Experimental and analytical evaluation of the drying kinetics of Belchatow lignite in relation to the size of particles

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Abstract. Water removal is a key technology for enhancing efficient utilization of lignite in power generation. An inherent characteristic of lignite, attributed to the large amount of water kept within the fuel, is the factor decreasing the thermal efficiency of lignite-fired power plants. This paper presents the research results on investigating the drying kinetics of Belchatow lignite excavated in the Central Poland in prior to developing a water removal system. Lignite drying test was conducted in superheated steam atmosphere at the temperature range of 110-170 °C. Spherically shaped samples, of which the diameter is 2.5 mm, was used. The experimental results were then analysed with previously conducted measurements of 5, 10, 30 mm samples to investigate the influence of particle size. The presented analysis shows the agreement of the evaluated drying rate at the CDRP to the experimental data. The obtained experimental results were used to predict the drying behaviour of the group of particles. The proposed investigation clarifies the size dependence of the drying characteristics of the multi-size group of lignite particles.

1. Introduction
Lignite (brown coal and/or low-rank coal) pre-treatment has the consequence for the future prospective of advanced utilization in terms of both efficient use of fossil fuel and environmental preservation [1]. This is because of an inherent characteristic of lignite that contains a large amount of water (typically 40-60\% in mass). The large amount of water in this energy carrier devastates its potential in combustion process, in which the large part of heat has to be used for the vaporization of the water. Thus, the efficient water removal from lignite recently receives attention in the actual utilization in power plant engineering [1].

Water removal from lignite has been attempted for long time, however the conventional solution does not contribute substantially to above mentioned criteria. Additionally, large capacity applicable to conventional plants, fast processing, hazardless, compact design and the high energy efficiency has to be fulfilled for the real application [2–4]. Superheated Steam Fluidized Bed Drying seems to be the...
one that can answer to these requirements, and thus many effort can be found to realize this concept of dryer, though the technical difficulties are not overcome yet.

For design issue of such a dryer, the process design is one of the important concerns to be noted. In this perspective, drying characteristics of lignite in superheated steam must be well understood. Previous work of authors in this paper has investigated drying kinetics of the Belchatow lignite and quantitative evaluation of the drying process, time, the influence of degree of superheat of steam and drying speed have been carried out [5]. The size dependence was also considered with a larger size lignite particles [6]. This paper particular focuses on the drying characteristics of a small size grains and their results are presented. For summarizing the size dependence issue, this paper presents the simulated results of drying behaviour of the group of multi-size particles based on the obtained experimental data and discusses the significance of the size distribution in the potential application.

2. Experimental methodologies

2.1. Investigated samples

Sample used in the present experiment has been excavated from the Belchatow lignite mine located in the Central Poland. General coal properties of the investigated sample are shown in Table 1.

| Proximate analysis (As-received basis) | Value | Ultimate analysis (dry basis: free moisture) | Value |
|--------------------------------------|-------|-------------------------------------------|-------|
| Total moisture (wt%)                 | 51.60 | C (wt%)                                    | 56.90 |
| Surface moisture (wt%)               | 43.00 | H (wt%)                                    | 4.51  |
| Inherent moisture (wt%)              | 8.60  | O (wt%)                                    | 22.32 |
| Fixed carbon (wt%)                   | 16.78 | N (wt%)                                    | 0.68  |
| Volatile matter (wt%)                | 24.14 | Combustible sulphur (wt%)                  | 0.19  |
| Ash (wt%)                            | 7.48  | Sulphur total (wt%)                        | 1.30  |
| Higher Heating Value (MJ/kg)         | 10.81 | Ash (wt%)                                  | 15.40 |

2.2. Sample preparation

The experiment was conducted with spherically shaped lignite samples, of which diameter is 2.5 mm. Firstly, an initial granulated sphere was roughly prepared with a knife. The shape of the sample was polished on a plate by rolling in a hole precisely punched with an electrical discharged machining process. The size of the sample was adjusted step by step to the desired diameter: 2.5 mm ± 6.9 × 10⁻³ mm. The accuracy of the sample size depends on the precision of the electrical discharged machining process. The precisely smoothed sample was then drilled by 0.1 mm drill blade for the purpose of putting the suspension wire (chromel wire: 0.1 mm) to set at a glass rod. The prepared samples were hanged on the glass rod (see figure 1). Note that, due to the precision of the used electronic balance (±0.1 mg), four samples are used in a single test at the same time, since one sample weighs around 9.72 mg (average of all used samples). Using four samples together in a single test allows to omit the influence of the precision of the used electronic balance on the measurement.

