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# Optimization of drying of low-grade coal with high moisture content using a disc dryer

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ABSTRACT

In this study, low-grade coal with high moisture content was dried in a novel disc dryer equipped with a heating plate and rotary blades. Raw coal was fed into the center of the disc dryer and then was transferred from the center of the heating plate to the outside of the plate by the rotary blades during the drying process. According to a numerical analysis using a model of a single solid spherical particle without any porosity, the temperature of the coal particles reached that of the heating plate within 5 min. The analysis also showed that at a heating plate temperature of 150 °C, the moisture content of the raw coal was lowered from 34% to below 3% within 5 min, and all of the raw coal was dried after 10 min of drying time. Experimental studies were used to investigate the influence of the following factors on the effectiveness of the novel disc dryer: heating plate temperature, coal feed rate, rotational speed of the rotary blades, drying environment, and position of the coal on the heating plate. When the heating plate temperature was high, the moisture content of the dried coal was greatly decreased. However, on the basis of energy-efficiency considerations, it was recommended that the temperature of the heating plate be maintained at 150 °C. Furthermore, a decrease in the coal feed rate could lower the moisture content, and a high rotational speed of the rotary blades could slightly reduce the moisture content as well. In addition, the reduction in moisture content could be remarkably enhanced by using a vacuum pump to remove the evaporated water vapor from the inside of the dryer. The position of the coal on the heating plate was also important. The temperature of the raw coal could be increased without evaporation up to a certain distance from the center of the dryer. However, the moisture of the raw coal began to evaporate in a region near the outside of the heating plate before discharging, where the raw-coal temperature reached about 100 °C. Overall, it was concluded that the size and temperature of the heating plate should be considered in the design and operation of a disc dryer for drying low-grade coal. In addition, the dispersion of raw coal on the heating plate was important during the drying process. The disc dryer could enhance the conductive heat transfer coefficient between raw coal and a heat source and mixing of the coal to reduce drying time.



## 1. Introduction

Fossil fuel resources (especially oil) are rapidly depleting, and thus, oil prices are abruptly increased recently. The price of high-grade coal, which is commonly used as a fuel, is also increasing because high grade coal reserves are quite limited as well. Because low-grade coal is relatively rich in reserves and low in price, many researchers have been highly interested in upgrading it for use as a source of highly efficient energy, while lowering the consumption of oil and high-grade coal [1,2].

The total reserves of coal in the world amount to 7.14 trillion tons, of which 3.27 trillion tons is bituminous coal and anthracite, and 3.87 trillion tons is subbituminous coal and lignite. However, only 0.98 trillion tons of coal is in recoverable reserves, of which 47.3%, or 0.46 trillion tons, is low-grade coal [3]. In general, low-grade coal is classified as such because it contains high levels of impurities such as ash and moisture that result in low energy values; it is therefore less desirable for direct use as an energy source. The use of low-grade coal as an energy source requires that its moisture content first be decreased in a drying process.

The water contained in coal is typically removed by mechanical and thermal methods, including thermal drying and thermal dewatering. The dewatering process of mechanical methods is primarily used to separate coal solids from slurry, while that of thermal methods is used to produce dry coal by removing the moisture inherent in low-grade coal. In the thermal drying method, combustion gas or superheated water vapor is utilized to reduce the moisture content of the coal. This can usually simplify the drying equipment, but requires consumption of a huge amount of energy. On the other hand, in the thermal dewatering method, the moisture of the coal is removed in a liquid state by using saturated water vapor or hot water in a pressurized reactor; this is advantageous in terms of energy consumption, but the

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**Table 1**
Physical properties of coal used in this study [7].

| | |
|---|---|
| $\rho_v$ (kg/m$^3$) | 1500 |
| $k$ (W/m·K) | 0.26 |
| $C_{v,v}$ (J/kg·K) | 1520 |
| $C_{v,\infty}$ (J/kg·K) | 550 |
| $V_\infty$ (m/s) | 0.5 |
| $\varepsilon$ (emissivity) | 0.9 |
| $T_D$ (disc temperature, °C) | 130, 140, 150, 160 |

overall configuration of the equipment is very complicated, mostly owing to the pressurization. Such thermal methods are often used in the SynCoal Process developed by the Western Energy Company in the United States. Moreover, other drying processes based on the thermal methods have been actively developed; for instance, the K-Fuel process (USA), the binderless coal briquettes (BCB) technology (Australia) [4], the upgraded brown coal (UBC) process (Japan) [5], the Integrated Drying Gasification Combined Cycle (IDGCC) (HRL, Ltd., Australia) [6], and so on. These drying processes based on the thermal methods use microwaves [7], solvent [8], oil [5], or specific reactors for long residence time such as a fluidized bed reactor [9] or a long duct [10]. Most of the drying processes are operated with heating mediums and are complicated in the system constitution, which causes high costs of construction.

