



City Research Online

City, University of London Institutional Repository

Citation: Nikolopoulos, N., Violidakis, I., Karampinis, E., Agraniotis, M., Bergins, C. & Panagiotis, G. (2015). Report on comparison among current industrial scale lignite drying technologies. *Fuel*, 155, pp. 86-114. doi: 10.1016/j.fuel.2015.03.065

This is the accepted version of the paper.

This version of the publication may differ from the final published version.

Permanent repository link: <https://openaccess.city.ac.uk/id/eprint/8701/>

Link to published version: <https://doi.org/10.1016/j.fuel.2015.03.065>

Copyright: City Research Online aims to make research outputs of City, University of London available to a wider audience. Copyright and Moral Rights remain with the author(s) and/or copyright holders. URLs from City Research Online may be freely distributed and linked to.

Reuse: Copies of full items can be used for personal research or study, educational, or not-for-profit purposes without prior permission or charge. Provided that the authors, title and full bibliographic details are credited, a hyperlink and/or URL is given for the original metadata page and the content is not changed in any way.

City Research Online:

<http://openaccess.city.ac.uk/>

publications@city.ac.uk

Report on comparison among current industrial scale lignite drying technologies (A critical review of current technologies)Nikolopoulos Nikolaos (All of the highlighted pink names are the first names of the authors and not the surnames.)^aViolidakis Ioannis^{a,*}

violidakis@certh.gr

Karampinis Emmanouil^aAgraniotis Michalis^bBergins Christian^bGrammelis Panagiotis^aKakaras Emmanouil^{a,b,c,1}^aCentre for Research & Technology Hellas/Chemical Process and Energy Resources Institute (CERTH/CPERI), 4th km. N.R. Ptolemais-Mpodosakeio, GR-50200 Ptolemais, Greece^bMitsubishi Hitachi Power Systems Europe GmbH, Schifferstraße 80, 47059 Duisburg, Germany^cLaboratory of Steam Boilers and Thermal Plants, Thermal Engineering Sector, School of Mechanical Engineering, NTUA, 9th Heron Polytechniou Str., Zografou Campus, GR-15780 Athens, Greece

*Corresponding author at: 52, Egialias Str., GR-15235 Maroussi, Greece.

¹Tel.: +30 210 7723604.

Abstract

Lignite constitutes a major energy source and has long been used for energy production despite its contribution in greenhouse gas (GHG) emissions, as a fossil fuel. For example, 27.4% of Germany's electricity originates from lignite power plants, while in Greece more than 55% of its electric energy consumption is provided by lignite. 45% of the total global coal reserves consist of low-rank coals (LRCs) such as lignite. With this background, the utilization of lignite for energy production is expected to remain a common practice in the decades to come since the availability of lignite is considerable in many countries of Europe and the world (e.g. Germany, Poland, Greece, USA, and Australia). Therefore, problems regarding the combustion and use of lignite should be addressed in a more efficient and environmentally friendly way. One of the main existing problems is the high moisture contained in raw lignite as received from the mine. The high moisture content results in higher CO₂ emissions per unit of energy produced and is responsible for high capital and transport costs as well as other technical problems such as reduction in coal friability and difficulties in its blending and pneumatic transportation. Therefore, processing of lignite through drying is considered of great interest in the implementation of energy production in lignite power plants. Taking into account the significance of the subject and the usefulness of such an attempt, an overview of the currently existing drying technologies, including both evaporative and non-evaporative drying methods is reported in the present paper.

Keywords: Lignite; Drying; Pre-drying; Fuel preparation; Preprocessing

1 Introduction

Lignite is considered the lowest rank of coal due to its high moisture and ash content and its low carbon content. Low-rank coals (LRCs) constitute about 45% of the total global coal reserves [1]. The combustion of lignite in power plants is widespread in many countries (Australia, the United States, Canada, India, Germany, Greece, Poland, Serbia, Russia, and many other parts of Europe). 27.4% of Germany's electricity originates from lignite power plants [2], while in Greece more than 55% of its electric energy consumption is provided by lignite (Fig. 1) [3].

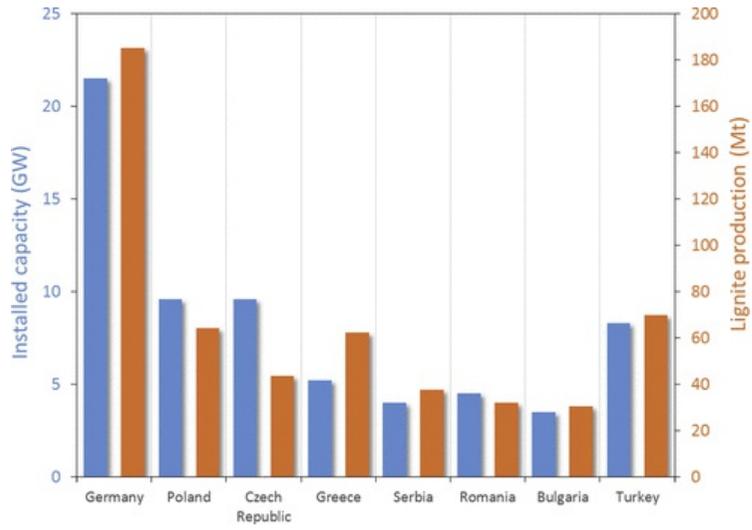


Fig. 1 The role of coal for power production in Europe [3].

The high moisture content of lignite is a major issue in terms of its commercial utilization. High moisture means a decreased heating value and, as a result a lower energy density. Therefore, the high moisture content of lignite lowers the plant efficiency, leads to higher CO₂ emissions per unit of energy output and increases the capital costs due to larger size of lignite boilers compared with the current state of the art hard coal fired boilers. Moreover, due to the high moisture content, it is economically not feasible to transport lignite over larger distances, as is the case with hard coal, and for this reason lignite power plants are typically located at or very close to lignite mines. Drying and pulverization is therefore required in the large scale applications, in order to assure efficient ignition and stable combustion of lignite. The impact of moisture content on the efficiency of coal fired power plants is depicted in Fig. 2. In addition, the presence of moisture also causes reduction in coal friability and impose serious difficulties in its feeding behavior, blending and pneumatic transportation.

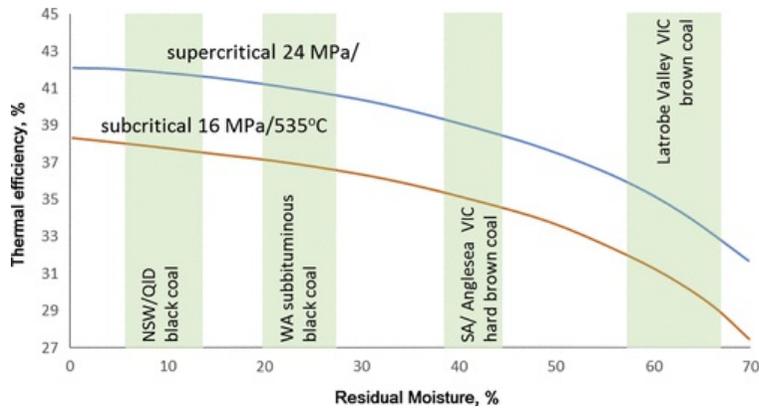


Fig. 2 Power plant thermal efficiency as a function of moisture content of coal [4].

On the other hand, lignite can offer many advantages such as low mining cost, high reactivity, high amount of volatiles and low pollution-forming impurities such as sulfur, nitrogen and heavy metals. For these reasons, the utilization of lignite in the power sector is still relevant and is expected to grow in the coming decades in a global level.

The lignite pre-drying concept is a step toward optimal lignite utilization and upgrade. Decreasing the amount of moisture in LRC leads to lower energy losses during combustion, lower flue gas mass flow, higher plant efficiency, low transportation cost, but increases the safety measures for their transportation and storage, etc. [1], owed to their higher risk for self-ignition.

2 Drying process

For each material, there is a representative curve, the drying curve, which describes the drying characteristics for that material at specific temperature, velocity and pressure conditions. The drying curve can be derived if the rate of moisture loss is plotted against time, for a sample of the material exposed to the drying medium at controlled constant conditions. The exact curve shape and values representing the drying rate always varies with (a) the velocity of the drying medium, (b) the heating medium temperature, (c) the particles size distribution (PSD), and the (d) the particles' own structure characteristics (e.g. pore size and distribution).

There is an initial period during which the material heats up and the drying rate increases. This is followed by a period of constant drying rate, the constant rate period, during which diffusion of water through the solid is sufficiently rapid to maintain saturated conditions at its surface with its evaporation mechanism to resemble that of a water body. Finally, during its final stage the internal diffusion of water can no longer maintain saturated conditions at the particle surface and during that period the drying rate is characterized by a decreasing slope. The latter period is often divided into one period during which the material surface is partially wet and neither mechanism dominates fully and an additional period where the material surface is completely dry and the diffusion of water through the solid is fully determining the drying rate. One of the key variables to be determined is the moisture content at which the constant rate drying period ends and falling rate drying begins – the so-called *critical moisture content*, and it depends on several parameters such as material structure, material thickness and initial moisture content.

Clearly, drying to low moisture levels implies progressively longer drying time (and therefore larger size of equipment) to achieve the desired final moisture level, and therefore drying beyond a predefined limit should be generally avoided, given the condition that a longer drying time results in too large and high energy consuming industrial sized facilities [5].

3 Dryer classification

Dryers can be classified into different categories according to certain parameters, such as the drying method followed, controlling heat transfer mechanism, heating and drying media, heat source and pressure.

The different alternatives of dryer types, according to the previous classification categories are presented in Table 1.

Table 1 Classification categories of dryers.

Parameter	Alternatives
Drying method	Evaporative or non-evaporative
Heat transfer mechanism	Direct or indirect
Drying media (i.e. the stream passing through the material to be dried)	Flue gas, hot air or superheated steam
Heating media	Flue gas, hot air, steam or hot water
Heat source	Dryer burners, boiler (flue gas or steam), recovered waste heat from facility processes
Pressure	Atmospheric, vacuum or high pressure

3.1 Drying method (evaporative–non-evaporative)

Evaporative dryers operate by providing an amount of heat to the material, in order to evaporate the moisture content. In the evaporative processes the moisture is released into the gaseous phase (as steam) during the course of drying. The heat provided to the material corresponds to the latent heat of vaporization increased by an amount of heat to cover heat absorbed by the dried material and other heat losses.