2.3. Experimental apparatus and procedure

Figure 2 shows the configuration of the experimental apparatus. The cylindrical drying chamber, of which the diameter is 133 mm and the height is 152 mm, was operated with 3 heaters. Pure water was degassed, pumped up and provided to an evaporator and then to a superheater. The superheated steam was sent to the drying chamber, through a baffle plate attached to the vicinity of the chamber inlet for dispersing the supplied steam to the entire chamber. Additionally, two fans were installed near the test chamber: at the exhaust of test chamber and at the outside of the test section, next to the orifice (see
figure 2). These implementations are aimed to control the flow pattern inside the test section to ensure dispersed down-stream laminar flow.

The sample weight was measured to calculate the moisture content and drying rate. The electronic balance was connected with a metal suspension wire, on which the glass rod with the sample was hanged. The suspension wire was surrounded by an acryl pipe for protection. Air was supplied to the pipe to stabilize the temperature and flow inside the pipe and ensure accurate weight measurement.

The temperature of the sample surface was treated as the representative temperature of the investigated samples, and was measured by an infrared camera equipped with infrared bolometers in the range of wavelength detection from 8 to 12 µm. The infrared camera was connected to the test section by an optical path starting from the window in the test chamber. The optical path was heated to avoid the condensation of the steam on the film separating the test chamber from the ambient. The film provided proper conditions for conducting measurements: the film average transmittance in the range of wavelengths from 8 to 12 µm was equal to 90%.

The samples were dried at test temperatures of 110, 130, 150 and 170 °C. To define the exact moment of starting superheated steam drying, the sample setting process was conducted in the isolation from the superheated steam with the raise of a starting pipe up to the test chamber. The starting pipe was filled with nitrogen while setting the glass rod with a sample into the test chamber. After lowering the starting pipe and exposing the sample to the superheated steam, the changes in weight $W$ and temperature $T$ of the lignite particle were consequently and simultaneously recorded in 1 s intervals. Once the sample reached to the equilibrium moisture content, steam was switched to nitrogen in order to remove the residue of moisture left inside the sample. Nitrogen is fed and heated up in the gas heater to reach the same temperature as the superheated steam was maintained during the measurement. The weight of the sample after the nitrogen drying was regarded as that of the dry coal. The experiments were conducted three times at each test temperature (110, 130, 150 and 170 °C). In this study, (dry basis) moisture content $X$ is defined as:

$$X = \frac{W_w}{W_c}$$  \hspace{1cm} (1)

The ratio of the weight of water to the initial weight of the sample is defined as $WP$ wt%:

$$WP = \frac{W_w}{W_{ini}} = \frac{W_w}{W_{w, ini} + W_c}$$  \hspace{1cm} (2)

The drying rate $r_{SSD}$ was calculated from the change in dry-basis moisture content as follows:
\[ r_{\text{SSD}} = \frac{-dX}{dt} \]  

(3)

where \( t \) indicates the time (s). Because the lignite drying process involves a change in the heat transfer area of samples due to the structural change that was caused by the shrinkage after water removal, the drying rate was evaluated as the change in the moisture content over time. The shrinkage behaviour becomes specially significant after the shift to the Decreasing Drying Rate Period (DDRP) from the Constant Drying Rate Period (CDRP) [5].

3. Results and Discussion

3.1. Drying behaviour of the investigated lignite sample in 2.5 mm diameter sphere

The drying behaviour of the 2.5 mm diameter lignite spherical sample is shown in figure 3, counting the influence of the earlier mentioned test temperatures of 110, 130, 150 and 170 °C. The drying rate curve along the moisture content is presented in figure 4. The influence of the temperature is visible on the drying behaviour: a higher drying rate and shorter time of the process at a higher test temperature. The drying process can be categorized to the CDRP and DDRP as observed in the previous investigation, however the shortest CDRP was found in the present investigations.

