Chapter 4

Evaporative Drying of Low-Rank Coal

Saban Pusat, Mustafa Tahir Akkoyunlu and
Hasan Hüseyin Erdem

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Abstract

Low-rank coals including the brown and the subbituminous coals are commonly known to contain high moisture content (up to 65%, wet basis), which limits their utilization around the world in spite of their low cost. Today, the most of the drying technologies are based on the evaporation of the water from the moist product. In this chapter, the most effective parameters on the evaporative coal-drying process are investigated with the data in the recent literature. The effective parameters are evaluated in three categories as follows: (1) the parameters about the drying media (the type of the media, the temperature, the pressure, the velocity and the relative humidity), (2) the coal parameters (the type of the coal and the size) and (3) the drying method.

Keywords: low-rank coal, lignite, drying, evaporative drying, coal

1. Introduction

Today, the lignite is one of the cheapest energy sources [1, 2]. The lignite reserves constitute about 45% of the total coal reserves and are distributed throughout the world [3]. The low-rank coals (LRCs) including the brown and the subbituminous coals, which are known to contain high moisture content (up to 65%, wet basis), are very important for the LRC-fired power plants, the gasification and the liquefaction [4]. The high moisture content of the LRC limits its availability in spite of its low cost [5].

The moisture in the coal causes problems in the handling, the storage, the transportation, the milling and the combustion [4, 6]. In the coal combustion, the important part of the energy is consumed to evaporate the moisture inside the coal [5–7]. The combustion of the high moisture content coal creates some problems such as the additional energy consumption for the moisture evaporation, the insufficient combustion and the additional exhaust discharge [8]. The LRC should be dried to the required moisture level to decrease the energy losses and the transportation costs, and to increase the quality of the products [9, 10]. The drying of the LRC may be divided into the evaporative drying or the non-evaporative dewatering [11]. In this study, only the evaporative drying of the LRC is considered.

The drying of the LRC decreases the problems caused by the high moisture content. In a coal-fired power plant with the coal drying, the heat lost with the flue gas, the water consumption in the cooling tower and the energy consumption in the mill decrease [12]. The efficiency of the coal-drying process for a coal-fired power plant mainly depends on the source of the drying energy. The low-quality heat source for the drying process can enhance the efficiency of a coal-fired power plant [13].

In the drying process, both the heat and the mass transfer mechanisms are active. In the evaporative drying of the coal, the heat is provided to remove the water from the coal particle. In references [5, 14, 15], it is stated that the effective parameters on the drying of the lignite are the temperature, the drying media flow rate, the sample thickness and the particle size. Many studies have been conducted on the lignite drying. In the literature, there are some attempts to review the studies about the coal drying such as references [11, 16–22].

The estimation of the exit coal moisture content of the dryer is an important research topic. However, there is not much study on this issue. The thin-layer drying models and the neural network methods were applied to estimate the drying curve [23–29]. The performance of the used models and methods seem so satisfactory.

There are various studies on the evaporative coal drying. In this study, the most effective parameters on the evaporative coal-drying process are investigated with data in recent literature open to the authors. The effective parameters are evaluated in three categories as follows: (1) the parameters about drying media, (2) the coal parameters and (3) the drying method. The effective parameters on the drying media are the type of media, the temperature, the pressure, the velocity and the relative humidity. Different coals in varying sizes are investigated in the section of parameters about coal. Finally, the drying methods used in the literature are studied. The main aims of this study are to summarize the recent studies on the LRC drying and to investigate the most effective parameters on the drying.

2. Parameters about drying media

In this section, the most effective parameters on the drying media are examined. These parameters are as follows: the type of drying media, the temperature, the pressure, the velocity and the relative humidity. All of these parameters should be defined before the design of the dryer.

2.1. Parameters about drying media

In the coal-drying literature, four drying medium (air, steam, exhaust gases and nitrogen) are used in the studies. The summary of the types of drying medium used in the coal-drying studies is presented in **Table 1**.

Drying media	References
Air	[3, 4, 6, 8, 9, 23, 26–46]
Steam	[8, 9, 25, 27, 37, 47–52, 54, 55]
Exhaust gases	[7, 54]
Nitrogen	[25, 31, 33, 53, 56, 57]

Table 1. Types of drying medium used in the literature.

The high temperature (700–900°C) air or the exhaust gases are used in the conventional evaporative dryers [18]. In the power plants, the exhaust gases can be used in the drying process, so the overall efficiency of the plant can be increased [36]. Akkoyunlu et al. [58] studied the economic upper limit of a possible dryer for the coal-fired power plants without considering the method, the conditions, the source of energy, etc.. However, in the coal drying, the air and the exhaust gases may cause some problems. The air and the exhaust gases with the high temperatures are not applicable because of the spontaneous combustion of the coal and the loss of the volatiles [11, 59].