Non-evaporative dryers on the other hand use other methods in which the moisture is removed as a liquid. Typical examples include mechanical thermal dewatering and hydrothermal dewatering.

3.2 Heat transfer mechanism (direct–indirect)

In terms of heat and mass transfer, the available evaporative dryers can be classified into: (a) direct drying systems; (b) indirect drying systems.

- *Direct (or convective)* dryers implicate direct contact of the material with the heating medium, through which heat transfer is conducted. Usually, the heating medium, which in this type of equipment also plays the role of the drying medium, is hot gas and the governing heat transfer mechanism is described by convection. Direct drying has two main variants, in terms of (a) the respective flows of the material to be dried and (b) the heating medium flow; parallel or counter-current flow (Fig. 3).
- *Indirect (or conduction)* dryers include equipment types in which heat is transferred primarily by conduction and radiation and the heating medium is physically wall-separated from the drying material (Fig. 4) [6,7].

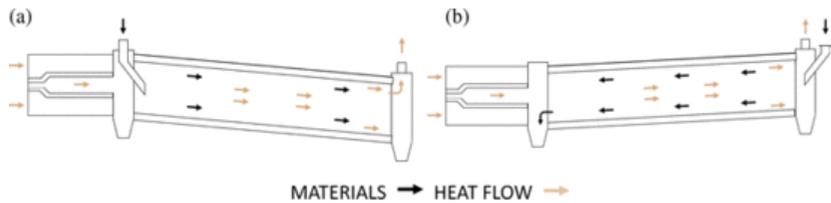


Fig. 3 Direct fired dryers: (a) parallel flow and (b) counter current flow [9].

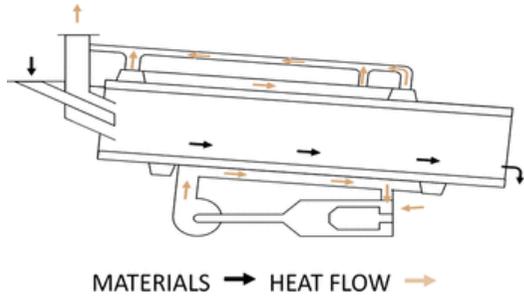


Fig. 4 Indirect firing [9].

Indirect dryers are more suitable for thin products or for very wet solids. Heat of evaporation is supplied through heated surfaces (stationary or moving) placed within the dryer to support, convey, and/or confine the solids. The evaporated moisture is carried away by vacuum operation or by a stream of gas that is mainly a carrier of moisture. Vacuum operation is recommended for heat-sensitive solids [8] ~~(see Table 2)~~.

Table 2 (Please remove table 2 from here and insert it below as stated in the following comments) Comparison of characteristics between direct and indirect dryer.

Dryer type	Capital & operating cost	O&M requirements	Environmental emissions	Energy efficiency & heat recovery	Fire hazard
Direct dryer	Lower	Lower	Heating medium treatment required	High efficiency	Relatively high
Indirect tube dryer	Higher	Higher	Less emissions	Low efficiency in general	Decreased fire hazard – absence of oxygen
				Equally efficient with direct dryers when heat recovery option from steam is available	

Direct dryers are generally more efficient than indirect-fired dryers, which introduce an inefficiency associated with the heat transfer from the steam tubes to the material. The efficiency of an indirect dryer is increased if (a) no air is injected and (b) the moisture vented away from the dryer in the form of steam is recovered to serve any process heating needs [7].

There are also efficient combined systems, which are capable of combining the characteristics and advantages of both the direct and indirect drying methods (Fig. 5), such as fluidized bed dryers with immersed heating tubes or coils for the drying of heat-sensitive materials. This dryer can be only one third of the size of a purely convective fluidized bed dryer for the same duty [8].

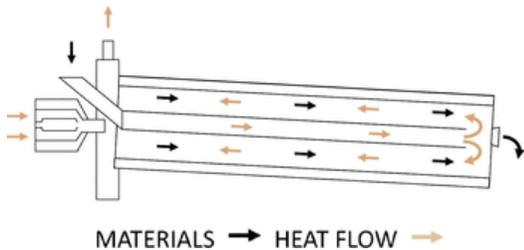


Fig. 5 Indirect/direct firing [9].

A comparison of the main characteristics between the two aforementioned dryer types is presented in Table 3. [\(Please remove Table 3 and insert Table 2 in the following line\).](#)

Table 3 [\(Please remove this table, replace it with table 2 and transfer table 3 below, where indicated.\)](#) Advantages and limitations of superheated steam dryers [53].

Advantages	Limitations
– Energy is easily recovered at high temperature by condensation of steam. This reduces operating costs through substantial net energy saving	– Need for tightly closed system to prevent high pressure steam from escaping and to prevent air from entering the system. This adds to capital costs
– Emissions mainly appear in the steam condensate and can be easily removed, reducing the need for expensive accessories like after-burners, scrubbers or filters. This reduces capital costs	– Need for stainless steel parts to prevent corrosion since condensation at start-up and shut-down is unavoidable. This adds to capital cost
– High drying rates are easily achievable due to high heat capacity of steam and high drying temperatures. Reduced drying time enables the dryer to be built smaller thereby reducing capital costs	– Higher product temperatures compared to hot air drying during constant drying rate period. Too high a temperature may cause unwanted melting, lumping, and stickiness
– Solvents and volatiles are easily recovered from the condensate by separation or distillation	– Condensation of incoming material causes rapid heating of product but also temporarily wets the product
– Explosion and fire risks are eliminated due to the absence of air, enabling high temperature drying if necessary	– Cleaning of heat exchangers required due to deposition of fine particles during condensation of steam

3.3 Heating medium (flue gas–air–steam)

The heating medium which can be used in the dryers can vary according to the process demands and the availability of streams in the drying installation. The heating medium can be (a) flue gas, (b) air or (c) steam.

(a) Flue gas dryer

A flue gas dryer has the advantage of using waste heat which improves the gross energy efficiency of a plant. However, a large flow of flue gas is required, when the flue gas temperature is low. The large volume of flue gas mandates a large-scale dryer with considerable electricity consumption. Typical energy consumption for a flue gas dryer is about 3200 kJ/kg H₂O [10]. Typically, around 2600 kJ/kg water is required to evaporate the moisture. Apart from the latent heat of water evaporation, extra heat is required to compensate heat losses and to preheat the material up to the drying temperature.

(b) Air dryer

Recently, low temperature air dryers have received significant interest for drying systems because of low grade heat and low gas emissions. The heat demand for a low temperature air dryer is estimated to be around to 2700 kJ/kg H₂O (including heat recovery) [11].

(c) Steam dryer

Steam dryers have the advantage of being able to recover a large amount of input heat through the condensation of the evaporated moisture at a later stage in the process. Due to this energy recovery step, the net heat demand for a steam dryer can be as low as 600 kJ/kg H₂O [12].

4 Types of coal dryers

Both direct and indirect dryers are applied for coal drying at an industrial level. Combustion gases or steam may be used as the heating medium. Steam-heated dryers are used mainly for drying of lignites in the coal briquetting process. What is more, this type of tubular steam dryers is the only one which has been widely used commercially in the large industrial scale.

Frequently, coal drying is carried out in various types of drying and dewatering equipment [8], e.g.:

- Rotary dryers.
- Fluidized-bed dryers.
- Pneumatic dryers.
- Mill-type dryers.

- New dryers operating with a high velocity air flow stream for grinding/drying.
- Hydrothermal dewatering (HTD).
- Emerging techniques, etc.

There are also other types of dryers emerging, using superheated steam, while other types of novel drying technologies are also currently being developed.

4.1 Rotary dryers

4.1.1 Direct rotary dryers

Rotary dryers can be of either direct or indirect type. In many industrial plants, rotary dryers are used for the drying of coal and coal muds. Generally, in order to avoid the possibility of fuel self-ignition during operation, a co-current mode is suggested for this type of dryers. Natural gas or coal is used to generate flue gas to be used as the drying medium. The layout of a typical rotary dryer is shown schematically in Fig. 6. The main component of this dryer is the steel drum (3) lined with a refractory lining and set up on rollers (7) by means of bandages (hoops, 10) located on the drum. A toothed gear (5) is typically used to rotate the drum. The drum is set up obliquely with a slope of $2\text{ to }5^\circ$ to the horizontal.

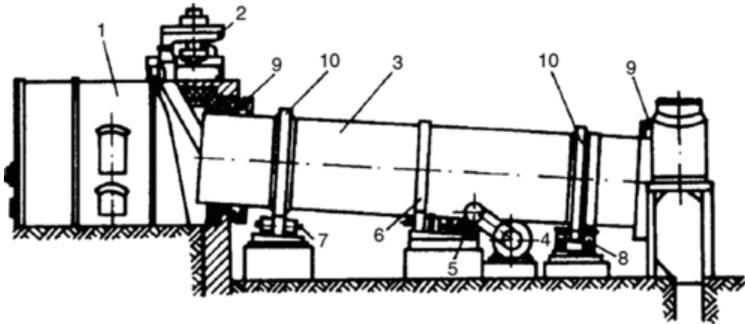


Fig. 6 Schematic of a rotary dryer [8].

Inside the drum, there are lifters attached to the inner surface of the drum. During operation, as the drum rotates these lifters lift the coal granules and shower them gradually inside the drum in the stream of the flowing heating gas [8].

Various lifters are shown in Fig. 7.

