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Effect of Critical Variables on Air Dense Medium Fluidized Bed Coal Drying Efficiency and Kinetics

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ABSTRACT

Calorific value, as a key component for fuel quality assessment, directly affects the thermal power plants' efficiency. While high-quality coal is consumed as metallurgical coal, low-rank coals are used by coal-fired power plants. The high moisture content of the thermal coals significantly influences their heating values. In this study, the drying performances of the fixed bed and air dense medium fluidized bed (ADMFB) dryers were investigated under the superficial air velocity of 15-18 cm/s, inlet air temperature of 55-75 ºC, and up to 80 minutes of operation. Low air consumption is an intrinsic characteristic for ADMFB, while a low-temperature range for drying air was selected to address the coal-fired power plants' waste heat. It was found that an increase in air velocity and temperature favored the drying efficiency of both systems (i.e., 18 cm/s and 75 ºC), with the temperature being more effective than the air velocity. The ADMFB dryer removed comparatively more moisture than the fixed bed for the shorter drying durations. For example, for 10% moisture reduction at 75 °C, the ADMFB dryer needed 5 minutes less time than the fixed bed. The fitting quality and goodness of serval well-known thin-layer models for describing fluidized bed and ADMFB coal drying kinetics were assessed by several models and statistical evaluators, respectively. It was found that the Middilli & Kucuk model best describes the fixed bed coal drying (i.e., R^2=0.999, *RSE*=0.001, *RMSE*=0.008), while the Page model much properly simulates the ADMFB coal drying (i.e., R^2=0.998, *RSE*=0.002, *RMSE*=0.009).

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1. INTRODUCTION

According to IEA (International Energy Agency), coal is the second primary energy source of the world after oil and the primary energy source for electricity generation. IEA estimated approximately 60% growth for world energy demand over the next 30 years, which necessitates low-rank coal (LRC) utilization for supporting low-cost energy production [1]. Different coal classification systems are developed and implemented, according to downstream utilization purposes. Four classes of coal could be considered according to the ASTM classification system, which has been developed based on the fixed carbon and gross calorific value on a moist basis, i.e., lignite, sub-bituminous, bituminous, and anthracite. Lignite coal attributes with the lowest calorific heat value (<4600 cal/g) and highest moisture content (up to 70%), while anthracite coal has the highest calorific heat value (>8300 cal/g) and lowest moisture content (<5%) [2, 3].

However, higher ash and moisture contents and comparatively lower heating values are the limiting factors for LRCs, despite their lower mining costs, abundance, and usually lower sulfur content [4]. Therefore, any reduction in moisture and ash content of the LRCs could improve their application as the thermal coal in coal-fired power plants.

The lower heating value of the coal, due to high moisture content, reduces coal-fired power plant thermal efficiency. Such efficiency reduction is a consequence of using high-temperature heat (high quality) in the boiler/furnace for moisture evaporation before ignition. For solid fuels such as thermal coal, it is well proven that high moisture content delays coal ignition, creates

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additional exhaust discharge, causes inappropriate combustion, and delays the start of emission of the combustible volatile matter [5-9]. The 3-5% increase in boiler efficiency due to the elimination of moisture before feeding it to the furnace has been reported by several researchers [10-13]. Bullinger et al. [10] reported even more energy-saving opportunities (up to 50% less energy requirement in milling), once 20% or more moisture reduction has been achieved. Hu et al. [13] did simulate the effect of moisture content on the efficiency of the boiler and overall power plant. They showed that, in a 1000MW conventional coal-fired power plant, a 20% reduction in coal moisture by a fluidized bed dryer would result in a 1.43% increase in overall plant efficiency. In another study, Liu et al. [12] discussed the effect of pre-drying on the performance of a hypothetical lignite-based coal-fired power plant. They showed that a 10% reduction in moisture content due to pre-drying, could increase plant efficiency by 1.78%. It is necessary that the consumed energy for moisture removal imposes minimum costs, therefore, employing waste heat from a coal-fired power plant for excess moisture removal could be a suitable solution.

Several drying systems are prevalent in the industry for LRC drying. Drying arrangements such as, packed/fixed bed dryer, moving bed dryer, fluidized bed dryer, assisted fluidized bed dryer (microwave, vibration, pulsed, immersed heater), flash dryer, rotary tube/drum dryer, microwave dryer …, or the non-evaporative methods such as, mechanical, thermal, hydrothermal, and solvent dewatering are well discussed in details in literature [4, 8, 14-19], with each method merits and issues [4, 20-22], such as energy consumption, efficiency, heat and mass transfer rates, and capital/process expenses. But regardless of the implemented method type, improvements in mass and heat transfer rates play a significant role in the success of the process. It should be addressed that, in evaporative methods, the provided heat can just remove freezable moisture from the surfaces and pores of particles while the carrying phase transfers it out.

Some inherent properties of the fluidized beds, i.e., solid mixing and relatively high heat and mass transfer rates between gas and solid phase, are relevant to the fluid dynamics of the system [23]. These unique properties have made fluidized bed dryers a right choice for LRC drying such as Illinois coals [11], Turkish coals [16, 19, 24], polish coal [25], Indonesian coal [26], Chinese coals [5, 27], Victorian brown coal [28-30]. The high capacity, maximum gas-solid contact surface, low maintenance costs, and rapid moisture transfer between phases (shorter drying time), could be entitled as the advantages of the fluidized bed coal drying. In contrast, the possibility of self-ignition during the drying process, higher superficial air velocity requirements, unsuitability for irregularly shaped particles, agglomeration of wide particle size range feeds in high moisture coals, attrition of particles while drying, and channeling could be addressed as this methods' disadvantages [5, 13, 20, 24, 30]. Jangam et al. [21] have summarized the advantages and limitations of different coal drying methods thoroughly. According to available references [4, 5, 15, 20, 30], the effective parameters in favor of performance improvement of the fluidized bed coal dryers are air temperature, air velocity and residence time, where bed thickness, particle size, and initial moisture content of both phases (coal and hot air), have some adverse effect on the operation output.