Using superheated steam as the drying media has many advantages over the air and the exhaust gases [18, 60, 61]. The energy consumption in the air drying is more than the superheated steam drying [25]. In the superheated steam drying, the risk of oxidation and the fire are highly unlikely due to the oxygen-free atmosphere [60, 61]. Therefore, the drying temperature can be raised and the higher drying rates can be achieved [18]. The exhaust of the superheated steam drying is pure steam, and so its latent heat can be recovered by the condensation [8, 49, 53]. Moreover, using superheated steam for the coal drying with high capacities in the power plants seems more effective than the others [6].

Using nitrogen as the drying media is not applicable. However, the results of these studies can be evaluated in conjunction with the exhaust gases. The significant proportion of the exhaust gases are nitrogen.

Drying with the air and the steam are the most important topics in the coal-drying literature. The pros and cons for both are presented in many papers. In **Figure 1**, the drying rate curves for the lignite in the hot air and superheated steam are shown. For the same drying temperatures (120, 140 and 160°C), the final moisture content in the air drying is nearly zero. However, in the superheated steam drying, the final moisture content is about 0.7 kg/(kg db). The drying rate increases as the temperature increases. At the temperature of 120°C, the air drying is faster but at the temperatures of 140 and 160°C, the steam drying is faster.

Inversion temperature term is used in the comparison of the air and the steam drying. It shows the temperature point above which the drying rate in the steam is greater than that in the air. In reference [13], the inversion temperature was found in the range from 120 to 140°C.

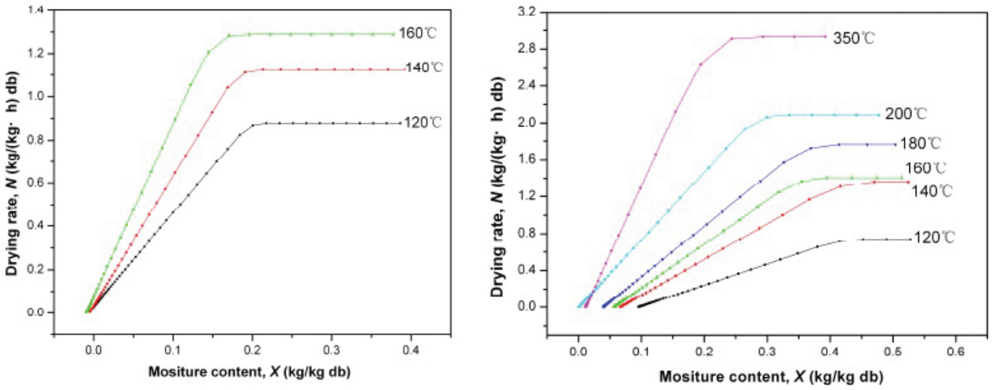

Figure 1. Drying rate curves for lignite in hot air (right) and superheated steam (left) [8].

2.2. Temperature

The drying temperature is one of the most important parameters affecting the drying rate and time. Using the high-temperature drying media requires short drying time. However, the high-temperature values are not applicable for the coal drying due to the spontaneous ignition and the loss of volatiles [59]. The drying temperature levels used in the literature are categorized in two classes (below and above the boiling temperature), and they are presented in **Table 2**.

Temperature	References
Below boiling temperature	[4, 6, 23, 28, 29, 32, 34–36, 38–41, 46, 57]
Above boiling temperature	[3, 4, 6–9, 23, 25–31, 33, 37, 38, 43–53, 55, 56]

Table 2. Drying temperature levels used in the literature.

The LRC is liable to the spontaneous combustion because of its reactive nature [62]. The high-temperature media comprising oxygen may result in combustion of the coal. Using the air or the exhaust gases (comprising uncontrolled rate of oxygen), the drying media may cause the spontaneous combustion of the coal even in the low temperatures. In some of the applications, the rate of oxygen in the exhaust gases is regulated, so the risk of the fire is controlled. However, there is still risk of the fire.

In addition, in the high temperatures, the coal losses its volatiles, which in turn decreases its calorific value [59]. Moreover, the volatiles increase the risk of the fire.

The effects of the drying temperature on the coal weight loss and the drying rate are shown in **Figure 2**. As can be seen, the higher temperature provides faster drying and short drying time.

