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An experimental investigation on the drying kinetics of a single coarse particle of Belchatow lignite in an atmospheric superheated steam condition

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ABSTRACT

The efficiency of lignite-fired power plants is sacrificed by the high moisture content of this energy carrier. The most adequate effort for upgrading the potential of lignite is the drying process, influenced by both the drying conditions and the physicochemical features of lignite. This paper presents studies on the drying kinetic of the Belchatow lignite originating from the biggest Polish lignite mine. Experimental attempts were conducted for spherical lignite samples dried in a superheated steam atmosphere at the temperature range of 110–170 °C. Each experiment includes the simultaneous measurements of changes in weight and temperature profiles for a single sample. Additionally, the drying process was recorded to observe the cracking on the surface of the sample and its shrinkage. The kinetics were described in the form of moisture content, drying rate and temperature profiles over the drying process. The time and rate of the superheated steam drying process depending on the sample size and steam temperature were estimated. Those parameters are essential for the design of an effective industrial coal drying system, which allows for the latent heat recovery of water evaporation from the lignite, which in turn will improve the thermal efficiency of the lignite-fired power generation.

1. Introduction

In countries where the share of power generation with lignite (also recognized as brown coal or low-rank coal: LRC) is relatively high, lignite plays a significant role in meeting their power demand; Poland is, for instance, one of those countries and the share of lignite in energy mix occupies 35–37% of the gross electricity generation [1,2]. Thus, lignite is considered to be a strategic fuel, especially considering low production costs, which result in low final cost of electricity from lignite-fired power plants, and aspects connected with energy independency. Coal-fired power generation with lignite has unfavorable limitations in improving thermal efficiency due to the high moisture content of the as-received form of this fuel. It typically contains 50–70% of water within a mass of raw coal, though several types of lignite, such as North Dakota lignite, contain 35–40% [3]. With regard to extending the usability of lignite resources and improving the thermal efficiency of the power generation process fuelled by the lignite, water removal is thus the most appreciable technological breakthrough in coal-firing and coal gasification power generation. The market value of lignite can be warranted by increasing its calorific value by drying, resulting in higher thermal efficiency and smaller coal utilization equipment [4]. Water removal from lignite may also result in reducing the cost of energy storage, handling and transportation [4].

Lignite drying is needed not only for increasing calorific value in power plants, but also for briquetting, coking, gasification, low-temperature carbonization, liquid fuel synthesis and other applications [5]. The drying methods for lignite (and for sub-bituminous coal) are classified into evaporative thermal drying, non-evaporative thermal drying and other non-evaporative dewatering processes [6]. Among the proposed applications, the evaporative thermal process is the most often used technology for drying lignite in power generation plants. Some of the evaporative thermal methods are realized in the existing lignite-fired power plants, although their thermal efficiency is not high. The recirculation of hot flue gas from a pulverized coal firing boiler directly to a drying and pulverizing mill is the commonly implemented method, the so-called hot gas drying method [6]. This technique allows for the spontaneous handling of the drying process and the simultaneous feeding of an extensive amount of lignite.

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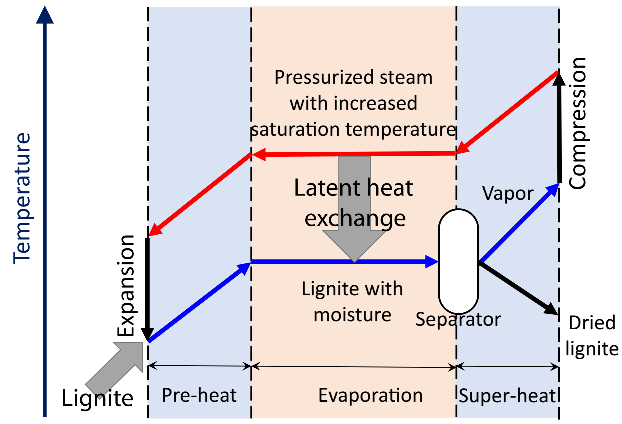

Fig. 1. Principle of a drying process with self-heat recuperation and the recovery of latent heat.

However, this approach does not solve the essential problem concerning the recovery of latent heat, which is the major loss in the drying of high moisture content lignite, since the existing technology used to recover latent heat from flue gas is laborious and expensive [7].