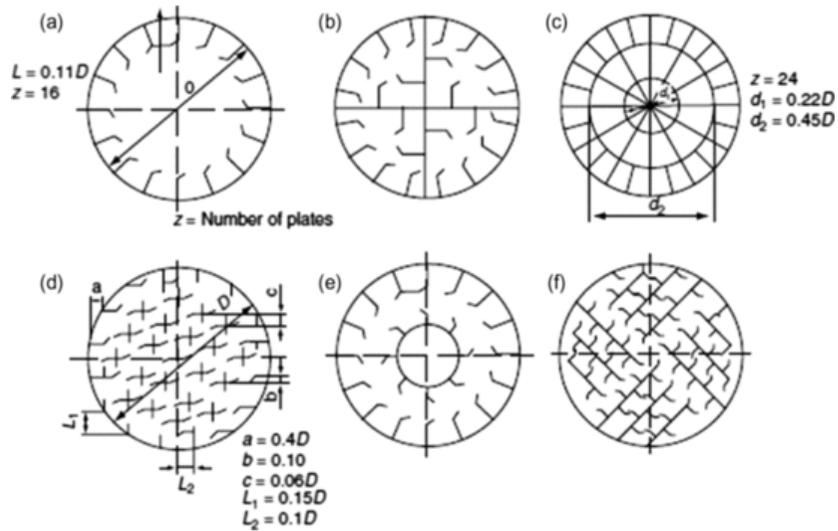


Fig. 7 Scheme of the lifting-mixing devices for rotary dryers [8].

4.1.2 Rotary-tube (indirect) dryers

The rotary-tube dryers are used widely for coal drying in lignite briquetting plants. They are also used for hard coal drying. These dryers are indirect dryers heated by saturated steam at pressures in the range of 0.15–0.55 MPa. Indirect drying can be achieved in a number of ways. Most commonly, an indirect rotary dryer consists of a jacketed drum through which steam or other heating medium flows. At any time, a very small fraction of solids is exposed to the heated wall, resulting in low heat transfer rates and low drying efficiency. One way to improve the performance of an indirect dryer is to increase the area of contact between the heated wall and the particles. This is achieved by introducing a series of tubes through the rotary shell and passing steam through the tubes. In the steam-tube dryer, wet solids are lifted and showered within the rotary shell in the usual sense, and heated by radiant heat and contact with the outer surfaces of the tubes [13].

There is another type of rotary-tube dryer type in which the tubes carry coal rather than steam. Wet feed flow stream enters the inclined tubes under the influence of gravity, which in turn is distributed among the tubes as the vessel rotates. The tubes have a diameter of at least 150 mm and house helical wires which serve as stirrers, regulating the flow of coal being dried and ensuring sufficient residence time. This coal-in-tube dryer is designed to reduce the moisture content of 3 mm coal particles from 20% to 4% by maintaining the shell temperature above 120 °C always controlling the rotation speed of the dryer. The coal-in-tube dryer, should produce less dust compared to the steam-tube dryer since the tumbling action in the former is not as intense. A number of the coal-in-tube dryer has been manufactured by Kawasaki Heavy Industries with evaporation rates in-between 6.7 tons/h and 13.1 tons/h, and unit throughputs between 95 d-tons/h and 420 d-tons/h. No reports are available on the flow behavior of the particulates through the tubes [14]. The layout of this type of dryer is shown in Fig. 8. It consists of a sloping drum (1), in which the perforated walls have seamless tubes fastened to them (2). The dryer drum rolls on special rings (6) and rollers (7) and is driven by power transmitted (8) by means of a gear wheel (9). The heating steam enters the drum through the pin (3). The moist coal is fed in the heating tubes.

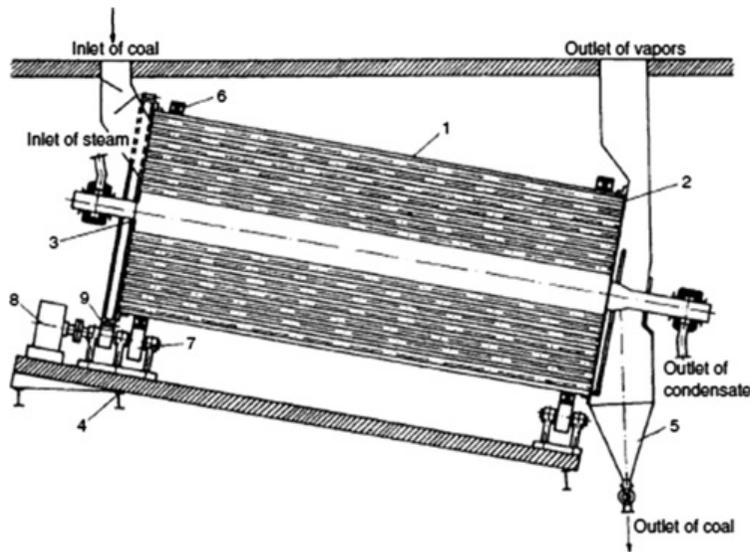


Fig. 8 Rotary-tube dryer layout [8].

As a consequence of the slope and rotation, the coal is displaced gradually in the heating tubes from the inlet to the outlet. The displacement of coal is controlled by screw guides installed at the heating tubes. The variable-pitch guides prevent the rapid displacement of coal between tubes.

The dried coal is collected in the lower part of the chamber (5). The steam condensates is drained through a pin placed in the lower end of the drum.

In this type of dryer, the convective heat transfer coefficient from steam to coal is about $25 \text{ W/m}^2 \text{ K}$ [8].

4.1.3 Existing applications of rotary drying

4.1.3.1 Steam-fluidized-drying with rotary tube dryers for briquetting in Victoria, Australia In Australia, indirect drying has been used for many decades to prepare lignite for briquetting. In this process, low-pressure steam is condensed on the outside of tubes conveying lignite to provide process heat; the more water removed in liquid form, the higher the efficiency. After reducing the moisture to nominally 15%, dried lignite is compacted into strong briquettes using stamp presses [8].

Large-scale briquetting of Victorian lignite commenced at Yallourn in 1924 using the German technology. The original Yallourn plant closed in 1970 but the Morwell plant, which commenced in 1959, is still operating, with a nominal production capacity of 1.2 Mtpa of briquettes and 170 MW of electricity. The Morwell briquette and power complex is one of the largest cogeneration plants in the Southern Hemisphere. A sister briquetting plant to that in Morwell is operating on Indian lignite at Neyveli, south of Madras.

Briquette production in Victoria peaked at 1.9 Mt/a in 1966 prior to the introduction of natural gas. Production has now stabilized around to 400–500 kt/a, primarily for industrial and commercial heat applications, char production and occasional niche market export opportunities because of the high quality of the product.

In the briquetting process, lignite is crushed to 8 mm, dried in rotary steam tube driers from 66% to about 15% moisture. The dry coal is then cooled and briquetted without a binder, using an Exter extrusion press at 1200 kg/cm^2 to form hard compacts with an energy content (21 MJ/kg Net Wet basis) comparable to many higher rank coals. However, as a result of changes in the quality of Yallourn coal with the development of Eastfield, and competition between the privatized mines, Loy Yang coal now provides 75% of the briquetting coal, with Yallourn Eastfield providing the balance [15].

4.1.3.2 Superheated steam rotary drying in Victoria, Australia Another recent example of drying which uses the superheated steam rotary drying process was developed by Keith Engineering [16] for drying of lignite from Victoria, which has high moisture content of 50–70%. It was reported that the moisture was reduced to a low level (11% wet basis) starting at around 61%. The feed rate of the lignite was 23–46 kg/h and steam temperature was 180–230 °C with a drum rate of 3–6 rpm. Superheated steam drying was used for drying of Indonesian coal of relatively low moisture content that was rich in sulfur [17]. A steam temperature of 300 °C was found to be sufficient to remove the moisture to expected level.

However, these types of dryers are mainly suited for very large-scale power plant applications on site. The investment costs are very high, although they report high efficiency and safe operation [1,16,18,19].

4.2 Fluidized-bed dryer (FBD)

Fluidized-bed dryers (FBDs) can achieve a high intensity of the drying process due to good mixing, use of a high-temperature heating (and fluidizing) medium and ease of control. A fluidized state is achieved when gas with a proper velocity passes through the coal layer. The gas flow velocity at which the packed bed is converted into a fluidized bed is known as the minimum fluidization velocity.

Due to their simple design and high capacity, FBDs are widely applicable in the industry for coal drying. One type of fluid-bed dryer commonly used for coal drying is the Fluo-Solids dryer marketed by Dorr-Oliver (United States). This dryer operates with a small coal bed (300–400 mm) and has a very high drying rate per unit exposed surface of 2000 kg H₂O/m² h. Fig. 9 schematically shows the Fluo-Solids dryer with the roller chamber designed by Dorr-Oliver for coal drying.

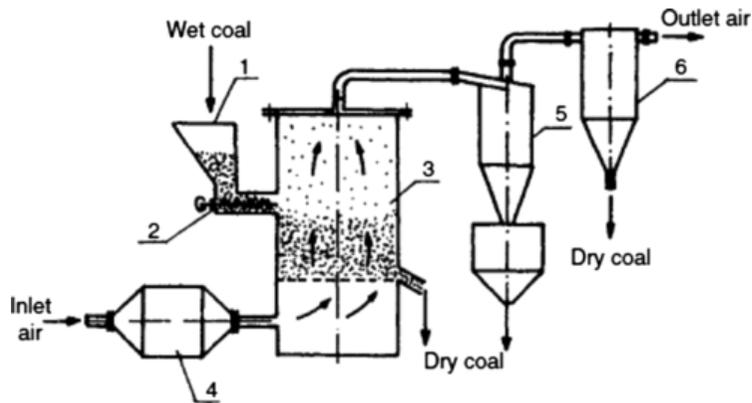


Fig. 9 Schematic of Fluo-Solids-type fluidized bed dryer [8].

Wet coal from the bin (1) is proportioned by feeder (2) to the drying chamber (3). Combustion gases from the combustion chamber (4) are mixed with air to obtain the desired temperature (300–700 °C). The heat consumption is typically in the range of 3100–4000 kJ/kg H₂O. The hot gases pass through a screen and the coal layer, causing fluidization of coal. The exhaust gases leaving the dryer are cleaned in a cyclone (5) and cloth filter (6) [8].

4.2.1 Fluidized-bed dryer with fountain bed (spouted bed)

In recent years, FBDs with a fountain (spouted beds) bed have become popular for coal drying. The fountain bed is achieved in a conical–cylindrical apparatus, as the one depicted in Fig. 10.

