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Fluidized bed drying of Loy Yang brown coal with variation of temperature, relative humidity, fluidization velocity and formulation of its drying rate

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HIGHLIGHTS

- ▶ Fluidized bed drying of as-received brown coal at low temperature was carried out.
- ▶ Temperature, relative humidity, fluidization velocity were examined as variables.
- ▶ Lower humidity, higher temperature and fluidization velocity are favorable for drying.
- ▶ Drying rate can be described in a simple drying equation as $dw/dt = -k(1-X^{*})^{n}$.
- ▶ Using $n = 0.25$, k can be expressed in a linear function of each variable.

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ABSTRACT

The fluidized bed drying of Loy Yang coal, which is one of Australia's representative Victorian brown coals exhibiting a high moisture content (up to ca. 65 wt.%, as-received base), using air as the bubbling gas was examined by varying temperature, relative humidity, and fluidization velocity at 40–80 °C, 0–40%, and 10.0–35.0 cm/s, respectively. The effects of the three variables on the drying rate and drying time were investigated. Higher temperature, lower relative humidity, and higher fluidization velocity were favorable for drying, i.e., they showed high drying rate. Drying rate was maximum immediately after the set drying temperature was attained; then, it decreased at a roughly constant rate, indicating a falling-rate drying period (constant-decrease drying period) and finally became zero.

Drying rate could be described by a simple equation, $dw/dt = -k(1-X)^{n}$; therefore, it was a function of the drying rate constant k, drying fraction X, and drying rate order n. The drying rate order n could be taken as 0.25; it is independent of temperature, relative humidity or fluidization velocity. The drying rate constant k could be expressed as a function of temperature, relative humidity, fluidization velocity; within the limits of the experimental error, k was a linear function of each variable, and it increased with increasing temperature, decreasing relative humidity, and increasing fluidization velocity.

1. Introduction

Although a future energy mix of fossil fuels and renewable energies is considered as a practical approach to the energy delivery, limited fossil fuel deposits and underdeveloped extraction and power generation technologies restrict the development of such an energy mix. Coal, especially abundant low-rank coals, will probably be included in the future energy mix.

However, low-rank coals such as brown coal generally exhibit high moisture content (up to 65 wt.%, wet basis) because of the abundant oxygen-containing functional groups in their structures [1].

Because of the energy requirements of the drying process, low-rank coals utilized for power generation release 20% more CO_2 per unit of power produced than that by bituminous coals [2]. Thus, the development of a more efficient drying process including carbon capture and storage is essential.

For evaporative drying, past and present technologies primarily employ high-temperature energy sources such as hot gas, hot steam, hydrothermal dewatering, and hot water drying [1,3].

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Nomenclature

H, R.H.	relative humidity (%)	w	weight of water (g)
k	drying rate constant (g/min)	w_i	initial weight of water (g)
n	drying rate order, 0.25	w_r	remaining water (g) (equilibrium moisture contents)
t	time (min)	X	drying fraction (–) $\left(= 1 - \frac{w}{w_i}\right)$
T	temperature (°C)	X^*	drying fraction [–] $\left[= 1 - \left(\frac{w-w_r}{w_i-w_r}\right)\right]$
U_f, V	fluidization velocity (cm/s)		

However, to avoid the loss of volatile components that are required for effective coal combustion, coal should be dried at low temperatures. Using low quality heat for coal drying can increase the efficiency of a power plant [4].

To explore drying kinetics, various models have been proposed for drying in a fluidized bed. Models reported by Viswanathan and Chandran et al. neglected the details of bubble activity within the bed [5,6]. Kannan et al. developed a model employing a two-phase hydrodynamic description; however, they neglected the effect of particle temperature variation with residence time and moisture content in a bed, as identified by Chen et al. [7]. Chen et al. suggested a steam drying model in a fluidized bed, which was the extension of an earlier single-porous-particle model. They introduced the inversion temperature, above which the vaporization rate in steam is greater than that in air. However, their results are useful, because they identify that this value can vary with evaporation rate, and drying rate is highly dependent on operating conditions such as feed conditions and the steam tube duty [8].