Superheated steam fluidized bed drying (SSFBD), especially using self-heat recuperation configuration, can be an alternative approach for the recovery of latent heat. Fluidized bed drying can be applied in the wide range of application with a variety of choice in drying medium: hot air, flue gas after combustion and superheated steam [8–10]. Fushimi et al. mentioned that using superheated steam in a self-heat recuperation configuration enables the recovery of both latent and sensible heat [11]. The drying method used in superheated steam can be considered for many industrial applications including the drying process of solid fuel. The SSFBD process produces steam from water evaporated out of lignite during drying. Reuse of that steam inside the dryer allows for the recovery of latent heat, which is then consumed in the evaporation process of the next portion of lignite [7] (see Fig. 1). A superheated steam fluidized bed drying system has been demonstrated for lignite drying on an industrial scale [8,12–15]. Superheated steam, as a fluidization medium, offers many advantages: no explosion hazard, better heat transfer, a higher drying rate than during air drying (above the inversion temperature), no oxidative damage, product quality etc. [16]. The idea of using superheated steam for a drying medium is very beneficial; however, system and operation strategy is more complex due to technical limitations [7]. A technological breakthrough and relentless effort are needed to realize this drying system for commercial use in the light of upgrading the value of lignite utilization.

Table 2
Ash composition of Belchatow lignite (dry basis) measured with the inductively coupled plasma–atomic emission spectroscopy (ICP–AES).

Chemical species	Value
SiO_2	29.30%
Na_2O	0.11%
Fe_2O_3	4.06%
Al_2O_3	17.30%
K_2O	0.14%
TiO_2	1.14%
CaO	27.20%
MgO	1.08%
SO_3	18.20%
P_2O_5	0.09%
Others	1.38%

At the same time, for an optimal design of the dryer, knowledge about the characteristics and behavior of a particular lignite from a chosen seam is crucial. Pikon and Mujumdar have mentioned: "Superheated steam seems to provide all the required advantages but few vendors have developed these technologies for coal and for large-scale operations necessary. The drying conditions will need to be optimized for specific grades of coal and also the utilization of the product." [5] This statement can be applied for any dryer and drying process with various types of drying medium; therefore greater understanding of drying kinetics on a specific type of lignite should be essentially pursued for the practical development of the fluidized bed dryer. The general approach on modeling drying kinetics of lignite was reported [17–20]; however, a limited number of works, focusing on drying kinetics of specified lignite with different geological origin, were published. For superheated steam drying, Kiriyama et al. have reported the temperature and sample size dependencies of the drying characteristics of Loy Yang lignite at atmospheric conditions in the temperature range of 110–170 °C [21,22]. They also successfully built a drying model for Loy Yang lignite. Looi et al. have developed a drying model of Victorian (Australian) lignite to predict the drying behavior in pressurized superheated steam and their model was validated with experimentally obtained results [19]. Bongers et al. have studied the drying kinetics of Loy Yang lignite at pressurized conditions together with those of Morwell lignite [23,24]. Their experiment was conducted in the range of 180–260 °C and the equilibrium moisture content and the shrinkage of the lignite after drying were evaluated. Zhang and Yu experimentally and numerically studied the drying kinetics of Chinese Huolinhe and Hailaer lignite in hot air, of which the temperature was 140 °C [25]. Furthermore, Tahmasebi et al. have studied chemical structure changes of Victorian and Shenhua (Chinese) lignite after drying [26,27]. Among the countable number of the publications in the literature, experimental attempts in

Table 1
Proximate and ultimate analyses of Belchatow lignite based on the Japanese Industrial Standard (JIS) methods.

Terms	Unit	Value			Methodology for measures
		As-received	Air-dried	Dry	
Total moisture	mass%	51.6	14.6	–	JIS M 8820
Surface moisture (<35 °C)	mass%	43.0	–	–	JIS M 8820
Proximate analysis (measured as air-dried basis)					
Inherent moisture	mass%	8.6	14.6	–	JIS M 8812
Fixed carbon	mass%	16.8	29.6	34.7	JIS M 8812
Volatile matter	mass%	24.1	42.6	49.9	JIS M 8812
Ash	mass%	7.5	13.2	15.5	JIS M 8812
Higher heating value (HHV)	MJ kg^{-1}	10.9	19.1	20.9	JIS M 8814
Ultimate analysis (measured as dry basis)					
C	mass%	27.5	48.6	56.9	JIS M 8819
H	mass%	2.2	3.9	4.5	JIS M 8819
Sulfur total	mass%	0.6	1.1	1.3	JIS M 8813
Combustible sulfur	mass%	0.1	0.2	0.2	JIS M 8813
O	mass%	10.8	19.1	22.3	JIS M 8813
N	mass%	0.3	0.6	0.7	JIS M 8813
Ash	mass%	7.5	13.2	15.4	JIS M 8812