Drying of coal

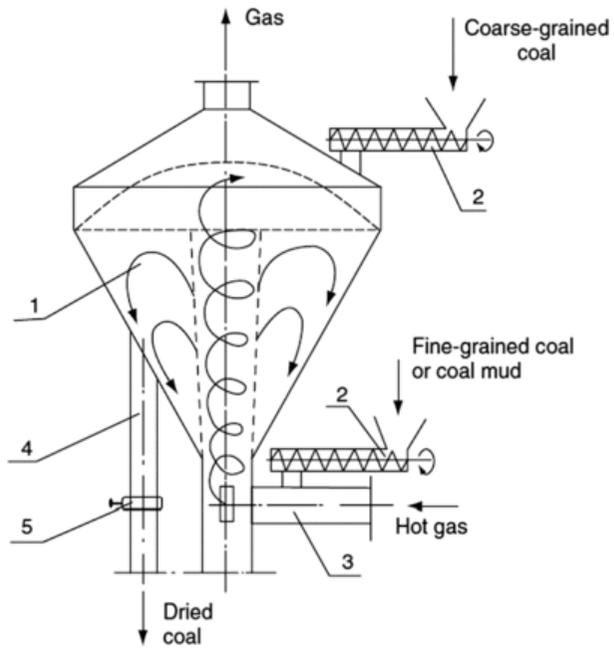


Fig. 10 Schematic of dryer with spouted bed [8].

The hot gas stream supplied to the dryer by tube (3) carries away the coal particles supplied by screw (2) and moves them upward. The lifted coal grains fall aside and move downward along the annulus.

Fig. 11 shows a schematic depiction of a spouted bed dryer for coal as designed by Fiodorov and Michailov [8]. Wet coal is fed to the conical drying chamber, and it is carried by the flue gas upflow. The coarser coal grains fall downward due to the gradual increase of the cross section and the corresponding decrease of the flue gas velocity in the conical chamber. The finest grains are entrained by the gas stream and then separated in the cyclone (3). The intermediate fractions are circulated in the drying chamber (1), after which they pass through a vertical slit in the chamber wall for discharge. Control of the slit opening allows control over the dryer holdup. The coarse coal particles fall into the bin (5) from which they are recycled to the dryer by a bucket elevator (6).

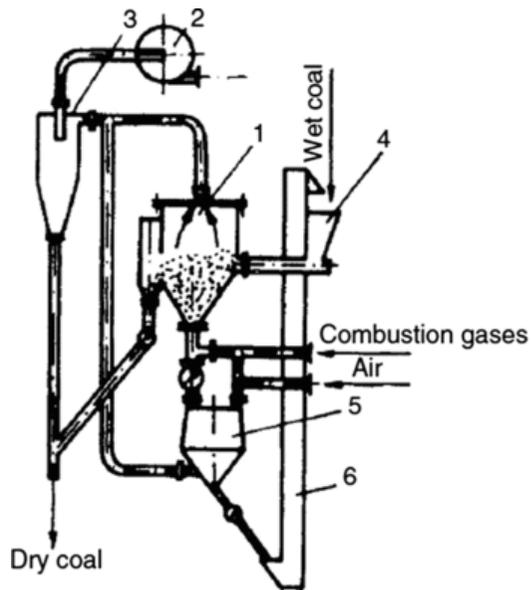


Fig. 11 Schematic of fluidized system with spouted bed [8].

For spouted bed dryers, it is very important to determine the gas velocity at which the spouting process begins and ends. The critical velocity for spouting regime depends on the bed height and the physical properties of the coal and gas, as well as on the geometric shape and the dryer dimensions. For coal drying, the temperature of the drying medium (e.g. combustion gases or air) is usually not more than 200 °C, unlike the case of conventional FBDs, which operate under much higher inlet temperatures [8].

4.2.2 Fluidized-bed dryer with immersed heater

Excellent gas–particle contact in FBDs offer high heat and mass transfer rates, as well as high drying rate while preventing the overheating of individual particles. Thermal efficiency is also high, and can be increased further by immersed heat exchangers in the particle bed. Drying in fluidized beds with immersed heating elements combines the convective (gas flow) with the conduction heat transfer (immersed heaters) mechanisms. Fluidized bed dryers modified to incorporate heaters in the bed region have been reported to intensify the drying process due to the increase in temperature and vapor uptake capacity [20].

It is to be noted that the heat transfer coefficients strongly depend on the local hydrodynamic condition, which differs depending on the position, geometry, and properties of the internal element, the gas flow characteristics, and the form of the bed [21]. Vibrated beds with internal heat exchangers immersed in the bed yield high thermal efficiency but are not common due to the need to keep the bed height modest to allow vibration effect to appear throughout the bed [14].

4.2.3 Fluidized-bed dryer (WTA)

RWE Power in Germany has also developed a fluidized bed drying technology for lignite. The technology concept developed by RWE is called Wirbelschichttrocknung mit interner Abwärmenutzung (WTA) technology (English: Fluidized-bed drying with internal waste heat utilization), which is arguably the most advanced superheated steam drying technique [22].

In the applied WTA process (Fig. 12), lignite is first milled to a fine particle size by hammer mills in direct series with a two-stage fluidized bed dryer. The dried fuel exiting the stationary bed is separated from the gas stream and mixed with coarser lignite solids collected from the bottom of the dryer bed and then fed directly to the boiler. The heat needed for the drying of the fuel is supplied by external steam, which is normally taken from the turbine with the heat transfer taking place in tube bundles located inside the bed.

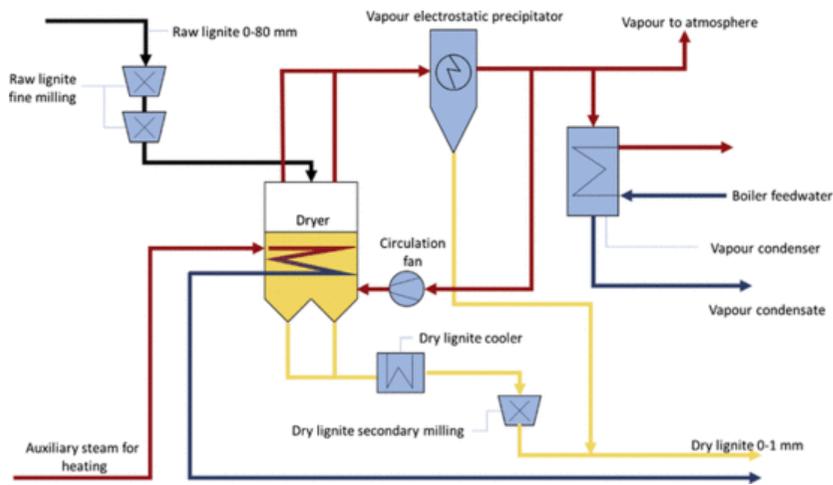


Fig. 12 WTA concept with vapor condensation in RWE Power – Niederaussem power station [23].

Another concept for the WTA process has also been investigated. The important features of the WTA process in this case (Fig. 13) include (a) an FBD using superheated steam, (b) a vapor compression step for recovering the latent heat from the process, and (c) the supply of energy to the drying solids. The coal is dried from around 60% moisture content to 12% using steam at 110 °C at a low pressure of 50 mbar. A part of the steam at higher temperature is used for indirect heating of the fluidizing bed through submerged tube bundles [24].

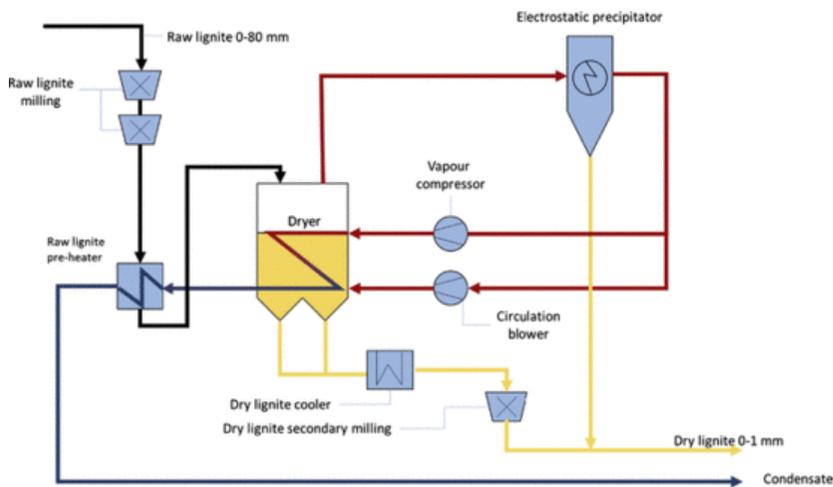


Fig. 13 Process principle of WTA fine-grain drying with vapor recompression [23].

4.2.4 Pressurized fluidized-bed dryer

Recently, Lechner et al. [19] have successfully carried out high-pressure superheated steam drying of lignite using a pilot scale reactor. Experiments were carried out for a flow rate of 240–500 kg/h dry lignite starting in on a raw basis from 50–60% moisture and ending to a 5–30% moisture content (mass basis). The process is similar to WTA with internal heating of fluidized bed, except for the fact that high pressure steam, up to 10 bar, is used for drying.

The process is presented in Fig. 14.

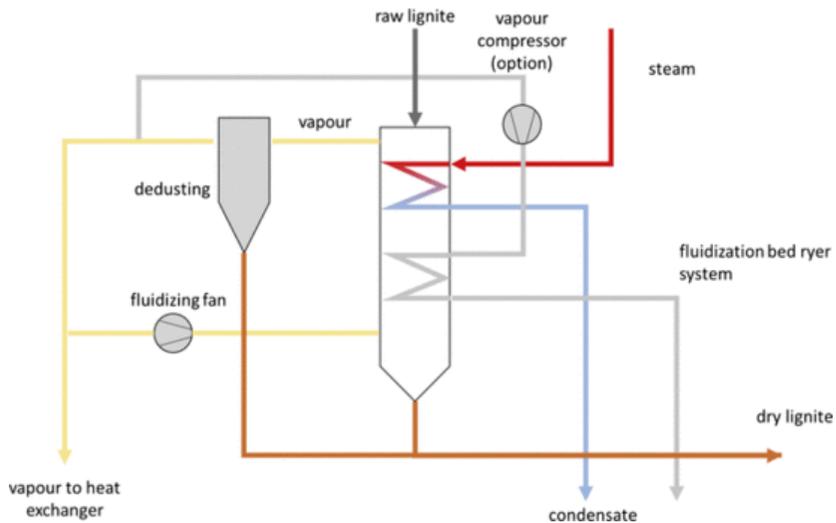


Fig. 14 Schematic view of the pressurized fluidized bed drying process (PFBD) [25].