The air dense medium fluidized bed (ADMFB) idea was introduced after the development of the fluidization concept. In an ADMFB the upward airflow fluidizes very fine particles (i.e., fluidization medium), and consequently, the generated suspension creates a pseudo fluid with an average density between air and solid particles. Any external particle with higher densities than the pseudo fluid density sinks in the bed while lighter ones remain suspended on the top.

The ADMFB system has several advantages over the conventional packed/fluidized bed coal drying systems and highly benefits the overall economy/efficiency of the coal-fired power plants. The necessary airflow and drying heat could be supplied via the final exhaust flue gas from the furnace (waste heat) with no limitations. The major difference between an ADMFB and a conventional fluidized beds the lower superficial air velocity requirements for floating the coarse coal particles (e.g., on average, 8 times less for the coal particles studied here) due to the much higher average density of the created pseudo fluid than the regular hot air. In an ADMFB, the coal particles float in a pseudo-fluid instead of entirely or partially being lifted by air as it occurs in conventional fluidized beds. Therefore, the subsequent exhaust gas handling or dust collecting system would be even smaller than conventional fluidized beds, which would need less energy for gas de-moisturizing and particulate matter emission control.

The heat and mass transfer are high in a fluidized bed, where feeding a pre-heated fluidization medium would decrease the drying time as the hot medium particles act as high energy packs floating in the hot gas. In fact, the hotter fluidization medium results in faster and more efficient drying with lower residual moisture on the final product .

Not much of a proper beneficiation or efficient pre-drying systems are practiced by the power industry yet, but it is receiving more and more recognition. Elimination of moisture, ash, and harmful components from thermal coals (non-metallurgical) even though imposes some extra costs, but reduces overall electricity generation expenses, energy production carbon footprint, as well as expanding mining opportunities for some low-rank thermal coal deposits (e.g., lignite coals) [31-34].

In this study, the effectiveness of the critical parameters on the fixed bed and ADMFB low-temperature coal drying was studied and compared using a thermal coal sample (could be classified as lignite coal). The hot air temperature was limited to 75 °C to support the idea of the coal-fired power plant waste heat utilization for LRC heat value improvement. The drying air superficial velocity was selected to be suitable for ADMFB operations (enough to fluidize medium particles, but not coal particles), therefore for mono-coal particles, fixed bed status occurred. It was intended to examine if lower air consumption in ADMFB system could benefit the drying process or not. Also, the hotness of air was limited to lower temperatures (in the range of waste heat of power plants), which facilitates faster medium heat up and recovery. The kinetics of drying phenomena is a key component once conducting process performance evaluation, as well as, industrial application considerations. Therefore, both systems drying capabilities and kinetics were studied and evaluated using well-known thin layer kinetics models and were compared respectively.

2. MATERIALS AND METHODS

2. 1. Coal Sample and Fluidization Medium

The prepared coal sample was crushed to finer than 13.2 mm, and after mixing, sub-samples were prepared by Jones riffle. The 2 to 4.6 mm size fraction was sieved and used in the experiments.

The proximate analysis of the coal was performed following the ASTM D3174, D3175, and D3302 procedures using a muffle furnace. Samples were dried in a vacuum oven for 8 h considering ASTM D-7582 method, before the proximate analysis. The amount of the removed moisture in the vacuum oven was also taken into consideration once the total moisture contents for the samples were reported. The average moisture content, volatile matter, and ash content of the 2-4.6 mm samples were determined to be 21.5, 34.5, and 29.6 %, respectively.

Different solids were used as a fluidization medium and are reported in literature [35-37]. In this study, the silica sand with a density of 2.6 g/cm^3 and average particle size of 327 µm (the -354, +300 µm particles were separated by dry sieving) was used as the fluidization medium. The selected fluidization medium (silica sand) is classified as Geldart group B [38] particles and has low acquisition and preparation costs. In this case, the abondance and chemical inertness are the other advantages of the silica sand over the other medium types employed in ADMFB systems.

2. 2. Experimental Setup And Procedure

The inlet airflow rate, and consequently, the superficial air velocity, was adjusted by a mass flow controller (with Accuracy: ±1%) and the air temperature was adjusted to the desired temperature by an inline 2500 Watt electric heater. A 150 µm steel screen was used at the bottom of the bed to support solid materials as well as to distribute airflow uniformly into the bed-chamber. Plexiglas pieces (ID of 8 cm) with a maximum height of 60 cm were used to form the bed body. Layers of glass wool were used to cover pipes, connections, and the bed body to minimize heat loss between the air heater and the ADMFB. The employed setup is presented in Figure 1 (not including the heating system, since it was fully covered in glass wool).

In general, two different types of experiments were conducted: packed bed or ADMFB drying experiments. During the drying procedure, hot air passed through the system to heat up components and apparatus prior to adding coal samples and initiating the test. The determined hot air temperature was achieved and steady-state status inside the bed was insured by minimizing the temperature difference of thermocouples installed at the bottom of the bed, and the second one, 20 cm above it. Once a steady-state was reached, an empty bed weight (or bed filled with the determined fluidization medium) was obtained by a balance (accuracy of ±0.1 g). Following the same procedure, the aggregate weight of the bed, fluidization medium, and added coal sample were measured in the determined time intervals, and then moisture loss was calculated considering the fixed and variable mass components. For ADMFB coal drying, the fluidization medium was also heated up with the bed body until reaching a stable temperature, and its weight was considered as a part of the bed body during the periodic weight measurements as they were dried entirely before introducing to the bed.

Three different drying temperatures, 55, 65, and 75 °C, were used, and weight loss was tracked for up to 80

Figure 1. ADMFB filled with silica sand and connected to the mass flow controller (not covered in the wool glass yet)

minutes, from the moment a coal sample was added to the bed, either fixed or fluidized system. At the end of any drying experiment, coal particles were collected or separated from the fluidization medium, weighted, and sealed to avoid moisture loss/gain. Later ash and moisture content of the dried coal samples were determined. The weight loss during the drying period was calculated considering the initial sample weight, net sample weights in time intervals, and final moisture content of the dried particles.