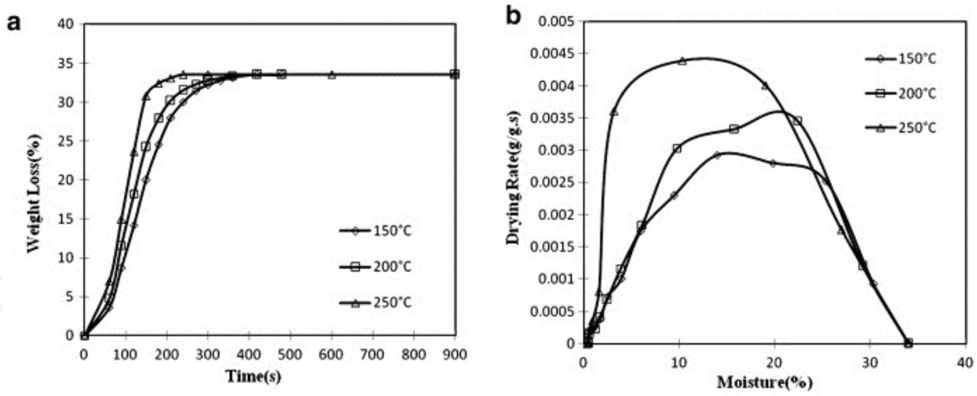

Figure 2. Change of coal weight loss with time (a) and drying rate with moisture content (b) at different temperatures [33].

2.3. Pressure

The pressure of the drying media also affects the drying of the LRC. The increase in the pressure improves the overall heat transfer coefficient [49]. However, the higher pressure values result in the higher equilibrium moisture content. The effect of the pressure can be investigated in three categories such as the atmospheric, the vacuum and the high pressure. The drying pressure levels used in the literature are presented in **Table 3**.

Pressure	References
Atmospheric	[3–6, 8, 9, 23–41, 43–47, 50–53, 55–57]
Vacuum	[47]
High	[6, 7, 47–51]

Table 3. Drying pressure levels used in the literature.

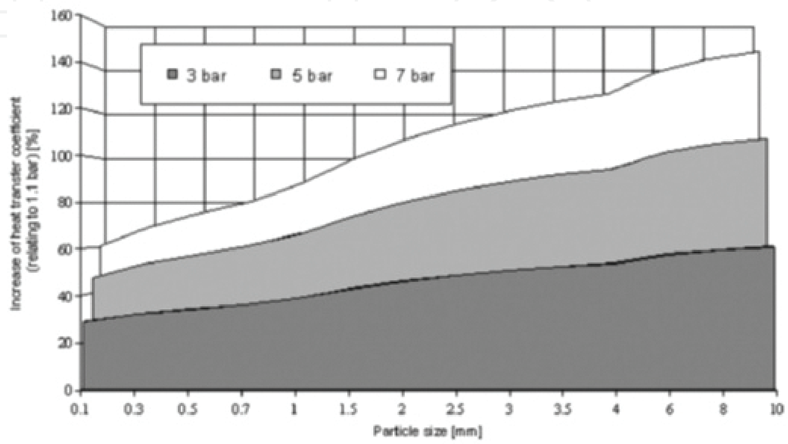

Figure 3. Effect of pressure on heat transfer coefficient [49].

The effect of the pressure on the heat transfer coefficient is shown in **Figure 3**. The percent increase in the heat transfer is calculated relating to the pressure at 1.1 bar. The pressure seems significantly effective according to reference [49]. Moreover, according to reference [63], the higher pressure values result in the faster drying. However, according to reference [48], the pressure does not affect the drying rate. The effect of the pressure on the drying should be presented clearly.

2.4. Velocity

The velocity of the drying media is effective on the LRC drying. In the literature, the different velocity values are studied. In the fluid bed coal-drying studies, the fluidization velocity is also studied. For the case of the fluid bed drying, the level of the drying media's velocity according to the minimum fluidization velocity is very important.

The effect of the drying media is investigated in reference [39] (**Figure 4**). The higher velocity value provides the faster drying rate. The velocity does not affect the drying rate significantly in the last part of the drying. For the fluidized bed dryers, the higher fluid velocities increase the heat transfer rate and the solid mixing [33].