Raw lignite is fed into the pressure vessel containing the fluidized bed. Steam condenses in a heat exchanger in the fluidized bed, while releasing its heat. The transferred heat vaporizes the water in the lignite, which then exits the dryer at its top, where subsequently is de-dusted. The heat of the vaporized lignite moisture can be recovered and used either internally for the heat requirements of drying with a vapor compressor or elsewhere besides the dryer (see Fig. 15).

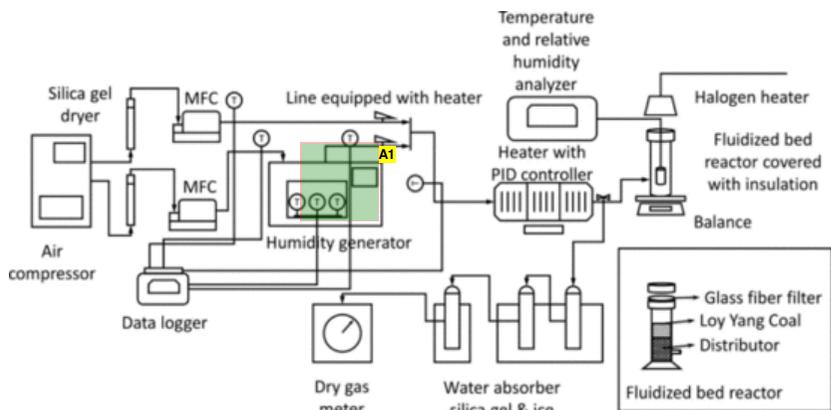


Fig. 15 Schematic of fluidized bed dryer at Loy Yang [26].

Annotations:

A1. This Figure should be included in paragraph 4.2.5.1

Recently, Hoehne et al. [18] have reported their extended work on pressurized steam FBD. It is reported that the mean heat transfer coefficient for pressurized steam drying with internal heating of 250–300 W/m² K can be easily achieved depending on the type of coal and the coal particle size. They also have reported the effect of steam pressure, velocity, and particle size on heat transfer coefficient. It was found that overheating of the fluidized bed results in removal of more water because the temperature required to remove the water in the capillaries is greater than the required temperature for surface water.

4.2.5 Existing application of fluidized bed drying

4.2.5.1 Steam-fluidized bed drying of lignite in Victoria, Australia A 150,000 t/a (dry coal) steam fluidized bed drying plant is operated for several years at Loy Yang, supplying pneumatically conveyed dry coal dust over 3 km to Edison Mission's Loy Yang B power plant

for its use as a start-up and auxiliary fuel. The drying process being implemented at the plant operated by the State Electricity Commission of Victoria, Australia (SECV) used a heat exchanger supplied by an external high pressure steam source to dry finely ground lignite. A tube network immersed in the bed supplies the heat (see Fig. 15). The high heat transfer rates of the bed, together with condensing steam, contributed to a rather compact heat exchanger (Please insert Figure 15 below this line, and remove it from the previous place).

Water evaporated from the coal was used as the fluidization agent. Test results have shown that the water content of Victoria's lignite can be reduced from 60% to 15%, while carbon dioxide (CO₂) emissions can be decreased to 17%.

Despite the technical advantages of the process, the product has proven to be too expensive to attract other markets for the Loy Yang plant's surplus capacity. The plant has now ceased operation and Loy Yang B is now using pulverised briquettes as auxiliary fuel, and may switch to natural gas [8,15].

4.2.5.2 Fluidized bed drying in Coal Creek Station, North Dakota LRC can also be dried at the processing plant site using waste heat from the plant as well as the flue gases for drying [27]. Levy has also reported that the use of ambient air heated using the waste heat from condenser (Fig. 16) can result in a 3.8% increase in the plant efficiency [27].

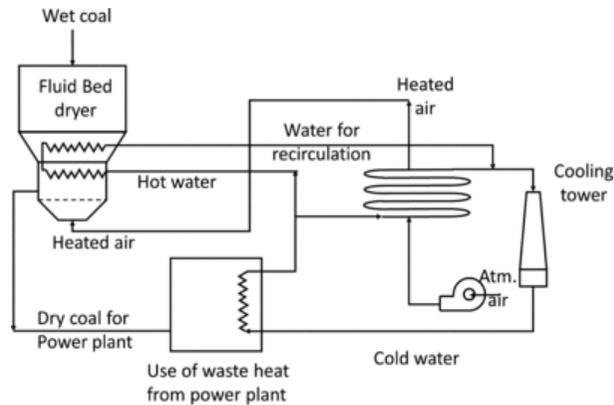


Fig. 16 Use of plant waste heat for drying coal [1].

In another case, low-grade waste heat was used to evaporate a part of the moisture from lignite feedstock at a 550 MW unit at Coal Creek Station, North Dakota [1,28] (see Figs. 17 and 18).



Fig. 17 Pilot testing at Coal Creek Station [29].



Fig. 19 Photo of the WTA 1 plant (left part) and WTA 2 plant (right part) at Frechen.

4.2.5.3.2 WTA Niederaussem plant The WTA-1 plant at the Niederaussem power plant was also designed based on a coarse-grain drier with an integrated vapor compressor, but does not include a coal preheater. The particle size of the feed coal and dry lignite is the same as for the Frechen WTA-1 plant. To ensure that the energy balance is maintained (necessary in the absence of a coal preheater) some of the heat exchangers installed in the drier are heated with LP steam from the power plant network. The plant was operated in conjunction with unit H of the Niederaussem power plant only for a short time, **owing to changes in the consortium structure during project realization.**

The Niederaussem WTA-2 plant is a fine grain drier with an integrated vapor condenser for a double-stage preheating of boiler feedwater. The feed coal has a particle size of 0–2 mm, while the dry lignite lies in the range of 0–1 mm. The plant shown in Fig. 20 was erected right next to the 1000-MW BoA unit of the Niederaussem power plant. The interaction of the power plant and drying plant in operation was tested here on a commercial scale for the first time. The process is shown in Fig. 12. The Niederaussem WTA-2 plant corresponds to the latest development of the proposed concept before its commercial introduction. The plant size is equivalent to that of future commercial plants. Its design is based on the specific performance data of the Frechen WTA 2 plant, scaled up by a factor of 8 [31]. The prototype commercial-scale drying plant with a capacity of 210 t/h using the WTA process corresponding to the process of Fig. 12, began operation in 2009 at the utility's Niederaussem Power Station site.

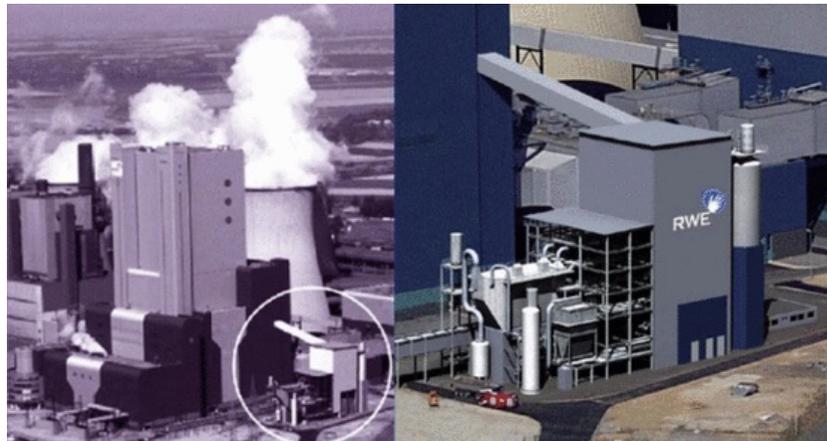


Fig. 20 Photo of the prototype WTA plant at Niederaussem [29].

Based on the WTA technology development work completed up to date, the net gain in cycle efficiency is reported to be on the order of 4 percentage points, depending on the moisture content of the raw coal and the final moisture of the dried lignite [29].

It is reported that the WTA process consumes 80% less energy compared to rotary steam tube dryer accompanied by 80% less dust emission and lower capital investment [1,19,28].

4.2.5.4 Pressurized fluidized-bed dryer operated by Vattenfall, Germany The type of pressurized fluidized bed dryer, described in detail in Section 4.2.4 is nowadays industrially applied with a processing capacity of 10 tons per hour at Schwarze Pumpe (Vattenfall, SprembergSchwarze Pumpe, Germany).

The type of pressurized fluidized bed dryer, described in detail in Section 4.2.4 has been applied to a pilot-scale test plant with a processing capacity of 10 tons per hour at Schwarze Pumpe power plant (Vattenfall, SprembergSchwarze Pumpe, Germany) Fig. 21.

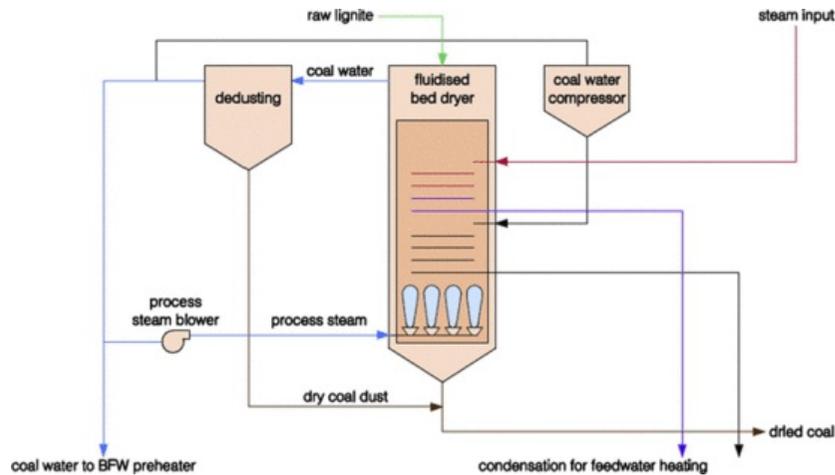


Fig. 21 Vattenfall's pressurized fluidized bed dryer concept [32].