In this study, a thermal method was used to dry low-grade coal using a disc dryer, which was so designed that heat for drying coal can be transferred from a heat source to the coal without a heating medium during the drying process. Thus, no use of a heating medium in the dryer can result in simplifying constitution of the equipment with reducing drying time. The bottom plate of the dryer was heated, and the coal fed into the center of the dryer was transferred to the outlets by adjusting the rotational speed of the rotary blades. The drying efficiency of the process can be affected by the following factors: coal particle size and feed rate, drying temperature, and residence time and drying environment within the dryer. This study examined the influence of the coal residence time, revolution speed of the rotary blades, and drying environment in the dryer, in order to determine the optimal conditions for a continuous coal-drying process. In addition, a numerical analysis was performed to predict the approximate drying time by calculating the heat transfer time of the coal particles for various particle sizes and disc temperatures.

## 2. Research methods

### 2.1. Numerical analysis

Numerical calculations using a model of a single solid spherical particle without any porosity were used to resolve the particle-size effect associated with coal drying [11,12]. The Stefan model [13] and a two-phase model [14] are often used for including the mass transfer effect of evaporated water vapor when drying a sufficiently large coal particle. However, because this study used significantly small coal particles, it was necessary to use a simplified numerical method, mainly owing to the rapid mass and heat transfer phenomenon in a fine-sized coal particle. Because the transfer of heat to a coal particle on the disc can evaporate the moisture contained in the particle, it is important to first calculate the heat transfer from the disc to the coal particle. For the numerical calculation, it is assumed that the single coal particle is spherical in shape, and therefore, the equations use spherical coordinates.

Assuming that there is no convective heat transfer inside the coal particle, the numerical calculation considers only the conductive heat transfer and heat loss for coal drying. The governing equation is as follows:

$$\frac{\partial}{\partial t}\left(\rho_c C_{pc} T\right) = \frac{1}{r^2}\frac{\partial}{\partial r}\left(kr^2\frac{\partial T}{\partial r}\right) - q_v G_v - \frac{\partial}{\partial V_p}\left(V_p G_v c_{pv} T\right) \quad (1)$$

where $\rho$, $c_{pc}$, and $k$ are the density of the solid particle, the specific heat at constant pressure, and the thermal conductivity coefficient, respectively; $c_{pv}$ is the specific heat of the evaporated component, $G_v$ is the drying rate, $q_v$ is the volumetric flowrate, and $V_p$ is the mass fraction of dried moisture. The variables $r$, $t$, and $T$ denote the radius of a coal particle, time, and temperature, respectively. The left-hand side of the above equation is an unsteady-state term, and the right-hand side includes terms for diffusion, the latent heat loss due to evaporation, and the sensible heat taken out by the evaporated component [15].

The universal E/K model suggested by Fu et al. [16] to calculate the volatilization rate of a component in a coal particle can be applied in this study by assuming that the volatile component is water at a temperature of less than 160 °C [17]. This model is expressed by an Arrhenius-type equation [see Eq. (2)] having an activation energy (E) term and a proportional constant (K), which are universal values, independent of the type of coal. The volatilization rate in this equation is therefore a function only of the temperature of the coal particle [16]:

$$\frac{dV}{dt} = (V_\infty - V)K\exp(-E/RT) \quad (2)$$

where $V$ is the volume of the evaporated component, and $V_\infty$ is the final volume produced by the evaporation. The boundary conditions on the particle are as follows:

$$\left.\frac{\partial T}{\partial r}\right|_{r=0} = 0 \quad (3)$$

$$k\left.\frac{\partial T}{\partial r}\right|_{r=R} = (T_\infty - T_s) + \varepsilon\sigma F\left(T_\infty^4 - T_s^4\right) \quad (4)$$

$$T(t,r) = T_0, t = 0. \quad (5)$$

Eq. (3) presents a symmetry condition at the center of the coal particle, and Eq. (4) implies that the heat conductively transferred at the surface of the coal particle is the same as the sum of the heat given off by radiation and convection at the outside of the coal particle. In Eq. (5) regarding the initial conditions, the initial temperature inside the coal particle is given as $T_0$.

The numerical analysis was performed with coal particle sizes of 1, 3, and 5 mm, and the temperatures of the bottom heating plate of the disc were set to 130, 140, 150, and 160 °C. The physical properties of the coal used in this study are summarized in Table 1 and were used to calculate the temperature and moisture content of the coal particle along with time [11].

**Table 2**
Characteristics of Indonesian low-grade coal.

| Proximate analysis (wt.%) | | | | Elemental analysis (wt.%) | | | | |
|---|---|---|---|---|---|---|---|---|
| Moisture | Volatile matter | Ash | Fixed carbon | Carbon | Hydrogen | Nitrogen | Oxygen | Sulfur |
| 34.27 | 33.64 | 2.01 | 29.99 | 70.50 | 5.14 | 0.99 | 21.33 | 0.03 |