2. 3. Kinetics Modelling The most commonly used empirical thin-layer models (examined successfully for coal drying) were selected (Table 2) and employed to determine the drying kinetics of the moisture removal.

M_0, M_t, M_R, W_t, and W_c are the samples' initial moisture content, residual moisture content at time *t*, relative moisture content at relevant time *t*, wet coal sample weight at time *t*, and dry coal (just solid material) weight, respectively. The M_t and M_R are obtainable through Equations (1) and (2).

$$M_t = \frac{W_t - W_c}{W_c} \times 100 \quad (1)$$

$$M_R = \frac{M_t}{M_0} \quad (2)$$

The fitting qualities of the selected models were evaluated by the standard statistical evaluators such as coefficient of determination (R^2), residual sum of square (RSE, i.e., Equation (3)), and root mean square error (RMSE, i.e., Equation (4)) once parameters were determined by non-linear regression analysis. The higher values of R^2, lower values of RSE, and RMSE indicate better and consistent model fitting.

TABLE 1. Packed bed and ADMFB drying parameters

Experiment	Superficial air vleocity (cm/s)	Solid height in bed (cm)	Set temp. (°C)	Duration (min)
Fixed bed	15-18	>5	55, 65, 74	Up to 80
ADMFB	15-18	~23	55, 65, 74	Up to 80

TABLE 2. Thin-layer drying models [39-44]

Model name	Mathematical presentation*
Newton	$M_R = \exp(-kt)$
Page	$M_R = \exp(-kt^n)$
Modified Page	$M_R = \exp(-(kt)^n)$
Henderson & Pabis	$M_R = a\exp(-kt)$
Wang & Singh	$M_R = 1 + at + bt^2$
Logarithmic	$M_R = a + b\exp(-kt)$
Middilli & Kucuk	$M_R = a\exp(-kt^n) + bt$

* *a, b, n, and k are constants*

$$RSE = \sum_{i=1}^{n}(MR_{exp,i} - MR_{prd,i})^2 \quad (3)$$

$$RMSE = \sqrt{\sum_{i=1}^{n}(MR_{exp,i} - MR_{prd,i})^2 / n} \quad (4)$$

The $MR_{exp,i}$, $MR_{pre,i}$, and n are the experimental moisture ratio, predicted moisture ratio, and the number of the data points used for modelling, respectively.

3. RESULTS AND DISCUSSIONS

3. 1. The Effect Of Air Velocity And Temperature The effect of an increase in superficial air velocity (at 65 °C as representative) for fixed and ADMFB coal drying is presented in Figures 2a and b, respectively. At first glance and as expected, coal drying improves for both systems by the increase of air velocity from 15 to 18 cm/s, since both heat and moisture transfer (from coal surface to gaseous phase) rates improve with it. A similar increasing trend has been observed for two other temperatures and both systems. Also, the gap between corresponding points for similar drying times increased by increasing air temperature from 55 °C to 75 °C. Once drying continues for over 40 to 50 minutes, an increase in moisture loss becomes almost negligible (<1%) for the fixed bed system, while moisture loss continues to increase for ADMFB rather than staying constant. It

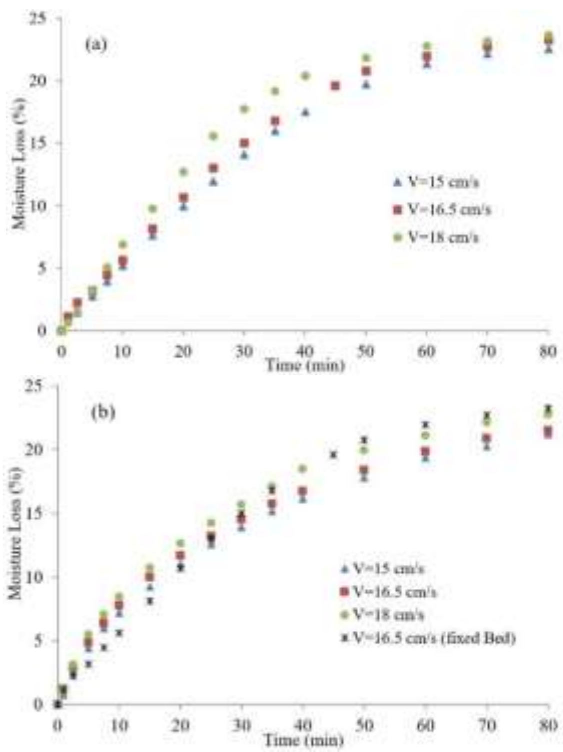

Figure 2. The effect of superficial air velocity on coal drying at 65 °C, (a) fixed bed, (b) ADMFB

should be noted that the superficial air velocity at which sand particles are fluidized is almost 8 times less than the examined coal particles. At the employed air velocities, there was almost no bubbling while fluidization status was maintained satisfactorily.

Comparison between the corresponding fixed bed and ADMFB drying experiment showed that, for drying times lower 20 minutes and at any of the air velocities, the moisture reduction happens with faster rates for ADMFB drying than fixed bed, and then it gets reverse once drying continues for longer times. That was because of the heat energy saved in sand particles, enhancing faster evaporation of the moister. The final moisture reduction after 80 minutes is slightly higher for fixed bed than ADMFB.

As addressed in the literature [5, 20], improvements in fluidized bed coal drying would continue up to 2-2.2 of the coal particles' Umf (i.e., 2.2-3.65 m/s for the tested coal particles [23, 45]). Kim et al. [28] suggested that the optimum drying gas velocity is around the Umf of particles, and higher velocities would only raise energy consumption and elutriation phenomenon. But in this study, the air velocity was limited to 0.18 m/s, which is almost 30% more than the sand particles' Umf and far less than coal particles' Umf.

Figures 3a and 3b show the effect of drying air temperature for fixed and ADMFB coal drying, respectively, at 15 cm/s air velocity. Generally, the drying rate increases in both Figures 3a and 3b, while drier coal is obtainable with an increase in air temperature, as data have been reported in literature [17, 46]. Unlike Figure 2a, drying curves do not reach a steady-state for fixed-bed once drying prolongs, indicating a higher significance of the temperature compared to the air velocity .

The comparison between Figure 1a and 3b indicate that ADMFB reduces moisture faster than the fixed bed for shorter drying durations at any hot air temperature. For 10% moisture reduction at 55 or 75 °C, drying should be continued 25 or 13 minutes within the fixed bed, while it takes 22 or 8 minutes once ADMFB has been used.

Similar to Figure 2b, fixed bed and ADMFB drying curves for the corresponding set temperatures, cross each other, but at higher drying times. As discussed, drying for shorter times yields more moisture removal by the ADMFB system (Figure 3b), and an ADMFB is more preferred. In the fixed bed, the heat exchange capacity of the system is limited and could just be partially used for evaporating the moisture off from the coal particles. Initially, when coal enters the ADMFB, due to higher heat energy saved in the sand particles, heat and consequently moisture transfer rates increase significantly. After almost 20 minutes and once sand particles lost some heat, some of the energy entering the bed by hot air would be consumed by sand particles for maintaining higher temperatures, rather than moisture

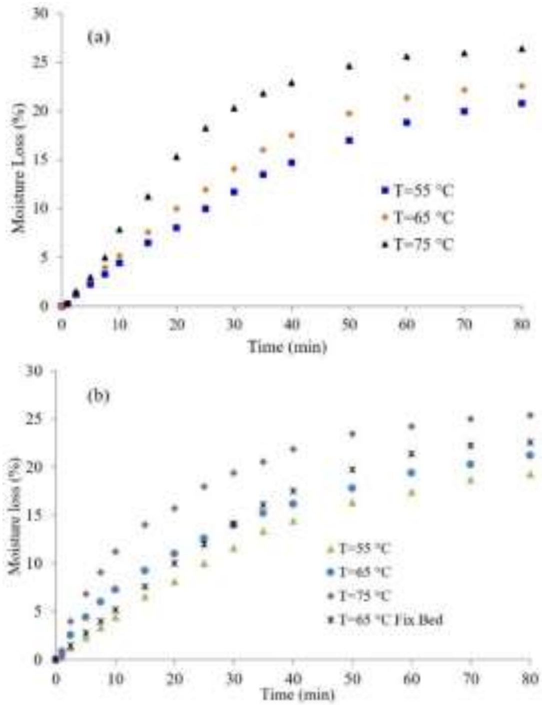

Figure 3. The effect of drying air temperature on coal drying at 15 cm/s, (a) fixed bed, (b) ADMFB

on the coal particles. That is when drying by ADMFB becomes less effective than the fixed bed (almost after 20 minutes). Such an issue could be solved easily, once ADMFB operates continuously, and reheating of the fluidization medium occurs while recirculating it back to the ADMFB (after separation of the dry coal somewhere out of the fluidization chamber).

Based on the obtained results, the performance of the batch ADMFB drying system is superior to the fixed bed system for drying times less than 20-25minutes, but if a significant reduction in product moisture is needed, employment of a continuous ADMFB dryer would be beneficial. In a batch ADMFB system, due to the nature of the operation, continuous support of the hot sand to the system during the operation is not possible. In a continuous operation, it is feasible to inject pre-heated sand with the same or even higher temperatures of the drying air to the system, while drying carries on in the bed-chamber. Fresh hotter sand has higher trapped heat energy in it and can improve drying efficiency in shorter process times. Auxiliary hot sand can get its energy from un-used hot flue gas (waste heat) once a coal-fired plant is in the vicinity or even a small preparation furnace.

3. 3. Coal Drying Kinetics The collected time versus moisture loss (in terms of MR) data from both ADMFB and the fixed bed was used to study the coal drying kinetics and modelling based on the selected thin layer models in Table 2. However, modelling efforts showed that the coal drying in fixed bed and ADMFB could not be represented by Wang & Singh model [44]. Also, the constant value of the Logarithmic model for the fixed bed was calculated to be zero. Therefore, the Henderson & Pabis model was considered here for coal drying modelling. Similarly, Middilli & Kucuk models' constant was also calculated to be zero for all nine ADMFB drying experiments and consequently was taken out from the comparison list. The average and standard deviations (nine experiments for each system) of R^2, RSE, and RMSE of the models for both fix and ADMFB systems, regardless of operating parameter variations, are presented in Table 3.

Based on the goodness, the statistical evaluators, and their standard deviations are given in Table 3, the Middilli & Kucukand, and then equally, both Page and Modified Page models do best represent fixed bed coal drying phenomena. For all mentioned models, the standard deviations of R^2s' were less than 1% of the corresponding R^2. The results of the model fitting on any individual fixed bed drying data set for the Middilli & Kucukand model, as well as model constants (*a*, *b*, *n*, and *k*), are presented in Table 4.

Figure 4a-b compares the experimental M_R vs. predicted M_R by Middilli & Kucuk model, for different air velocities at 65 and 75 °C. In both graphs, excellent fitness between experimental and simulated moisture ratio is presented. Generally, higher superficial air velocity and temperature increase moisture ratio, which is clearly presented in Figure 4a as moisture ratio (loss) for 18 cm/s is descending more sharply. The experimental and simulated moisture ratio curves are closer to each other at 75 °C dryings (Figure 4b).