The pilot plant operates at pressure of 1–6 bar and dries lignite to a moisture content of 8–17% from the starting 55–60%, with a corresponding LHV increase from 8.5 MJ/kg to 20.2 MJ/kg. Since the vapor which is produced by the dryer is at the operating pressure of the fluidized bed, it can be used as an input to the plant steam cycle. Results from the pilot plant indicate a potential increase of the power plant efficiency by several percentage points and a reduction of CO₂ emissions by up to 5–10% by the full-scale application of the technology. There were plans to integrate a large demonstration unit at the planned oxyfuel combustion demonstration plant in Schwarze Pumpe, however the progress has stopped since Vattenfall abandoned its research on CCS in spring 2014 [32].

4.3 Pneumatic (flash) dryers

Pneumatic dryers are widely used for drying coal and flotation concentrates. The basic element of the dryer is a vertical tube of diameter 650 to 1100 mm and length 14 to 35 m through which the hot drying medium (e.g. combustion gases or air) flows from the bottom to the top. The stream of the drying medium also carries the coal under drying and transports it pneumatically from bottom to top. The coal grains, while pneumatically transported, are heated and dried. Thus, the grain size of coal being dried determines the drying gas velocity, which in practice amounts to 10 to 40 m/s. In a commercial dryer, the disintegrator connected to the vertical drying tube at the bottom is installed, which serves to crush and dry moist lump coal from the feeding chute. Hot gas for drying enters the disintegrator and meets the moist coal. The moist coal is highly agitated and mixed with hot gas, accelerating highly the drying process. Generally, about 50% of the water to be dried is removed from the coal in the disintegrator. The most intensive drying occurs during the first 2 to 3 m of the dryer. The drying process is conditioned by the heating medium velocity in relation to the grain size of coal. This velocity increases with grain size. This is very important because coarser grains reside a longer time in the heating medium. The large contact surface of the grains with the heating medium allows rapid drying, which for finely ground coals is in the order of a few seconds. The short drying time relates only to the first drying period, i.e., to the evaporation of surface moisture. The heating medium parameters have a decisive effect on this period.

In general, the lengths of lifting tubes do not exceed 35 m. The coal feed to the lifting tube is situated 4 to 6 m above the gas feed. The dryer capacity depends on the diameter of lifting tube.

The heating medium temperature at the dryer inlet is 550 to 700 °C and 70 to 170 °C at the dryer outlet.

The initial moisture of coal is usually 10 to 15%, whilst the final moisture content is about 4 to 6%. A typical pneumatic dryer setup for coal drying is shown in Fig. 22.

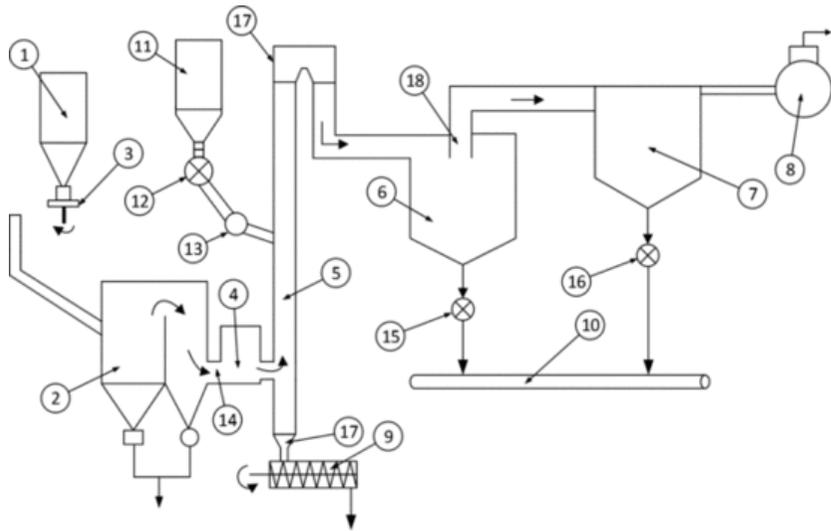


Fig. 22 Schematic of pneumatic dryer for coal drying [8].

Wet coal from the bin (11) is proportioned by feeder (12) to the lifting tube (5), where it is carried away by the combustion gas stream derived from fuel combustion in the furnace (2). Drying occurs in the tube, after which the coal is separated from combustion gases in the cyclone (6) and then in a bank of cyclones (7).

Negative pressure in the system is generated by an induced draft fan (8). The dried and separated coal is directed to the conveyor (10) through the shutter closures (15, 16), which are the lower seals of the cyclones (6, 7).

The heavier coal particles, which fall down in the lifting tube (5) are sent to the dried coal conveyor (10) through the screw (9). The system is equipped with explosion flaps (17) [8].

4.4 Mill-type dryers

Mill-type dryers are used for coal only when it is advisable to combine grinding and drying operations.

For satisfactory grinding performance, low moisture level should be achieved. The mill-type dryers are used generally in power plants using steam boilers fired by pulverized coal. Lignite milling differs fundamentally from milling bituminous and hard coals. Adequate drying while avoiding mill fires during lignite milling are the main issues for pulverizing lignite. In order to achieve this, flue gas in addition to air is used, providing the heat required which also reduces the oxygen concentration in the mills to a safe level.

Due to the soft nature of lignite, beater wheel mills are normally used to pulverize the lignite to achieve defined fineness and to lower its moisture content to a pre-desired level so that efficient combustion of the fuel can be ensured. A beater wheel mill crushes, shatters, or pulverises lignite upon impact. The fineness of pulverised coal is usually assessed on the basis of the residues on the 1 mm sieve. The typical values for pulverized lignite are well below 10% (usually between 3% and 6%), depending on quality of coal, the combustion system and boiler size [33].

4.4.1 Beater mills

For drying of lignite, beater mills are typically used. Several types of beater mills are shown in Fig. 23.

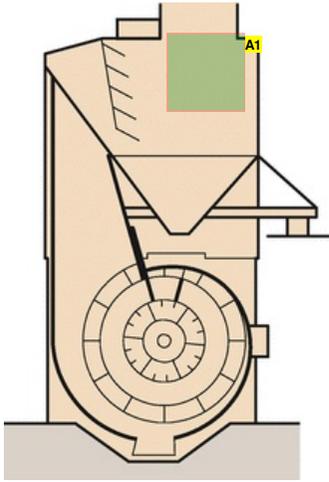


Fig. 23a Mill with classifier [33].

Annotations:

A1. It would be optimum to put figures 23a, b and c in the same line (adjusting the size if necessary)

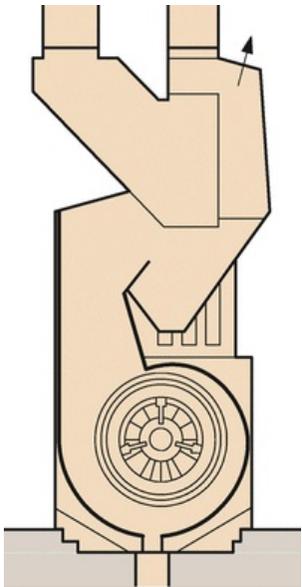


Fig. 23b Mill with vapor separator classifier [33].

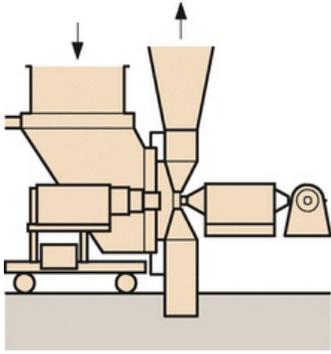


Fig. 23c Mill with staged grinding [33].

In beater mills, drying and grinding proceed without the use of a fan. The mill consists of articulated rotating beaters, while sometimes vapor separation, particle classification or staged grinding are as well included.

The beaters number 2 to 12 per row and weigh 4 to 10 kg each. The beaters are made up of manganese steel, manganese cast steel, cast iron, or carbon steel.

The beater size can be different. The beaters are subjected to abrasive wear and must be replaced periodically.

In grinding quick coke, the lifetime of the beaters is in-between 200 and 400 h. The rotational speed of the beaters is 40 to 60 m/s; the number of revolutions of the shaft is beginning from 720 and ends up to 1420 rpm. Wet coal from a bin is charged by gravity into the mill through the feeder and the hot air or combustion gases are supplied by lateral stub pipes.

The rotational motion of beaters causes bouncing of coal particles up to a certain height of the shaft (up to about 5 m), which results in intensive drying as well as grinding of coal grains owing to the aforementioned direct impact. Coarser grains are recycled for grinding; finer grains are entrained, forming a dust-air mixture supplied directly to the boiler furnace.

The power consumption for grinding is typically 15 to 20 kW h/tn for hard coal and 4 to 14 kW h/tn for lignite. The metal consumption is 60 to 160 g/tn for hard coal, 20 to 80 g/tn for lignite, and 2000 g/tn for quick coke. For coals at moisture levels of 10 to 14%, air at 300 to 400 °C may be used as the heating medium. When the moisture content is above 15 to 25%, combustion gases at temperature of 700 to 1000 °C should be used. Coal at a high moisture content (25 to 35%) should be pre-dried partially at the chute to the mill by means of hot combustion gases [8,33]. Following, several arrangements of beater mill dryers are described more thoroughly.

4.4.1.1 Beater wheel mill with classifier The lignite processing takes place in the mills without staged grinding. In this arrangement of mills, classifiers are included (Fig. 23a). No moving parts are involved in these classifiers, which operate as static separators. The use of the classifiers ensures that the residue on the 1 mm sieve does not exceed 3–5%. The fraction of <63 μm is equivalent to about 70–90%.

These devices use a deflection surface to separate the coarse dust fractions from fuel dust/gas mixture, while subsequently return the coarse grains to the mill for further grinding. These classifiers cannot meet with the increasing demands of modern large lignite-firing plants, since a high concentration in vapor stream (lack of vapor classifier) is injected within the boiler along with the fuel particles [33].