The results of initial water percentage \( WP_{\text{ini}} \) and residual water percentage \( WP_{\text{res}} \) and the drying time in superheated steam \( t_{\text{SSD}} \) are indicated in Table 2. They are average of conducted 3 tests at each condition. Note that each result is the average of randomly chosen and prepared four samples that was used in a single test. This may particularly influence the amount of \( WP_{\text{res}} \) that does not follow the trend of desorption isobar, though the \( WP_{\text{ini}} \) is very similar among the results conducted in different temperature conditions and the drying behaviour of the lignite sample has relatively similar tendency at every test temperature conditions.

| Terms                          | 170 °C | 150 °C | 130 °C | 110 °C |
|-------------------------------|--------|--------|--------|--------|
| Initial water percentage, \( WP_{\text{ini}} \) (wt%) | 54.3%  | 54.1%  | 54.3%  | 52.8%  |
| Residual water percentage, \( WP_{\text{res}} \) (wt%) | 5.2%   | 2.8%   | 2.4%   | 5.2%   |
| Steam drying time \( t_{\text{SSD}} \) (min)     | 6.2    | 9.6    | 16.7   | 43.0   |

3.2. Size dependence of drying characteristics of the investigated lignite sample

The influence of the sample size on the drying rate curve and the value of drying rate was evaluated. Figure 5 shows the drying rate curve with the various sizes of lignite samples. The data for the larger size, that was not indicated in Section 3.1, was taken from the previously published work of the authors [5,6]. Figure 5 clearly indicates that the smaller size of particle can have a higher drying rate.

Figure 6 shows the drying rate at the CDRP measured at the test temperature of 170 °C. The drying rate was plotted in correlation with the dry bulk density of lignite samples. The attempted three tests at each condition are presented. The drying mechanism of lignite at the CDRP can be simply described by the external factors (temperature and particle size) that have dominant influence on the drying rate, so that the drying rate can be expressed in the following formula:

\[ \frac{dX}{dt}_{\text{CDRP}} = \frac{6h(T_{\text{test}} - T_d)}{-\Delta H \rho_h} \frac{1}{d} \]  

(4)

The drying rate is determined by the heat transfer coefficient (dependence on the drying medium flow and temperature, and the size of the dried object; the detailed thermodynamic derivation and empirical formula were presented in previous work [5,7]), latent heat of water, size of dried object and steam temperature. The lignite properties, which also influence the drying behaviour, are expressed by ther dry bulk densities. The drying rate at the CDRP is calculated from Eq. (4) with the estimated dry bulk
density. Lines indicated in figure 6 are the prediction by using Eq. (4). The plotted results of 5 mm, 10 mm and 30 mm have very good agreement with the prediction. The drying rate obtained with the sample of which the diameter is 2.5 mm, does not have good agreement compared to the results with other sizes of particles. This may be resulted from the individuality of samples, since the results obtained from 2.5 mm samples are representatively chosen as the average of 4 particles used in a single test and the precision of the experimental setup.

Figure 3. Drying behaviour of the 2.5 mm lignite sphere in superheated steam atmosphere at the test temperatures of (A) 170 °C, (B) 150 °C, (C) 130 °C and (D) 110 °C

Figure 4. Drying rate curve of the 2.5 mm lignite sphere along the moisture content, in superheated steam atmosphere
Figure 5. Drying rate curve of different size of lignite sphere along the moisture content in superheated steam atmosphere.

Figure 6. Experimental and calculated drying rates at the CDRP expressed along the dry bulk density of lignite (test temperature of 170 °C)

3.3. The influence of particle size in the drying process using multi-size group of particles

Drying characteristics of lignite particles with different diameters were investigated in the preceded section and previously published work of the authors. Based on the obtained experimental data, the drying behaviour of group of particles with various size distribution is investigated. This investigation was carried out with following assumptions: i) there are only four representative sizes of group of lignite particles: 2.5 mm, 5 mm 10 mm and 30 mm. ii) Drying conditions are analogical to experimental drying conditions. iii) No interaction between single particles is assumed. iv) Drying temperature was at 150 °C. Note that this is a preliminary study to clarify the significance of the particle size to the drying characteristics in the potential application. In reality, the homogeneous size distribution of particles cannot be ensured. Thus, it necessitates to investigate the influence of the grinding procedure on the drying behaviour in the industrialized drying method.