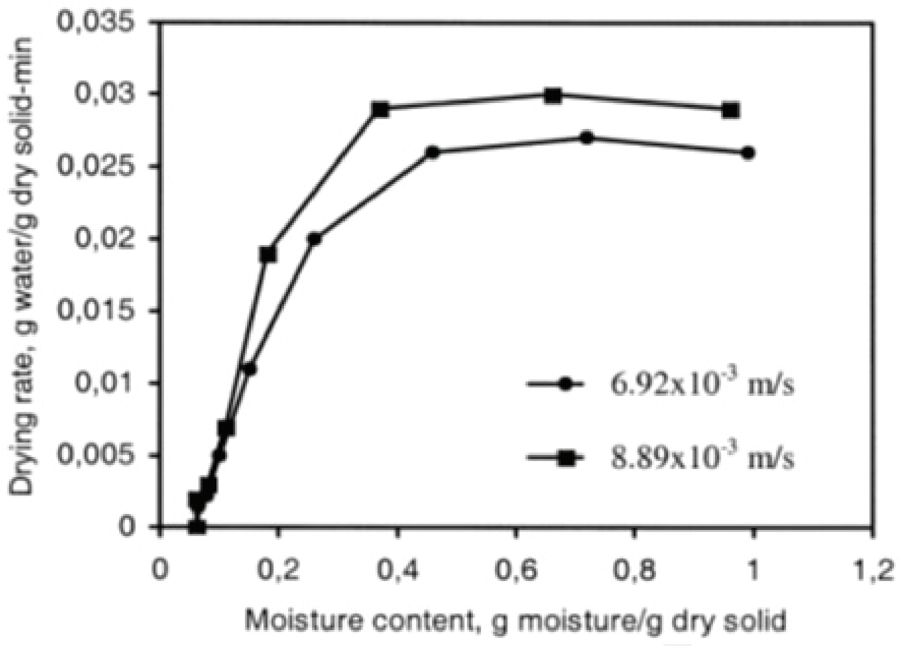

Figure 4. Effect of velocity on coal drying [39].

2.5. Relative humidity

The relative humidity of the drying media affects the drying of the LRC. As can be seen from **Figure 5**, the lower relative humidity means the higher drying rate. At the surface of the coal particles, the evaporation rate is dependent on the water vapour pressure difference between the coal surface and the drying media. The water vapour pressure of the drying media increases with the increase in humidity, and thus, the drying rate decreases with the increase in humidity. In addition, the equilibrium moisture content of the coal particles increases with the increase in the relative humidity.

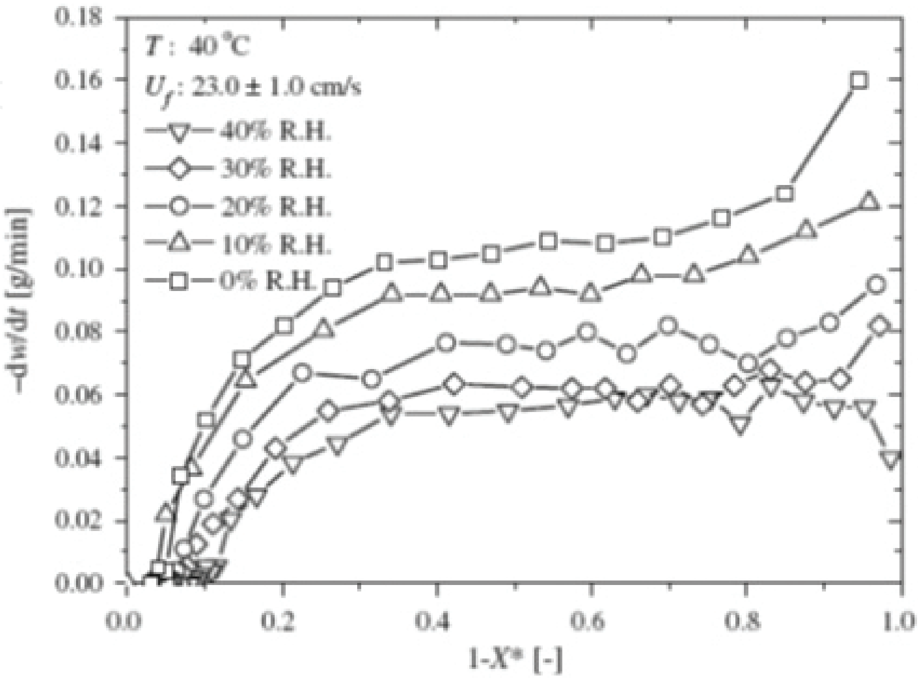

Figure 5. Effect of relative humidity on coal drying [41].

3. Parameters about coal

The characteristics and the particle size of the coal have an important effect on the drying. All types of the coals have different characteristics such as the initial moisture content, the porosity, the equilibrium moisture content, the volatile matter, the grindability, the ash content and the heating value. The effect of the moisture content on the coal heating value for different coal types is shown in **Figure 6**.