4.4.1.2 Beater wheel mill with vapor separation classifier The use of vapor separation classifiers results in an improved version of the mills discussed above (Fig. 23b). The vapor separation classifier performs two tasks. Firstly, it separates the coarse grains from the fuel dust/gas mixture and returns them to mill for further processing, and secondly separates the mixture into fuel-rich and fuel-lean vapor streams. The split streams are then fed to the combustion chamber separately. The degree of vapor separation can be set as 90% fuel dust with 70% of the initial carrier gas in the fuel-rich stream, and a 10% fuel dust with a remaining percent of 30% carrier gas in the fuel-lean stream. The fuel-rich stream is injected into the boiler through the lower main burners, while the remaining upper part burners inject the fuel-lean vapor stream. Alternatively, additional vapor burners above the main burners can be used [33].

4.4.1.3 Beater wheel mill with staged grinding For some lignites with high hardness and poor grindability, beater wheel mills with staged pulverising/grinding can be used to achieve the required fineness. The mills are designed without classifiers. There are greater fluctuations due to the lack of classifiers in the grinding of the mills and the residue on the 1 mm sieve is, on average, 6–9%.

Mills which include classifiers/vapor separation classifiers as well as staged grinding and combine the features discussed above are also available.

The mill design for the RWE's BoA 2 and 3 at Neurath Power Plant (Germany) features a three-stage prebeater and a beater wheel with a diameter of 4.3 m. The two-stage grinding process ensures the required product fineness of <6–10% residue on 1 mm sieve being maintained independent from load or lignite quality [34].

The number of mills in operation depends on the calorific value at nominal load. Apart from the number of mills in operation the mill conveying volume is adapted to the coal quality by means of mill speed control and conveying gas recirculation. The mills are arranged symmetrically around the furnace and they feed dried and finely-ground lignite directly to the corresponding burner columns.

In general, for lignite combustion there are no special demands on the fineness of the pulverized fuel in terms of primary NO_x emissions control. However, finer fuel particles tend to reduce deposition and slagging problems [33].

4.4.2 Ball mills

Fig. 24 shows a mill-type dryer, which is actually a ball mill in which the coal is broken and partly grinded by the balls. The dryer consists of a horizontal drum with cones fitted on both ends. From inside the drum is lined with the protective lining of basalt, cast iron, carbon, or manganese cast steel (14% Mn).

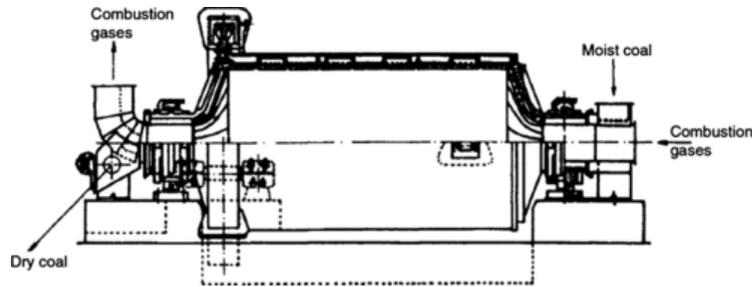


Fig. 24 Schematic of ball mill-type dryer [8].

The drum is filled with balls (diameter, 30 to 80 mm). The filling ratio of the drum is typically 14 to 30%. The filling ratio of the mill has a decisive effect on the quality and capacity of coal grinding. The balls are made of manganese or carbon steel toughened to obtain high hardness and durability. The ball consumption is 80 to 100 g/tn for soft coals, and it can reach up to 800 g/tn for hard coals. The drums are of 2 to 3 m diameter and 3 to 5 m long. The speed of rotation of the drum is in-between 16 and 30 rpm. For grinding, the electricity consumption varies over a wide range, from 7 kW h/tn for short-ton (the short ton is a unit of mass equal to 2000 lb (907.18474 kg)) lignites up to 30 kW h/tn for anthracite. Coal grinding in mill-type dryers requires additional electrical energy (5 to 10 kW h/tn), which is consumed by the fan. Coal is fed into the mill through one of the pins; the heating medium in the form of hot air or combustion gases is also supplied through the same pin. The rotary motion of the drum causes the movement of balls near the drum wall up to about three quarters of drum diameter as the falling down of balls under gravity. The falling balls break and partly grind the coal. The hot air or combustion gases supplied to the drum simultaneously heat the balls and coal as well as dry the coal.

The quantity of heating medium used in typical commercial units is 1.3 kg/kg for lignites and 2.0 kg/kg for anthracite. The heating medium temperatures depend on the moisture of the coal. The flow velocity of the hot medium in the mill is in the range of 1 to 3 m/s.

The temperature of the coal-air mixture is 70 to 80 °C for hard coal and 80 to 90 °C for lignite. The capacity of the mill-type drum dryers is 50 tn/h or more [8].

Ball mills are usually dedicated for hard coal, but the drying capacity for this type of dryer is relatively low.

4.4.3 Existing applications of mill drying in lignite-fired pulverized fuel power plants

Mill drying is the standard practice in lignite-fired pulverized fuel power plants. Most usually, drying takes place using a portion of the hot flue gas exiting the top of the furnace (~1000 °C), after being recirculated to the milling system, which consists of a number of beater wheel mills. The hot flue gases, along with the primary air and the evaporated moisture, comprise the transport or carrier gas which is used to pneumatically feed the pulverized lignite particles in the boiler.

In the standard system, all evaporated moisture is introduced in the boiler along with the lignite particles. This type of system is used in most lignite-fired power plants. A typical scheme of such a plant is presented in Fig. 25.

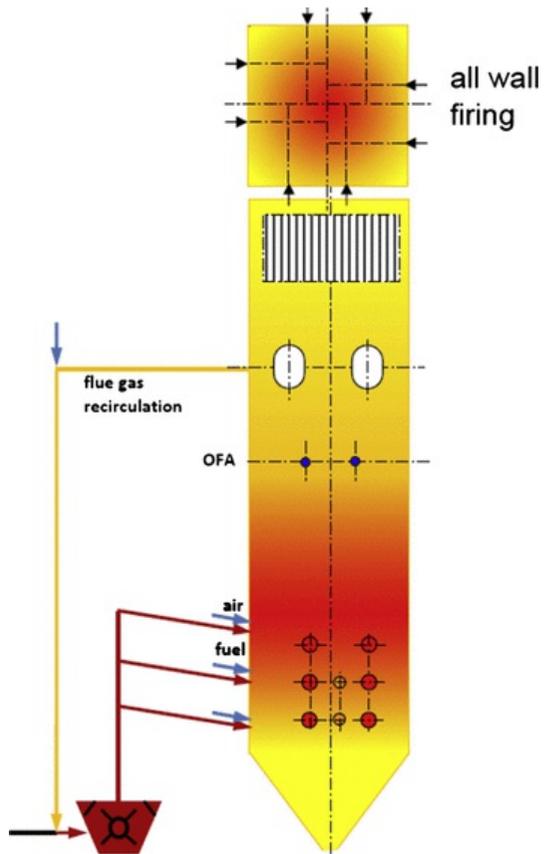


Fig. 25 Standard lignite fired boiler system with closed pulverizing mill system –[Mitsubishi Hitachi Power Systems Europe GmbH \(MHPSE\)](#).

However, for certain types of lignite with very high moisture and ash contents, it is necessary to separate part of the moisture before the fuel is introduced in the furnace.

This type of system is applied in the Megalopoli power plant in Greece (Fig. 26) and the Elbistan power plant in Turkey [35].

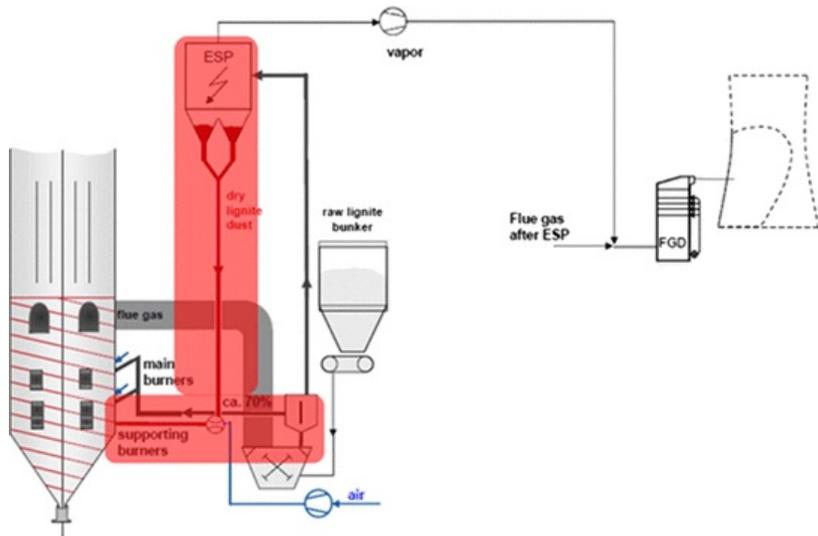


Fig. 26 Megalopolis IV – Mitsubishi Hitachi Power Systems Europe GmbH – (MHPSE) (MHPSE).

In this system, flue gas mixes with air, which is used as carrier gas. The lignite is inserted in the mill and at dryer outlet is separated (a) in a fuel-rich (large amount of coal particles) and (b) a fuel-lean stream (low amount of coal particles). The fuel-rich stream is heading toward the main burners, while the fuel-lean stream is heading to the Electrostatic Precipitators (ESP). At this point, the lean stream is separated from its ultra-fine particles, which in turn along with the carrier gas are moving toward the FGD. The rest of the particles, free of vapor, are then injected in the supporting burners (Fig. 26).

Megalopoli Unit III power plant was commissioned in 1977 and Unit IV in 1990. The rated power for each of them is 300 MW_{el}. The boilers were erected by VKW, and include six DGS DEUTSCHE BABCOCK type mills each. The capacity of each mill is about 180 t/h. (VKW and Deutsch Babcock power plant technology are within MHPSE today.)

Inside the mill, drying of the lignite takes place by hot gases (ca. 800 °C) and pulverization [36] (see Fig. 27).