More recently, Wang reported the lab-scale fluidized bed drying of three Illinois coals at low temperature and developed a theoretical model using four parameters, including coal moisture content, exit air temperature, exit air specific humidity, and exit air relative humidity by calculating an energy and mass balance equation [9]. These results are also useful; however, several assumptions were made that could lead to an error, especially in the initial drying step.

Although it is widely used, apparently, a suitable mathematical model for the plant design or optimization of operation by employing energy and mass balance has limitations because of its complexity, and poses ongoing challenges. Despite its inaccuracies, the plug-flow model, a conceptually simple model that requires minimal mathematical computation, still remains widely used by practicing process engineers [10].

Abhari and Isaacs have used $-\mathrm{d}X/\mathrm{d}t = -kX^n$ type kinetics, where $X = (W_{\text{wet coal}} - W_{\text{dry coal}})/W_{\text{dry coal}}$, to predict the drying rate of six coals from the Argonne coal sample series. However, they used TGA to investigate the drying coal by varying only temperature and analyzed the results by the regression method in Lotus 123 [11]. Moreover, Vorres et al. have performed research on drying on the basis of Abhari and Isaacs's equation; however, they focused on other aspects such as separating the drying modes [12].

Our research group has reported the drying kinetics of the Loy Yang coal in a form of $\mathrm{d}w/\mathrm{d}t = -k(1-X)^n$ using a halogen heat source, where X is the drying fraction equal to $1-w/w_i$. They found that if the drying rate order, n was set to 0.25, the kinetic form could be applied to the entire range of experimental conditions by using as-received Loy Yang coal, which has wide particle size distribution (<Φ 2 mm). However, in this study, the authors have only focused on temperature as a variable because of the limitations of the experimental apparatus [13–15].

The authors have attempted to reutilize the gases, including air that is produced from sub-processes within power-generation systems to retain maximum possible useful energy. In the present study, the low-rank Loy Yang coal was examined under low temperatures between 40 °C and 80 °C, various humidity levels, and fluidization velocity conditions using a fluidized bed dryer.

Other motivating factors for this study were to validate whether the previously suggested equation can be applied to steam fluidized-bed drying with three variables, namely temperature, relative humidity, and fluidization velocity, and to develop a simplified fluidized bed drying model that can be solved by an iterative numerical solution to reduce the calculation time by avoiding mass and heat-transfer process descriptions.

2. Materials and methods

2.1. Minimum fluidization velocity

The fluidization velocity of a bubbling gas in a fluidized bed is one of the most significant factors that can affect drying rate. The main objective of utilizing a fluidized bed is to enhance drying rate. First, the minimum fluidization velocity U_{mf} requires evaluation.

The minimum fluidization velocity required to the 2.5-g Loy Yang brown coal is approximately 9.0 ± 1.0 cm/s with temperature of 40–80 °C.

Ng and Tan conducted an optimization study of fluidized bed drying using an industrial-scale fluidized bed dryer. They showed that drying rates were approximately 10–12% higher as fluidization velocity increased from 1.5 to 2.0 U_{mf} [10]. After examining the behavior of fluidization with an increased fluidization velocity, a standard fluidization velocity of ca. 2.5 U_{mf}, U_f = 23.0 ± 1.5 cm/s was selected [16–22].

2.2. Fluidized bed dryer

As-received Loy Yang coal, which is classified as a soft brown coal and is considered as a lignite B under the US ASTM classification system, has 60-wt.% water content on wet basis, as shown in Table 1 [23]. For fluidized bed drying, the coal was milled to approximately 2 mm; then, it was sieved to a diameter of 600–850 μm. It was stored in an air-tight container to prevent the evaporation of water.

As depicted in Fig. 1, a fluidized bed dryer 200 mm in height and 22 mm in diameter was self-manufactured. Bubbling gas was

Table 1
Typical properties of Loy Yang coal used in this study.

Proximate analysis [wt.% (wet basis)]	
Moisture	59.3
Ash	0.4
Volatile matter	22.1
Fixed carbon	18.2
Ultimate analysis [wt.% (d.a.f. basis)]	
Carbon	70.86
Hydrogen	4.56
Oxygen	23.69
Nitrogen	0.63
Sulfur	0.26