The moisture in the coal can be categorized in three groups: the surface moisture (the free water), the physically bound moisture and the chemically bound moisture [32, 64]. The heat is provided to the coal particle, in the evaporative drying, for heating the particle, for evaporating the water, and for overcoming the binding forces (both the physical and the chemical) between the coal and the water [32, 49]. The surface water is easily removed by the evaporation but the other types of the moisture require more energy to be removed. As can be seen from **Figure 7**, the heat of the desorption of the water from the Yallourn brown coal increases with the decrease in the moisture content after a critical moisture value, which shows the end of the surface water and the start of the domination of the internal mass transfer mechanisms.

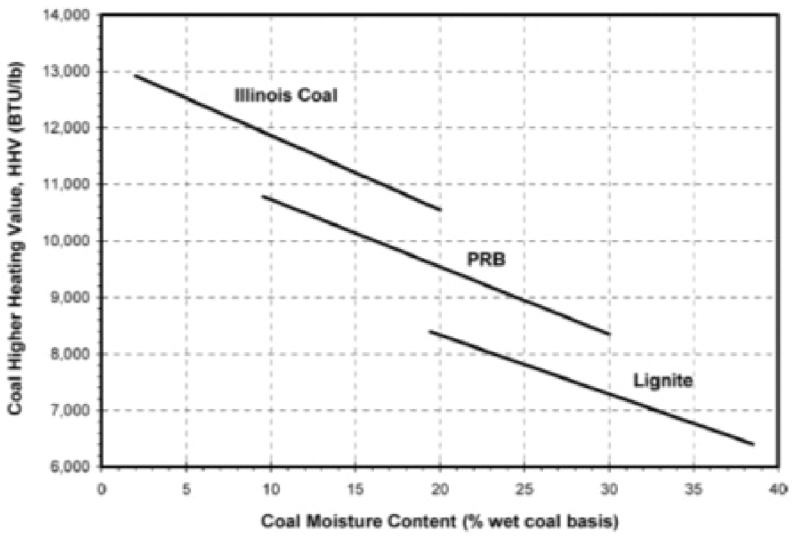

Figure 6. Coal heating value as a function of coal moisture content [32].

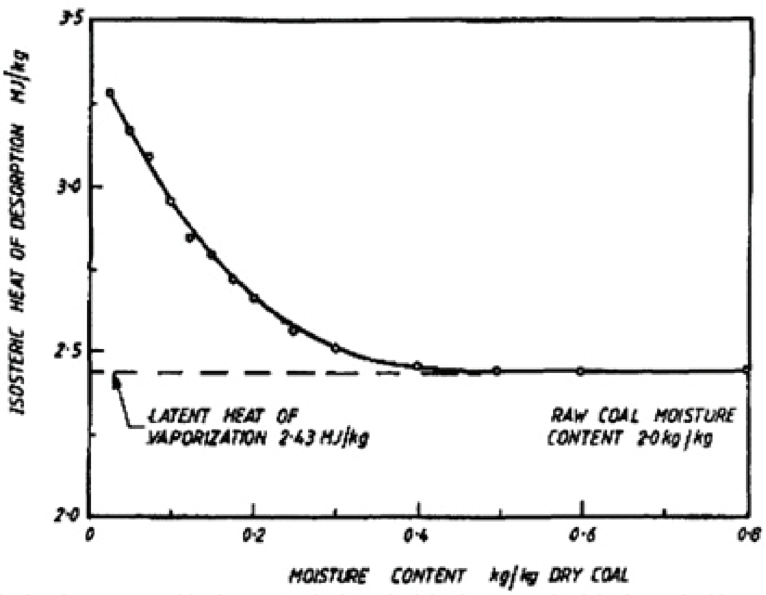

Figure 7. Heat of desorption of water as a function of moisture content [65].

It is important to understand the types of the water in the coal to be effectively removed. For different coal types, the binding forces change, and the binding enthalpy increases with the decreasing moisture content (**Figure 8**) [66–68].

The higher part of the water in the lignite is in the pores [69]. Therefore, the number, the size, the distribution and the shape of the pores in the LRC have important effects on the drying. The water in the smaller pores means difficult to remove. The importance of the effects of the coal parameters on the evaporative drying clarifies that all the types of the coal should be studied separately to obtain the drying characteristics.

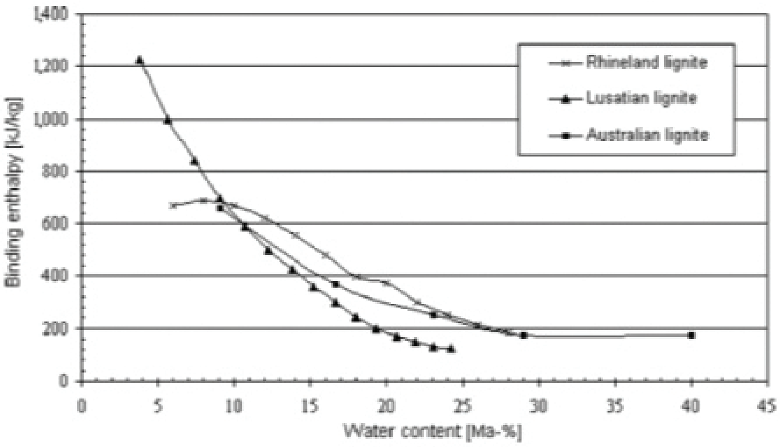

Figure 8. Change of binding enthalpy with coal and water content [49].

3.1. Type of coal

In the literature, there are many studies ([5, 7, 30, 32, 35, 36, 45, 50, 51, 57, 70], etc.), which investigated the effects of the coal type on the drying. In **Figure 9**, the drying curves of the North Dakota lignite and the subbituminous coal from the Powder River Basin (PRB) are shown. Different types of coals show different drying characteristics.

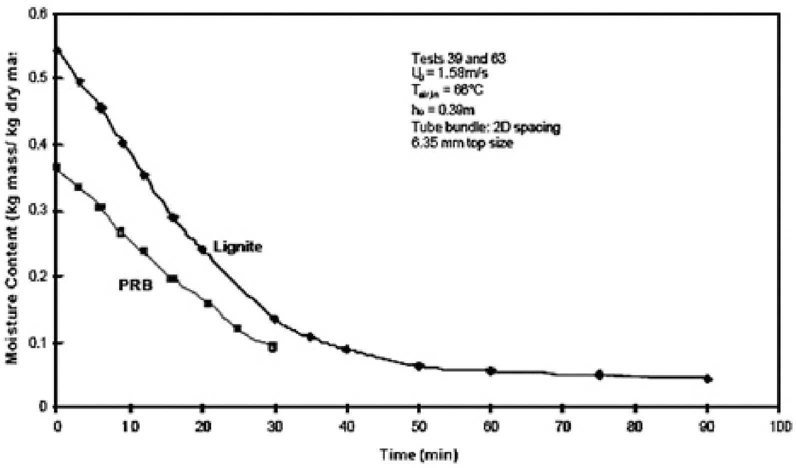

Figure 9. Comparison of drying curves for two different coals [35].

3.2. Particle size

The particle size is highly important in the drying process. In addition, the particle size is very important parameter in the fluidization of the fluidized bed. Moreover, the size of the lignite particles has an important effect on the heat transfer coefficient inside the superheated steam fluidized bed dryer [49]. The sizes of the coal particles used in the literature are presented in **Table 4**.

Particle size (mm)	References
<2	[5–8, 24, 25, 27, 33, 34, 39–41, 47, 53, 57]
<5	[3, 4, 9, 26, 31, 32, 35–37, 44, 49–52, 56]
>5	[23, 26, 28–30, 35–37, 43, 45, 46, 48, 49, 55]

Table 4. Coal particle sizes studied in the literature.

The effect of the particle size on the drying rate is presented in **Figure 10**. The drying rate increases as the coal particle size decreases. The smaller particle fractions have larger surface area, and thus, they dry faster [71]. In addition, the moisture transport distance inside the particle decreases as the particle size decreases.

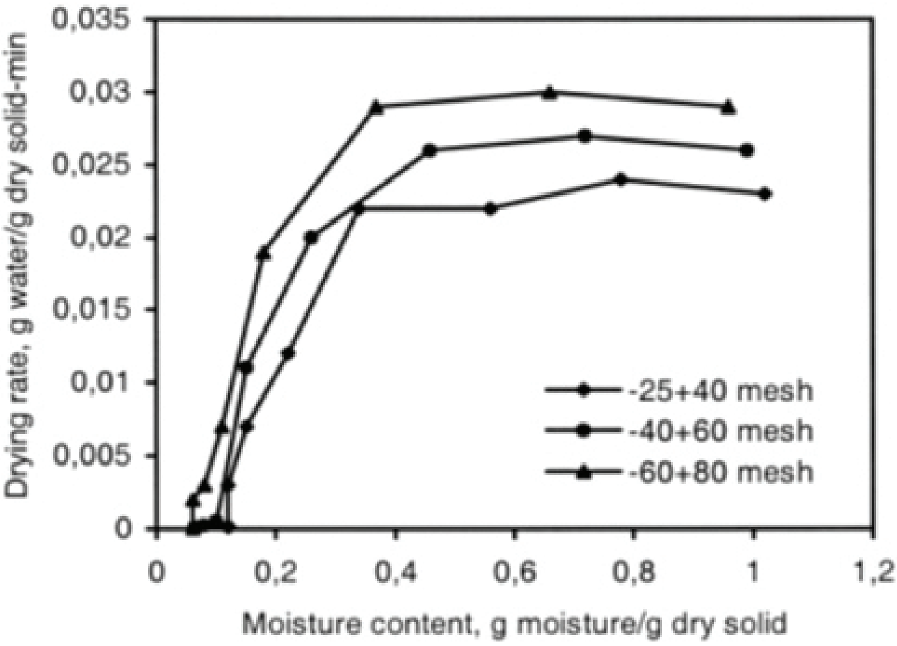

Figure 10. Effect of particle size on drying rate [39].

4. Drying method

In the literature, many different coal-drying technologies are seen. However, the common conventional drying systems are the fluidized bed dryer, the rotary dryer, the shaft dryer, the pneumatic dryer, fixed bed, etc. [72]. The experimental drying methods used in the literature are presented in **Table 5**.

Some of the experimental drying methods (the TGA-Thermal Gravimetric Analysis, the oven and the others) used in the literature are just for investigating, analysis and modelling. Therefore, they are not examined for the applicability of the methods. The results of these studies are important to understand the drying characteristics of the coals, to evaluate the effective parameters on the drying and to be able to model the drying of the LRC in a convenient drying technology.

Drying method	References
Fluidized bed	[3, 9, 25–27, 30–33, 35, 36, 38–41, 47–49, 53]
Microwave	[5, 24, 25, 53]
Moving bed	[43]
Flash	[7]
TGA	[34, 44, 56, 57]
Oven	[4, 6, 37, 50–52]
Fixed bed	[23, 28, 29, 46]
Others	[8, 44, 55]

Table 5. Experimental drying methods used in the literature.

The fluidized bed method is extensively used in the drying of the wet particulate and the granular materials [39, 72]. It has many advantages such as the better gas-drying medium contact, the high thermal efficiency and the drying rates [15]. However, it has some disadvantages such as the high-pressure drops and the non-uniform moisture in the output products [73].

The low-temperature fluidized bed drying method is developed in the United States [32, 74]. The low-grade waste heat is used in this process. This method decreases the risk of the oxidation and the fire due to the low-temperature air. The in-bed heat exchangers are used to increase the temperature of the air and its moisture carrying capacity. However, there is still a risk of the spontaneous combustion in the low-temperature air drying.

The superheated steam fluidized bed-drying technology is a promising one for the coal drying, especially for the high capacities such as the coal-fired power plants. For the power plants, the necessary steam for the drying process can be supplied from the turbine. The in-bed heat exchangers are also used in this method. The heat is supplied to the exchanger tubes by the steam in the lignite drying process [49]. The generated steam can be used in the process by increasing its temperature by the vapour compressor [49]. In addition, the generated condensate in the in-bed heat exchangers can be used for preheating [49]. Using the steam as the drying and the heating medium may increase the efficiency of the process considerably.

The microwave drying is used in a few coal-drying studies [5, 53]. It has some advantages such as the higher heating rates compared to the conventional heating and the more uniform heat supply [5, 60]. The microwave drying directly uses the electricity as the energy source, so it seems so expensive for the LRC drying. However, it can be used by integrating with a conventional drying system due to the advantages of the microwave drying in removing water inside the coal, which is difficult to evaporate with the other drying technologies (**Figure 11**) [75].

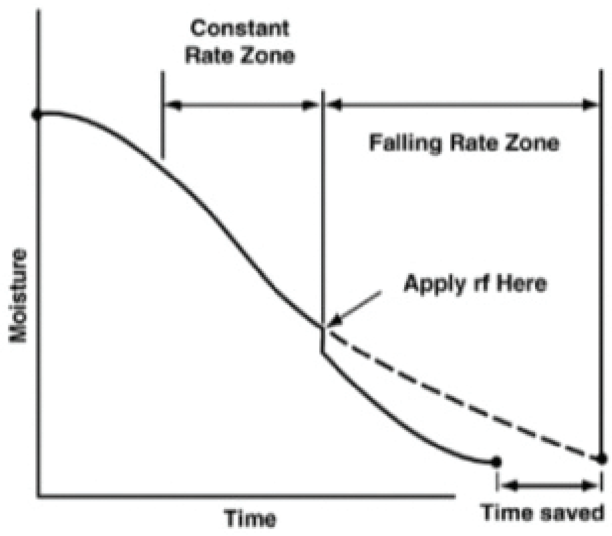

Figure 11. Effect of microwave drying on normal drying curve [75].