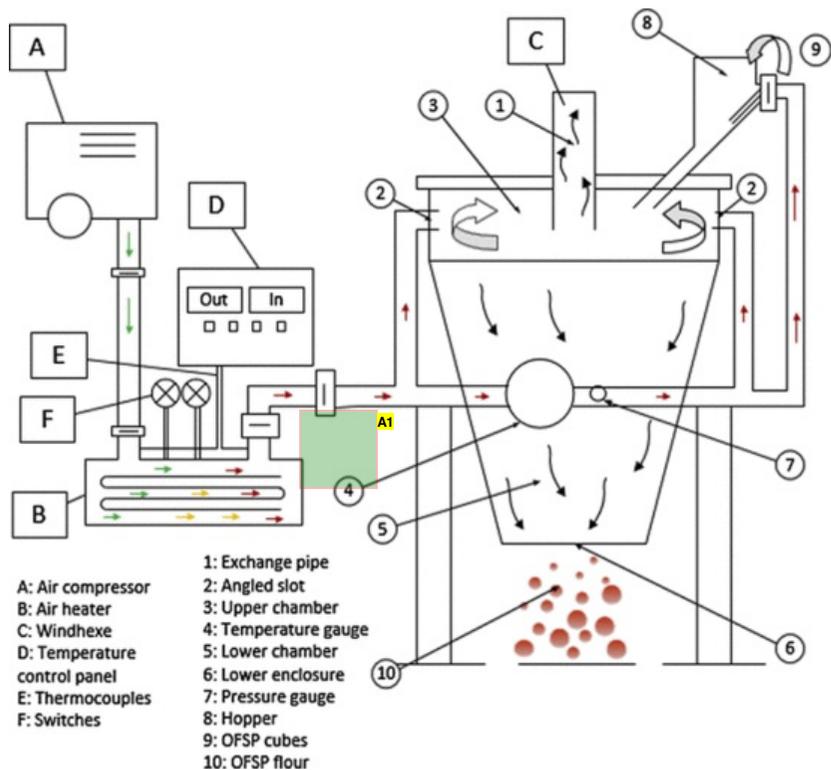


Fig. 27 Schematic Windhexe Dehydration System [23].

Annotations:
 A1. This figure (Fig. 27) is supposed to be included in paragraph 4.5.1.

4.5 New dryers operating with a high velocity air flow stream for grinding/drying

This type of drying technology uses air flowing with high pressure and velocity, which shatter coal particles into a micron-sized fine powder. Moisture contained within the coal pore structures is released in this way while the remaining amount in the fine particles can be considered as negligible. Drying and grinding can be achieved simultaneously as both the moisture content and particle size of coal decrease, thus eliminating the difficulties related to grinding of sticky low rank coals [33].

4.5.1 Windhexe technology

The Windhexe technology which was developed by a US company Vortex Dehydration Technology, LLC (VDT), is now commercially available for food processing and other industries. The Windhexe technology claims to be able to mill and dry coal simultaneously. Drying is performed in this process by evaporation and also through a moisture mechanical separation. The swirling air dehydrates the material using a combination of mechanical and evaporative energy and is therefore more efficient than any thermal drying device (see Fig. 27). The Windhexe device is described in a US patent as a cyclone with inlet tangential velocities equal to or approaching sonic velocity. Compressed pre-heated air is used to achieve high velocity. The claimed energy requirement to remove water from coal is significantly less than water evaporation. The governing mechanism achieving that, is still unknown [4].

According to VDT, over 800 tests of various materials were carried out and some of the most successful were related to power production applications, especially using coal. The Windhexe technology has been tested by International Power at the Hazelwood power plant to dry Australian lignite coal [33]. (Please remove Figure 27 from its previous place and insert it below this line.)

4.5.2 DevourX mill

DevourX mill is a vortex-based machine that is under development by DevourX Plc (Malaysia). Simultaneous grinding and drying of coal is achieved using aeroacoustics rather than a mechanical force. Aeroacoustics is the science of acoustic noise

generation caused by aerodynamic forces interacting with surfaces.

Pressure reaches around 1034 MPa pressure through a combination of air speed and sound. The particles are accelerated from 0 to 100 km/h in 1 m of travel. Tuning of the machine is critical because the sound frequencies shatter the particles, followed by comminution as the particles collide. Coal cells are 'pulled' apart and water is separated from the coal particle converting clumpy wet lignite into a fine flowable powder that is carried in the air flow into the furnace [25].

DevourX claims that the system can have high efficiency leading to reductions in processing costs and energy consumption, and requires a much smaller space for installation, while less maintenance is needed during operation resulting in significant savings in terms of capital and operational costs. It also has the advantage of liberating the colloidal moisture contained within the cells, as it breaks the cellular structure. Drying is achieved without the use of heat. However, the drying efficiency of DevourX can be enhanced by utilizing the waste heat produced in a power plant [33].

4.5.3 LamiFlo™ system

Developed by a UK-based company LF Pumping (Europe) Ltd., the LamiFlo™ system is an integrated electricity-driven process that can be used for drying, transporting and grading more than 80 different materials including anthracite, bituminous and lignite coals. The system consists of three bespoke components connected with coated steel flanged pipework: mass air generators, the Anudro™ expansion chamber and the Euroclydon™ cyclone. The typical layout of a LamiFlo™ system is shown in Fig. 28. A rotating Archimedes screw feeder feeds a moist feedstock into the Anudro™ expansion chamber where the solid is mixed with compressed air supplied by the mass air generator.

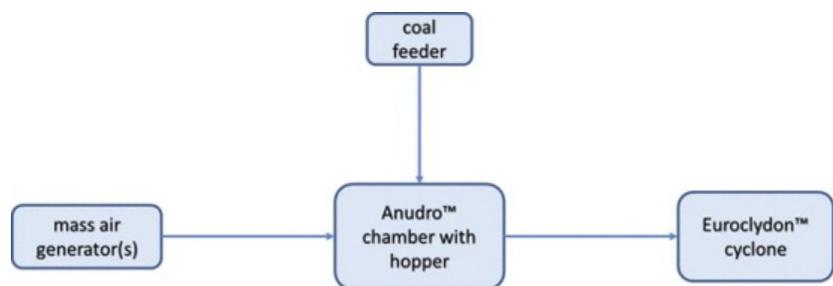


Fig. 28 LamiFlo™ process [33].

The mixture then is carried along the delivery pipe at high velocity up to 3000 m/min into a sealed cyclone with the trademark name Euroclydon™, where the aggregates are separated from the saturated air stream. During the process, the air surrounds the moist solids and removes the surface moisture through evaporation. The delivery pipe, typically 6 m long, can vary in length to suit the available space at a site. The retention time is up to 3 s for the whole process. Removal of surface moisture can reach up to 10% per pass through the system. Low pressure air is used while very high mass flow can be processed and no heat is used.

The LamiFlo™ drying system at low pressure removes free surface moisture. With an increase of pressure within the LamiFlo™ system inherent moisture can be also reduced. Additionally, the pressure can be increased which in turn increases the temperature of the air stream, resulting in inherent moisture reduction. In addition, particle reduction equipment can be incorporated to increase the surface to volume ratio of material and thereby enhance the drying efficiency. The LamiFlo™ system has design simplicity, is reliable to operate and easy to maintain. If the surface moisture content of a coal is to be reduced from 40% to 15%, the estimated operating cost is 0.58 \$/t at an output rate of 250 t/h or 0.63 \$/t at an output rate of 500 t/h based on electricity cost of 0.10 \$/kW h [33,37].

4.6 Hydrothermal dewatering (HTD)

In this process the coal is heated under pressure to reach temperatures in the range 250–310 °C. Under these conditions, the coal structure breaks down and shrinks, and the water is released as a liquid. Several hydrothermal dewatering processes are in development and are emerging in the commercial market.

4.6.1 K-Fuel®

A patented technology for low rank coal drying and upgrading, K-Fuel®, has been developed by Evergreen Energy Inc., a Colorado-based US company. The K-Fuel® process involves the heating and pressurization of low value coals, which irreversibly removes the water content thereby converting the product into a higher energy fuel. The flowsheet of the K-Fuel® process is shown in Fig. 29. A low rank coal is fed into the K-Fuel® processor. High temperature (204–260 °C) and pressure (2.7–3.4 MPa) are applied in the processor to crush the coal and under these conditions, the physical and chemical structure of the low rank coal is altered. A co-benefit of the K-Fuel® process is that it can also remove significant amounts of mercury (as much as 80%) and lower impurities present in the coal and thereby reduce overall emissions of SO_x, NO_x, CO₂ and Hg from coal-fired power plants.

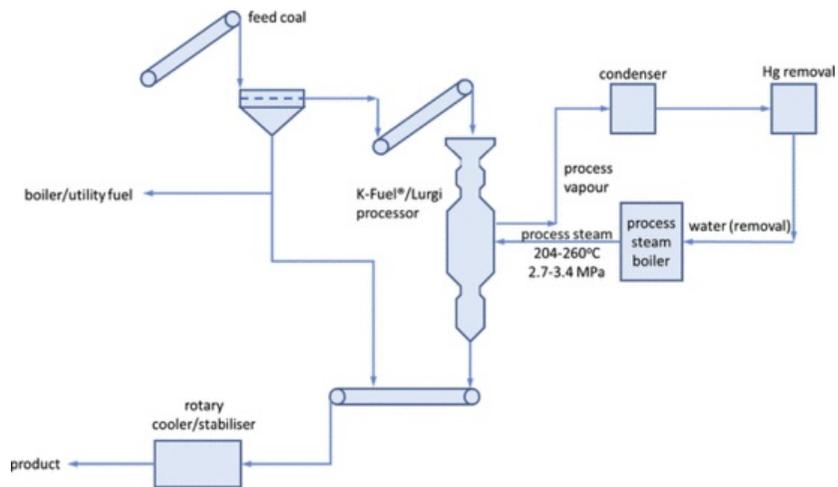


Fig. 29 Flowsheet of the K-Fuel® process [17].

A 750,000 t/y commercial K-Fuel® plant was built in Gillette, Wyoming, USA and operation, modification and test burns were carried out since December 2005. