi grain (kg of moisture/kg of dry solid)

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1. Introduction

Fluidized beds are widely used for the drying of granular solids such as grains, fertilizers, chemicals, pharmaceuticals and minerals, further to specialized applications such as drying of solutions, pastes and liquids sprayed on to the fluidized bed containing inert materials. Fluidized beds offer advantages such as: (i) the fluidity of the bed facilitating easy handling and transport of solids, (ii) high heat and mass transfer rates, (iii) perfect mixing of material in the bed, and (iv) the possibility of applying other sources of energy such as immersed heating coils, etc.

The mode of operation of a fluidized bed could either be batch or continuous. The batch dryer finds application for small-scale production, while the continuous systems are used for large-scale production. Prior knowledge on drying kinetics is essential for the design and sizing of fluidized beds. The drying rates in fluidized beds are strongly influenced by the characteristics of the material and the conditions of fluidization.
Drying of solids is generally understood to follow two distinct drying zones known as the constant rate period and falling rate period demarcated with critical moisture content. The critical moisture content is reported to vary with operating parameters and with the type of drying equipment. The constant rate period is understood to have a maximum drying rate, which remains constant until the critical moisture content with the resistance for moisture transfer in the gas phase. The rate of diffusion of moisture to the surface of solids becomes the limiting factor for moisture transfer as far as the falling rate period is concerned. The extent of drying zones is decided based on the type of material, with materials like sand, ion exchange resin, glass beads, etc., reported to have a larger duration of constant rate period and short linear falling rate period, while fibrous grains such as mustard, pepper, ragi, poppy seeds, etc., are reported to have a very short duration constant rate period and a longer curvilinear falling rate period [1].

The complex hydrodynamics and process calculations are material and dryer specific, and hence numerous mathematical models have been developed to estimate the drying kinetics. These range from analytical models solved with a variety of simplified assumptions to purely empirical models, often built by regression of experimental data.

The drying rate in the constant rate period in fluidized bed drying is modeled using (i) a simple empirical correlation relating drying rate to the influencing parameters or utilizing the heat/mass transfer coefficient between solids and gas in fluidized bed [2–6] or (ii) either two-phase or three-phase bubbling bed models, which assume the bed to be made of a bubble phase, emulsion phase or a dense phase with the exchange of mass and energy between these phases [7–13].

Similarly, drying kinetics in the falling rate period is modeled using simple models considering the rate of drying to linearly reduce from the critical moisture content to the equilibrium moisture content [14], which form characteristics of non-porous material as well as material with very high porosity. Materials such as food grains that offer high resistance for moisture diffusion exhibit a curvy falling rate period that could be modeled using simple exponential time decay models (Newton model, Page model, Henderson and Pabis model, two-term exponential model and approximate diffusion model) which are purely empirical in nature [15–17]. The model that best fits the experimental data is chosen as the appropriate model. On the other hand, complex models that serve the purpose of improving the fundamental understanding of drying kinetics are widely based on Fick’s diffusion equation [18–23]. The drying rate is estimated by solving the partial differential equation either using analytical solutions or using numerical techniques depending on the boundary conditions selected to represent the experimental conditions. The evaluated diffusion coefficients could well serve as a single kinetic parameter indicating the rate of drying, which could well be extrapolated beyond the experimental conditions within acceptable errors.

The use of Fick’s diffusion equation to represent the drying kinetics in a fluidized bed assumes all the solids in the fluidized bed to be exposed to uniform conditions.
The moisture in the solids is assumed to be uniformly distributed initially and the model predicts the varying moisture concentration profile in the solids with respect to time. The use of Fick’s diffusion equation is also used as an appropriate modeling tool in representing the drying kinetics in other kinds of dryers such as tray dryers, wherein the shape of the solid slab is taken into consideration. Irrespective of the kind of dryer, the diffusion coefficient estimated serves as an indicator for the estimation of the drying kinetics and often comparison of the performances of different dryers is based on the estimated diffusion coefficient.

It is the basic objective of this paper to test the reliability of the estimated kinetic parameter (diffusion coefficient) to serve the good purpose of predicting the drying kinetics of granular material in particular to fluidized beds. An inconsistency in the estimated diffusion coefficient from the experimental data is suspected, since the model only considers single particles in the bed, ignoring in the quantum of material in the bed. The dependence of the diffusion coefficient on the temperature and the concentration is well documented and understood from the basic concepts of mass transfer. However, the reported dependency on solids holdup could not be reasoned with any justification. This is basically due to the inability of the model to consider the geometry of the bed, resulting in the estimated diffusion coefficient showing a dependency on solids holdup. Towards this, experiments are conducted in columns of 0.148 and 0.245 m diameter, with the food grain ragi (*Eleusine corocana*), a granular material, by varying the solid holdup in a broad range from 0.3 to 2.6 kg. The variation in the column diameter is to ensure that the increase in the solids holdup does not affect the quality of fluidization.

### 2. Experimental

Drying experiments were conducted using fluidized columns of 0.148 and 0.245 m internal diameter with a height of 1.2 m. The schematic diagram of the experimental setup is shown in Fig. 1. The experimental setup consists of an air supply line from an air bower, control valve (1), orifice plate with monometer (2), electric heater with temperature control (3), thermocouple (4), plenum chamber (5), perforated air distributor plate (6), fluidization column (7) and cyclone separator (8). The gas distributor was 2 mm thick with 2-mm perforations having 13% free area. A fine wire mesh was spot welded over the distributor plate to arrest the flow of solids from the fluidized bed to the air chamber. Air from the blower was heated and fed to the fluidization column through the air chamber (plenum). The electrical heater consisted of multiple heating elements each of 2 kW rating. A temperature controller, provided to the air chamber, facilitated control the of the air temperature within ±3°C of the set temperature for the entire operating range of 30–110°C. Airflow was measured using a calibrated orifice meter.

Table 1 shows the physical characters of ragi as well as the experimental conditions covered in the present study. A good fluidization behavior in terms of perfect mixing of the bed material was observed visibly. This was substantiated with low
fluctuation in the bed pressure drop, which is an indication for smooth fluidization without the formation slugs. The minimum fluidization velocity was not found to vary with the temperature within the range of temperatures covered in the present study.

Air at the desired temperature and flow rate was allowed to flow through the fluidization column. A known quantity of ragi with a known initial moisture content was introduced into the column after ensuring the steady temperature and the air flow rate. As fluidization continued, ragi samples of approximately 1 g were scooped out of the bed each time, at regular intervals of time, for moisture con-
tent estimation. The samples were weighed and kept in an air oven at 105°C until no further weight change of the samples was observed. The ratio of difference in weight of the sample to the final weight of the sample after drying at 105°C is the moisture content of the sample (dry basis). The experimental data was checked for reproducibility and was found to deviate within ±2%. The equilibrium moisture content was estimated by keeping the samples in an air oven at the desired temperatures until no further weight change. The equilibrium moisture content is the ratio of the difference in weight of samples kept at the desired temperature until no further weight change to the bone dry weight of the samples, to the bone dry weight of the samples (dry basis).

3. Results and Discussion

The acceptability of the effective diffusivity coefficient estimated using Fick’s diffusion equation to serve as a single parameter to assess the drying kinetics in a fluidized bed is the subject of analysis in the present paper. The analysis is performed based on the experimental data generated in the present study.

Fick’s diffusion equation assumes that the moisture diffuses from inside the particle to the surface of the particle and evaporates at the surface, and that all the particles are uniform in size and spherical in shape. The fluidized beds are perfectly mixed beds and the solids at any point in the beds are exposed to the same drying conditions. The general form of Fick’s diffusion equation to estimate the drying kinetics for spherical particles is as given as:

\[
\frac{\delta C}{\delta t} = D_{\text{eff}} \left[ \frac{\delta^2 C}{\delta r^2} + \frac{2}{r} \frac{\delta C}{\delta r} \right].
\] (1)

Different boundary conditions are utilized, which are varied and are selected to reflect the experimental conditions. One of the common boundary conditions, which also accounts for the external mass transfer resistance, is:

\[
\begin{align*}
\text{at } t = 0; & \quad 0 < r < R_s; \quad C = C_i, \\
\text{at } t > 0; & \quad r = 0; \quad \delta C/\delta r = 0, \\
\text{at } t > 0; & \quad r = R_s; \quad -D_{\text{eff}}(\delta C/\delta r) = K(C_{sj} - C_{be}),
\end{align*}
\]

where \(C_{sj}\) is the moisture concentration just within the sphere and \(C_{be}\) is the concentration required to maintain equilibrium with the surrounding atmosphere. The analytical solution for equation (1) for the above boundary conditions was provided by Crank [24]:

\[
\frac{C - C_e}{C_i - C_e} = \sum_{n=1}^{\infty} \frac{6B_i^2 \exp(-\beta_n^2 D_{\text{eff}} t / R_s^2)}{\beta_n^2 (\beta_n^2 + Bi_m (Bi_m - 1))},
\] (2)

where \(\beta_n\) are the roots of the equation:

\[
\beta_n \cot \beta_n + Bi_m - 1 = 0.
\] (3)
The mass Biot number ($B_{im}$) is defined as $K R_s/D_{eff}$ and the mass transfer coefficient ($K$) can be calculated based on correlations reported in literature [25–27]. A compilation of a number of mass transfer coefficients correlations was due to Kunii and Levenspiel [28]. However, the equation due to Richardson and Szekely [29] is utilized in the present study as the mass transfer coefficient was evaluated for shallow beds:

$$Sh = \frac{K d_p}{D} = \begin{cases} 
0.374 Re^{1.16} & \text{for } 0.1 < Re < 15, \\
2.01 Re^{0.5} & \text{for } 15 < Re < 250.
\end{cases}$$ \hspace{1cm} (4)

The Sherwood number is the ratio of external mass transfer resistance to the molecular diffusivity, while the Biot number is the ratio of external mass transfer resistance to the overall mass transfer resistance. The effective diffusivity is estimated by minimizing the error between the experimental data and the model prediction.

It is not the objective of the present paper to estimate the effect of various parameters on the kinetics of drying. The experiments are designed to capture the variation in diffusion coefficient with the solids holdup by varying the size of the fluidization column to have identical conditions of fluidization. Figure 2 shows the plot of relative moisture content with respect to time for solids holdup from 0.30 to 2.6 kg. A good fluidization condition was maintained by having a column diameter of 0.148 m for solids holdup until 0.6 kg and a 0.245-m column for solids holdup above 1.3 kg. The moisture content is found to decrease with an increase in the time of drying irrespective of the solids holdup until attaining the equilibrium.

![Figure 2](image_url). Variation in relative moisture content with drying time ($T$, 80°C; $C_i$, 0.210 kg/kg; $U$, 1.2 m/s; $C_e$, 0.030).
moisture content. The rate of drying is found to decrease with the increase in the solids holdup.

The temperature of the bed at any given time during the duration of drying is found to be higher at a lower solids holdup as compared to drying with higher solids holdup. This possibly explains the reason for the higher drying rate with lower solids holdup. As the amount of solids is lower, the amount of moisture that diffuses from the solids to the gas phase is lower, resulting in a higher bed temperature. The higher bed temperature indirectly increases the rate of diffusion of moisture, thereby increasing the drying rate. Although the bed temperature is bound to vary from near the wet bulb temperature to the inlet temperature of the drying medium with corresponding variation in the diffusion of moisture from the particles, the model predicts only a single average constant diffusivity for the entire period of drying.

Figure 2 shows a significant variation in the drying kinetics with the increase in solids holdup. The effective diffusivity coefficient for each of the drying curves is estimated by minimizing the error between the model prediction and the experimental data. The estimated diffusivity coefficients are listed in Table 2. It can be seen (Table 2) that the effective diffusivity coefficient increases with the reduction in solids holdup. The variation of diffusivity coefficient with solids holdup is found to vary by orders of magnitude. This large variation in effective diffusivity coefficient cautions against the use of the effective diffusivity coefficient as a single parameter to compare the magnitudes of drying and its use in estimation of drying kinetics. Further, the empirical dependence of the model with additional parameters denies extrapolation beyond the experimental range, very much limiting its application.

The application of Fick’s diffusion equation for cases where the entire bed of material is considered as single particles with known dimensions does not show any additional dependence of the diffusivity coefficient. This finds wider application in fixed bed or static dryers/adsorbers. The application of Fick’s diffusion equation to fluidized beds does not consider the whole bed, but rather considers the individual particles that make the bed of material, with the assumption that all the materials are exposed to uniform conditions. The variation of the number of particles with the increase in the solids holdup could not be accounted for by the model, which brings in the additional dependence of the model parameters with the solids holdup.

Table 2.
Evaluated effective diffusivity coefficient with the variation in the solids holdup

<table>
<thead>
<tr>
<th>Dc (m)</th>
<th>Ws (kg)</th>
<th>Deff × 10^{11} (m^2/s)</th>
<th>RMSE × 10^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.148</td>
<td>0.3</td>
<td>8.2</td>
<td>3.3</td>
</tr>
<tr>
<td>0.148</td>
<td>0.6</td>
<td>6.1</td>
<td>4.6</td>
</tr>
<tr>
<td>0.245</td>
<td>1.3</td>
<td>3.2</td>
<td>4.2</td>
</tr>
<tr>
<td>0.245</td>
<td>2.6</td>
<td>2.4</td>
<td>5.5</td>
</tr>
</tbody>
</table>
4. Conclusions

The use of Fick’s diffusion equation to model the drying kinetics of the granular material in a fluidized bed shows a larger dependence of the evaluated effective diffusivity coefficient on solids holdup. The dependence of the effective diffusivity coefficient on solids holdup is due to the assumption of single particles in the bed, rather than representing the whole geometry of the bed. The variation of solids holdup causes the bed temperature to vary due to the variation in the number of particles in the bed. Since the model does not have the ability to capture the variation in the bed temperature due to the number of particles, an empirical dependence of the effective diffusivity with the solids holdup results.

With the fallacies in the use of the basic Fick’s diffusion equation in modeling the drying kinetics of the fluidized bed well known, the use of a simple empirical approach makes good sense, as the complex models require numerical computation. Further improvement of the basic models in terms of ability to account for the variation in bed temperature with time is necessary before the models could be utilized with a certain degree of confidence.

References