TABLE 3. Average (Ave.) and standard deviation (St.D.) of the statistical evaluators for ADMFB and fixed bed systems coal drying

Model name		***Fix bed drying***			***ADMFB drying***		
		R^2	*RSE*	*RMSE*	R^2	*RSE*	*RMSE*
Newton	Ave.	0.994	0.015	0.030	0.994	0.016	0.031
	St.D.	0.002	0.007	0.008	0.004	0.007	0.007
Page	Ave.	0.997	0.005	0.016	0.998	0.002	0.009
	St.D.	0.001	0.002	0.005	0.001	0.002	0.005
Modified Page	Ave.	0.997	0.005	0.016	0.998	0.0025	0.009
	St.D.	0.001	0.003	0.005	0.001	0.002	0.005
Henderson & Pabis	Ave.	0.994	0.01	0.024	0.991	0.009	0.024
	St.D.	0.002	0.004	0.006	0.005	0.005	0.000
Middilli & Kucuk	Ave.	0.999	0.001	0.008	--	--	--
	St.D.	0.001	0.001	0.002	--	--	--
Logarithmic	Ave.	--	--	--	0.997	0.003	0.014
	St.D.	--	--	--	0.001	0.001	0.003

TABLE 4. Results of statistical parameters for Middilli & Kucuk model fitting and model coefficients

V (cm/s)	*T* (°C)	R^2	*RSE*	*RMSE*	*a*	*b*	*n*	*k*
15	55	0.998	0.001	0.006	0.993	0.001	1.214	0.008
16.5	55	0.999	0.001	0.006	0.996	0.001	1.246	0.010
18	55	0.999	0.000	0.005	0.995	0.001	1.220	0.011
15	65	0.998	0.002	0.010	0.994	0.001	1.304	0.008
16.5	65	0.999	0.002	0.010	0.974	0.001	1.352	0.007
18	65	0.998	0.001	0.007	0.993	0.001	1.323	0.011
15	75	0.998	0.001	0.008	0.997	0.001	1.351	0.012
16.5	75	0.998	0.002	0.012	0.990	0.001	1.286	0.015
18	75	0.999	0.001	0.010	1.009	0.001	1.337	0.014

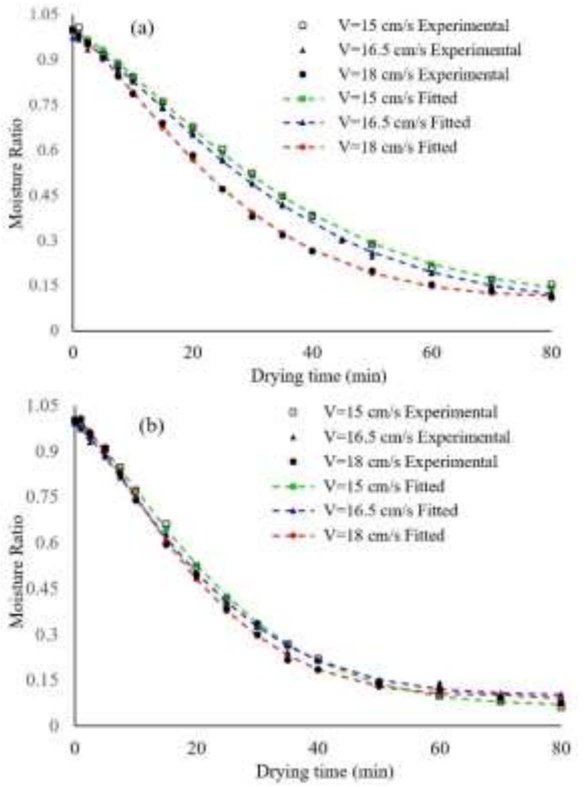

Figure 4. The experimental vs. fitted moisture ratio by Middilli & Kucuk model for fixed bed drying, (a) 65 °C, (b) 75 °C

Reaching almost the highest mass and heat transfer capacity could be an interpretation.

For ADMFB, model, fitting and statistical evaluator's analysis showed that both Page and Modified Page models equally describe coal drying precisely, where, Logarithmic model stands after them. The standard deviations of the modes were calculated and resulted in being less than 1%. The results of the model fitting on any individual ADMFB drying experiment for the Page model and model constants (*n* and *k*) are presented in TABLE . For any air temperature setting, k increases by the increase of air velocity, and for any certain air velocity, *k* increases with the increase of air temperature. In fact, stronger drying condition results in higher *k* values, indicating a direct relationship between *k* and drying force intensity.

Figures 5a and 5b show the capability of the Page model in representing ADMFB coal drying at 65 and 75 °C and different air velocities. Same as Figure 4 a-c, the simulated and experimental results are matching acceptably well. At lower drying times, the slopes of the curves are higher than the corresponding fixed bed curves. Drying was intense for 75 °C compared to the 65 °C, where curves are closer at a higher temperature than two other lower ones (55 °C curves are not included here)

3. 4. Benefits of Drying The main goal of this study was to upgrade LRC for thermal applications. Therefore, the higher heating value (HHV) of the head coal sample was determined using available correlations in the literature [5, 86]. Based on the ultimate analysis results, the HHV of the head sample was determined to be 19.32 MJ/kg.

Elimination of moisture (e.g., 10%) due to ADMFB drying (8 minutes of drying 75 °C), could increase HHV up to 21.45 MJ/kg. Several experimental/simulation studies have been conducted on the effect of ash or moisture reduction on the performance of coal-based power generation plants [14-17]. All emphasized the unit/plant efficiency improvements. A 10% reduction in moisture content (using ADMFB dryer) could promise around a 1.5 % increase in plant efficiency, as discussed in literature [16, 17].

In a conventional coal-fired power plant, the substitution of a 19.32 MJ/kg, feed stream with its upgraded product with 21.45 MJ/kg (upgraded using furnace waste heat) could increase the available energy for the furnace, at least 11%. A lower amount of flue gas

TABLE 5. Results of statistical parameters for Page model fitting and model coefficients

V (cm/s)	*T* (°C)	R^2	*RSE*	*RMSE*	*n*	*k*
15	55	0.997	0.001	0.007	0.836	0.032
16.5	55	0.999	0.000	0.005	0.795	0.037
18	55	0.998	0.000	0.005	0.842	0.039
15	65	0.999	0.000	0.005	0.852	0.034
16.5	65	0.999	0.000	0.004	0.835	0.040
18	65	0.999	0.001	0.008	0.855	0.041
15	75	0.999	0.001	0.008	0.863	0.051
16.5	75	0.996	0.005	0.018	0.816	0.055
18	75	0.999	0.002	0.010	0.774	0.068