The microwave power level has effects on the drying with the microwave. The weight loss increases with the increasing microwave power (**Figure 12**). In addition, the coal type affects the weight loss with the microwave drying.

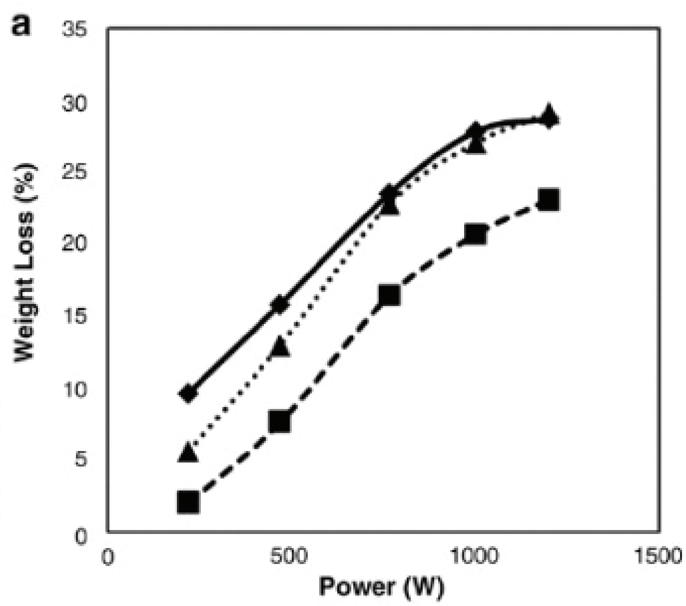

Figure 12. Effect of microwave power level on coal weight loss for three different coal types [5].

The flash drying is one of the most widely used technologies in the drying, and it is also known as the pneumatic drying [72]. As the drying medium, the steam, the air and the exhaust gases can be used. It requires the high drying medium velocities to transport the particles. The particle size range for the flash drying is usually 0.01–0.5 mm [72]. It is not applicable for the larger particle sizes.

The packed moving bed dryer was developed for the large capacities and it uses the 150°C exhaust gases with the controlled oxygen content [76]. Using of the exhaust gases at this temperature levels provides the waste heat recovery potential. In addition, the controlled oxygen content decreases the spontaneous combustion risk. This methodology seems applicable to the power plants with the high capacities and the heat recovery systems.

The fixed-bed drying technology was used to dry the coarse lignite particles [46]. However, there is not much study on the fixed-bed drying. This methodology is a promising one for the drying of lignite particles greater than 10 mm.

5. Conclusions

The coal is one of the most important energy sources in the world. The drying of the LRC is very essential to utilize it efficiently. Because the coal has a reactive and a combustible nature, the drying technology and the drying media should be determined carefully. Moreover, drying is an energy-intensive process; thus, the energy source for the drying process should be determined with care. There is not only one correct method to dry a product. There are numerous methods in the drying literature. Therefore, every drying process should be studied separately.

The drying of the LRCs is still a contemporary topic. There are many studies on the LRC drying, but the current studies are not enough. According to the authors, some further steps should be taken as stated below:

- There is not any detailed study, which examines the effect of porosity on the drying characteristics of the LRCs and links up the drying characteristics, the coal type and the porosity.
- The single-particle drying characteristics of different coals should be studied in detail, and all the effective parameters (particularly the pressure) on the drying should be presented clearly.
- One of the most important areas for the LRCs is the power plants. More elaborative studies should be conducted over the use of the LRC in the power plants such as:

  ○ All the stages (from the mine to the boiler) of the coal combustion in the power plant should be presented clearly, and the problems caused by the moisture content should be presented.

  ○ All the possible drying technologies should be presented.

  ○ All the possible energy sources should be presented, and especially the waste heat recovery sources should be determined.

  ○ For the technologies using the superheated steam, the possibilities of using the process steam should be evaluated, and the optimization studies should be conducted.

- The innovative coal drying systems should be created, and the hybrid and integrated coal-drying systems should be examined.
- There are many mathematical, numerical and theoretical models for the drying of the moist solids. The simple models should be developed for the coal drying.

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Author details

Saban Pusat*, Mustafa Tahir Akkoyunlu and Hasan Hüseyin Erdem

*Address all correspondence to: spusat@yildiz.edu.tr

Department of Mechanical Engineering, Yildiz Technical University, Besiktas, Istanbul, Turkey

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