To simulate the drying behaviour of representative particles, the specific experimental results that have similar initial conditions in terms of moisture content, which are close to the average moisture content of the lignite deposit obtained from proximate analysis, were chosen (see figure 7). The size distribution of group of particles is assumed and four cases are presented in figure 8. Figure 9 shows the change in the moisture content and the drying rate over the drying time obtained from Case 1, and figures 10 and 11 show the change in the moisture content and drying rate curve of all the presented cases. In the analysed Case 1, each subgroup of particles is accounted as 25wt%. The drying rate curve presented in figures 9 and 11 is superposition of the trend characteristic for the single particles; the CDRP and DDRP are not distinguishable, as rapidly drying process of smaller particles interfere the CDRP of larger grains.

The bending points visible at drying rate curve at figure 9 overlaps the points in which individual drying curves become flat and finally achieve the equilibrium moisture content. As the example, the 2.5 mm particles are dried after 6.3 min; at the same time the group of the particles (Case 1) has moisture content $X=0.69$ and drying rate curve changes its incline. Case 2 represents the composition of lignite particle mixture in which the domination of 5 mm particles takes place. It is used as reference for comparison with Case 3, where all particles of size of 30 mm were crushed to the size of 10 mm, and Case 4 where the half of 5 mm particles were crushed to 2.5 mm. In the comparison of moisture content and drying rate curves in figures 10 and 11, it is clearly visible that the drying rate in the beginning of the process is determined by the amount of small particles, while the total length of drying time is regulated by the share of largest grains. The influence of the larger grains is more dominant when the designated final moisture content is at lower level, as presented in Table 3. The general observation is the necessity to increase the share of small particles, when the goal is rapid pre-
Figure 7. The change in moisture content of several particle size of lignite samples

Figure 8. The assumed size distribution of lignite mixture sample

Figure 9. The moisture content and drying rate obtained from Case 1

Figure 10. The change in moisture content obtained from the assumed mixture of samples

Table 3. Drying time to the designated moisture content

| X (-) | Drying time, $t_{SSD}$ (min) |
|-------|-----------------------------|
| WP (%) | 0.3 | 0.2 | 0.1 |
| Case 1 | 32 | 57 | 118 |
| Case 2 | 12 | 18 | 64 |
| Case 3 | 11 | 15 | 27 |
| Case 4 | 8 | 13 | 26 |

Figure 11. Drying rate curve obtained from the assumed mixture of samples
drying to a higher final moisture level, as $X=0.3$. However, if the lower final moisture content is preferable to be achieved (as $X=0.1$), the strategy is rather to remove the largest grains by sieving and grinding procedures.

4. Conclusions
This paper presents the results of an attempt to clarify the size dependence issues of the drying characteristics of lignite from the Belchatow deposit in Poland. The lignite drying behaviour of 2.5 mm lignite particle was investigated in superheated steam atmosphere and the quantitative evaluation of the obtained drying rate was carried and compared with the other sizes of samples reported in the earlier work of the authors. The drying behaviour of the group of multi-size particles was predicted by using the experimentally obtained results. The prediction shows the significance of particle size and their distribution which dominate the entire drying process. For the sake of upgrading the quality of the lignite, smaller particles must be fed to the dryer and a large size of particles in the group has to be eliminated to make the drying time shorter. The typical approach for distinguish of the CDRP and DDRP is no longer visible, thus the designing process has to carefully take into the consideration the majority in the size distribution, which changes the drying rate curve. The obtained results implies to properly conduct sieving and grinding procedures for establishing the effective drying process and the strategy of operation.

Nomenclature

$\Delta H$ Enthalpy change required for the evaporation of free water at 100 °C and 101.325 kPa, 2.256 (MJ kg$^{-1}$)

$h$ Heat transfer coefficient (W m$^{-2}$ K$^{-1}$)

$r_{SSD}$ Drying rate (s$^{-1}$)

$t$ Time (s or min)

$\rho_b$ Dry bulk density of lignite (kg m$^{-3}$)

Subscripts

c Dried coal

$T$ Temperature (°C or K)

$W$ Weight (kg)

$WP$ Water percentage (%)

$X$ Moisture content (-)

$d$ Diameter of a sample (m)

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