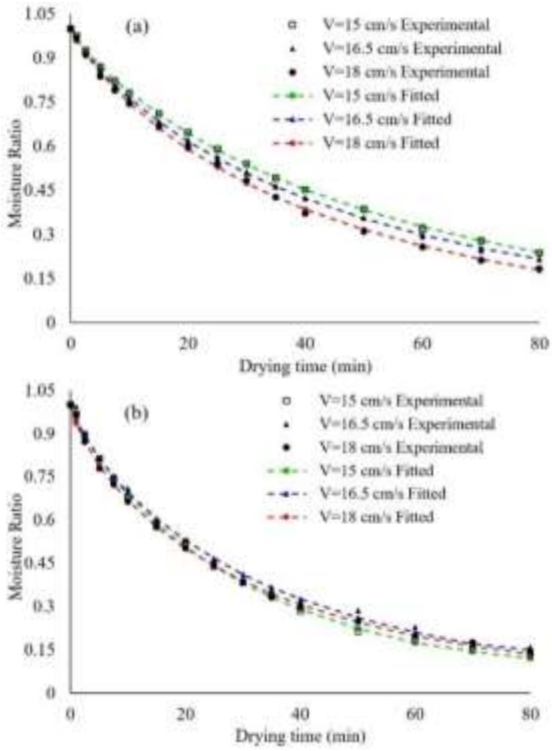

Figure 5. Experimental vs. fitted moisture ratio by Page model for ADMFB drying, (a) 65 °C, (b) 75 °C

to be dealt with would reduce the size of the flue gas treatment operation as well as a possible increase in its efficiency.

4. CONCLUSION

In this study, the effects of drying air temperature and its superficial velocity on a fixed bed and ADMFB coal drying were assessed. As LRCs are usually used as thermal coal in coal-fired power plants, a low-temperature range (<75 °C) was selected for drying air. Also, the superficial air velocity was selected to be suitable for dense medium fluidization (<18 cm/s), thus was not enough to fluidize coal particles (at least 8 times less than the required velocity to fluidize coal particles). After determination of the effects of parameters on both systems, simulation of coal drying for fixed ben and ADMFB systems were conducted using seven thin-layer kinetics models. Valid statistical evaluators were determined for model significance assessment. The following major conclusions were drawn.

For both fixed bed and ADMFB systems, moisture removal improved by increasing superficial air velocity and air temperature. Maximum moister removal was achieved at a superficial air velocity of 18 cm/s and 75 °C (i.e., 25% moisture removal). It should be addressed that the temperature was found to be more influential than the air velocity.

ADMFB drying is preferred if a shorter process time is favorable. For 10 % moisture reduction, increasing air temperature from 55 °C to 75 °C decreases drying time by 50 and 62% for fixed bed and ADMFB systems, respectively.

Kinetics studies using thin-layer models showed that fixed bed and ADMFB coal drying could be best presented by Middilli & Kucuk and Page models, respectively. Different statistical evaluators such as R^2, RSE, and RMSE were employed to determine the models fitting goodness. The model coefficients were determined for any set of conditions.

5. ACKNOWLEDGMENT

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6. REFERENCES

1. IEA. *World energy balances: Overview (2019 edition)*. https://www.iea.org/reports/world-energy-balances-2019].
2. Riley, J.T., "Routine coal and coke analysis: Collection, interpretation, and use of analytical data, 2nd edition, ASTM International Pennsylvania, (2014). doi: 10.1520/MNL57-2ND-EB
3. Berkowitz, N., "An introduction to coal technology, Elsevier, (2012). doi: 10.1016/C2012-0-01440-8
4. Osman, H., Jangam, S., Lease, J. and Mujumdar, A.S., "Drying of low-rank coal (lrc)—a review of recent patents and innovations", ***Drying Technology***, Vol. 29, No. 15, (2011), 1763-1783. doi: 10.1080/07373937.2011.616443
5. Zhao, P., Zhao, Y., Luo, Z., Chen, Z., Duan, C. and Song, S., "Effect of operating conditions on drying of chinese lignite in a vibration fluidized bed", ***Fuel Processing Technology***, Vol. 128, (2014), 257-264. doi: 10.1016/j.fuproc.2014.07.014
6. Khankari, G. and Karmakar, S., "Improvement of efficiency of coal-fired steam power plant by reducing heat rejection temperature at condenser using kalina cycle", ***International Journal of Engineering, Transactions A: Basics***, Vol. 31, No. 10, (2018), 1789-1795. doi: 10.5829/ije.2018.31.10a.23
7. Shi, Y.C., Li, J., Li, X.Y., Wu, J., Wu, M.G., Li, S., Wang, H.Y., Zhao, G.J. and Yin, F.J., "Experimental study on super-heated steam drying of lignite", in ***Advanced Materials Research,*** Trans Tech Publications Ltd. Vol. 347, No., (2012), 3077-3082. doi: 10.4028/www.scientific.net/AMR.347-353.3077
8. Ross, D., Doguparthy, S., Huynh, D. and McIntosh, M., "Pressurised flash drying of yallourn lignite", ***Fuel***, Vol. 84, No. 1, (2005), 47-52. doi: 10.1016/j.fuel.2004.08.006
9. Tiara, T., Agustina, T. and Faizal, M., "The effect of air fuel ratio and temperature on syngas composition and calorific value produced from downdraft gasifier of rubber wood-coal mixture", ***International Journal of Engineering, TransactionsC:Aspects***, Vol. 31, No. 9, (2018), 1480-1486. doi: 10.5829/ije.2018.31.09c.02
10. Bullinger, C., Ness, M. and Sarunac, N., "Coal creek prototype fluidized bed coal dryer: Performance improvement, emissions reduction, and operating experience", in 31st International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, Florida., (2006).
11. Kakaras, E., Ahladas, P. and Syrmopoulos, S., "Computer simulation studies for the integration of an external dryer into a greek lignite-fired power plant", ***Fuel***, Vol. 81, No. 5, (2002), 583-593. doi: 10.1016/S0016-2361(01)00146-6
12. Liu, M., Yan, J., Bai, B., Chong, D., Guo, X. and Xiao, F., "Theoretical study and case analysis for a predried lignite-fired power system", ***Drying Technology***, Vol. 29, No. 10, (2011), 1219-1229. doi: 10.1080/07373937.2011.582559
13. Hu, S., Man, C., Gao, X., Zhang, J., Xu, X. and Che, D., "Energy analysis of low-rank coal pre-drying power generation systems", ***Drying Technology***, Vol. 31, No. 11, (2013), 1194-1205. doi: 10.1080/07373937.2013.775146
14. Tahmasebi, A., Yu, J., Li, X. and Meesri, C., "Experimental study on microwave drying of chinese and indonesian low-rank coals", ***Fuel Processing Technology***, Vol. 92, No. 10, (2011), 1821-1829. doi: 10.1016/j.fuproc.2011.04.004
15. Kannan, C.S., Thomas, P. and Varma, Y., "Drying of solids in fluidized beds", ***Industrial & engineering chemistry research***, Vol. 34, No. 9, (1995), 3068-3077. doi: 10.1021/ie00048a018
16. Calban, T. and Ersahan, H., "Drying of a turkish lignite in a batch fluidized bed", ***Energy Sources***, Vol. 25, No. 12, (2003), 1129-1135. doi: 10.1080/00908310390233568
17. Jeon, D., Kang, T., Kim, H., Lee, S. and Kim, S., "Investigation of drying characteristics of low rank coal of bubbling fluidization through experiment using lab scale", ***Science China Technological Sciences***, Vol. 54, No. 7, (2011), 1680-1683. doi: 10.1007/s11431-011-4414-0
18. Kanda, H. and Makino, H., "Energy-efficient coal dewatering using liquefied dimethyl ether", ***Fuel***, Vol. 89, No. 8, (2010), 2104-2109. doi: 10.1016/j.fuel.2010.02.019
19. Pusat, S., Akkoyunlu, M.T. and Erdem, H.H., "Fragmentation of a turkish low rank coal during fixed-bed evaporative drying process", ***International Journal of Coal Preparation and Utilization***, (2018), 1-9. doi: 10.1080/19392699.2018.1451847
20. Si, C., Wu, J., Wang, Y., Zhang, Y. and Shang, X., "Drying of low-rank coals: A review of fluidized bed technologies", ***Drying Technology***, Vol. 33, No. 3, (2015), 277-287. doi: 10.1080/07373937.2014.952382
21. Jangam, S.V., Karthikeyan, M. and Mujumdar, A., "A critical assessment of industrial coal drying technologies: Role of energy, emissions, risk and sustainability", ***Drying Technology***, Vol. 29, No. 4, (2011), 395-407. doi: 10.1080/07373937.2010.498070
22. Arima, K., Tsuchiyama, Y., Sawatsubashi, T., Kinoshita, M. and Ishii, H., "Drying of wet brown coal particles by a steam-fluidized bed dryer", ***Drying Technology***, Vol. 36, No. 6, (2018), 664-672. doi: 10.1080/07373937.2017.1323337
23. Rhodes, M.J., "Introduction to particle technology, John Wiley & Sons, (2008). doi: 10.1002/9780470727102
24. Pusat, S., Akkoyunlu, M.T., Erdem, H.H. and Dağdaş, A., "Drying kinetics of coarse lignite particles in a fixed bed", ***Fuel Processing Technology***, Vol. 130, (2015), 208-213. doi: 10.1016/j.fuproc.2014.10.023
25. Pawlak-Kruczek, H., Plutecki, Z. and Michalski, M., "Brown coal drying in a fluidized bed applying a low-temperature gaseous medium", ***Drying Technology***, Vol. 32, No. 11, (2014), 1334-1342. doi: 10.1080/07373937.2014.909845

26. Park, J.H., Lee, C.-H., Park, Y.C., Shun, D., Bae, D.-H. and Park, J., "Drying efficiency of indonesian lignite in a batch-circulating fluidized bed dryer", ***Drying Technology***, Vol. 32, No. 3, (2014), 268-278. doi: 10.1080/07373937.2013.822385

27. Tahmasebi, A., Yu, J., Han, Y. and Li, X., "A study of chemical structure changes of chinese lignite during fluidized-bed drying in nitrogen and air", ***Fuel Processing Technology***, Vol. 101, (2012), 85-93. doi: 10.1016/j.fuproc.2012.04.005

28. Kim, H.-S., Matsushita, Y., Oomori, M., Harada, T., Miyawaki, J., Yoon, S.-H. and Mochida, I., "Fluidized bed drying of loy yang brown coal with variation of temperature, relative humidity, fluidization velocity and formulation of its drying rate", ***Fuel***, Vol. 105, (2013), 415-424. doi: 10.1016/j.fuel.2012.09.057

29. Tahmasebi, A., Yu, J. and Bhattacharya, S., "Chemical structure changes accompanying fluidized-bed drying of victorian brown coals in superheated steam, nitrogen, and hot air", ***Energy & Fuels***, Vol. 27, No. 1, (2012), 154-166. doi: 10.1021/ef3016443

30. Stokie, D., Woo, M.W. and Bhattacharya, S., "Attrition of victorian brown coal during drying in a fluidized bed", ***Drying Technology***, Vol. 34, No. 7, (2016), 793-801. doi: 10.1080/07373937.2015.1080723

31. Argimbaev, K.R. and Drebenstedt, C., "Korkinsk brown coal open pit as a case study of endogenous fires", ***International Journal of Engineering,TransactionsA: Basics***, Vol. 34, No. 1, (2021), 293-304. doi: 10.5829/ije.2021.34.01a.32

32. Dwari, R. and Rao, K.H., "Dry beneficiation of coal—a review", ***Mineral Processing and Extractive Metallurgy Review***, Vol. 28, No. 3, (2007), 177-234. doi: 10.1080/08827500601141271

33. Azimi, E., Karimipour, S., Xu, Z., Szymanski, J. and Gupta, R., "Statistical analysis of coal beneficiation performance in a continuous air dense medium fluidized bed separator", ***International Journal of Coal Preparation and Utilization***, Vol. 37, No. 1, (2017), 12-32. doi: 10.1080/19392699.2015.1123155

34. Ram, M. and Kumar, A., "Reliability measures improvement and sensitivity analysis of a coal handling unit for thermal power plant", ***International Journal of Engineering***, Vol. 26, No. 9, (2013), 1059-1066. doi: 10.5829/idosi.ije.2013.26.09c.11

35. Sahu, A., Tripathy, A., Biswal, S. and Parida, A., "Stability study of an air dense medium fluidized bed separator for beneficiation of high-ash indian coal", ***International Journal of Coal Preparation and Utilization***, Vol. 31, No. 3-4, (2011), 127-148. doi: 10.1080/19392699.2011.574936

36. He, Y., Zhao, Y. and Chen, Q., "Fine particle behavior in air fluidized bed dense medium dry separator", ***Coal Preparation***, Vol. 23, No. 1-2, (2003), 33-45. doi: 10.1080/07349340302268

37. Dave, P.C., "Dry cleaning of coal by a laboratory continuous air dense medium fluidised bed separator", (2012). doi: 10.7939/R3K339

38. Geldart, D., "Types of gas fluidization", ***Powder Technology***, Vol. 7, No. 5, (1973), 285-292. doi: 10.1016/0032-5910(73)80037-3

39. O'callaghan, J., Menzies, D. and Bailey, P., "Digital simulation of agricultural drier performance", ***Journal of Agricultural Engineering Research***, Vol. 16, No. 3, (1971), 223-244. doi: 10.1016/S0021-8634(71)80016-1

40. Midilli, A., Kucuk, H. and Yapar, Z., "A new model for single-layer drying", ***Drying Technology***, Vol. 20, No. 7, (2002), 1503-1513. doi: 10.1081/DRT-120005864

41. Diamante, L.M. and Munro, P.A., "Mathematical modelling of the thin layer solar drying of sweet potato slices", ***Solar energy***, Vol. 51, No. 4, (1993), 271-276. doi: 10.1016/0038-092X(93)90122-5

42. Chhinnan, M.S., "Evaluation of selected mathematical models for describing thin-layer drying of in-shell pecans", ***Transactions of the ASAE***, Vol. 27, No. 2, (1984), 610-0615. doi: 10.13031/2013.32837

43. Chandra, P.K. and Singh, R.P., "Applied numerical methods for food and agricultural engineers", (1994). doi: 10.1201/9781315137650

44. Wang, C. and Singh, R., *A single layer drying equation for rough rice*. 1978, ASAE paper. doi: 10.12691/ajfst-4-4-5

45. Coulson, J.M., Richardson, J.F., Backhurst, J.R. and Harker, J.H., "Particle technology and separation processes, Pergamon Press, Vol. 2, (1991). doi: 10.1016/C2009-0-25733-3

46. Zhang, K. and You, C., "Experimental and modeling investigation of lignite drying in a fluidized bed dryer", in Proceedings of the 20th international conference on fluidized bed combustion, Springer. (2009), 361-366. doi: 10.1007/978-3-642-02682-9_53

Persian Abstract

چکیده

ارزش حرارتی، بعنوان یک مولفه کلیدی در ارزیابی کیفیت سوخت، بطور مستقیم بر روی کارائی نیروگاه های حرارتی تاثیر می گذارد. زغالسنگ کیفیت بالا عموما بعنوان زغالسنگ متالورژیکی (کک شو) مورد استفاده قرار می گیرد، در حالی که کاربرد عمده زغالسنگ های کیفیت پایین در نیروگاههای تولید برق زغالی می باشد. رطوبت بالای زغال های حرارتی به شدت بر روی میزان انرژی قابل دستیابی از این مواد تاثیر می گذارد. در این مطالعه، عملکرد خشک کننده های بستر ثابت (Fixed bed) و بستر سیال کاذب (ADMFB) برای حذف رطوبت زغالسنگ در محدوده پارامتر های عملیاتی، سرعت ظاهری هوا ۱۵–۱۸ سانتی متر بر ثانیه، دمای هوای ورودی ۵۵–۷۵ درجه سانتیگراد در یک بازه ۸۰ دقیقه ای مورد بررسی قرار گرفت. مصرف کم هوا از خصوصیات ذاتی بسترهای سیال کاذب می باشد، درحالی که محدوده دمایی پایین برای هوای گرم، با توجه به دمای هوای باطله نهایی نیروگاههای حرارتی با سوخت زغال انتخاب شد. نتایج نشان داد که افزایش هر دو عامل (سرعت ظاهری هوا ۱۸ سانتی متر بر ثانیه، دمای هوای ورودی ۷۵ درجه سانتیگراد) منجر به افزایش میزان رطوبت حذف شده گشت، البته تاثیر افزایش دما بارز تر از افزایش دبی هوا بود. میزان رطوبت حذف شده در زمان های عملیاتی کوتاه تر برای سیستم بستر سیال کاذب بیشتر از بستر ثابت بود. بعنوان مثال برای کاهش ٪ ۱۰ رطوبت در دمای ۷۵ درجه سانتیگراد، خشک کننده بستر سیال کاذب ۵ دقیقه زمان کمتری نسبت به بستر ثابت نیاز داشت. کیفیت مدلسازی و میزان تطابق مدل های لایه نازک پرکاربرد در توصیف سینتیک فرآیند کاهش رطوبت به کمک سیستم های بستر سیال کاذب و بستر ثابت، با استفاده از پارامتر های معتبر آماری متعددی مورد بررسی و ارزیابی قرار گرفت. دیده شد که فرآیند خشک کردن در بستر ثابت به خوبی (R^2=0.999, RSE=0.001, RMSE=0.008) با استفاده از مدل Middilli & Kucuk و فرآیند خشک کنی با استفاده از بستر سیال کاذب به خوبی (R^2=0.998, RSE=0.002, RMSE=0.009) با استفاده از مدل Page قابل تصیف می باشد.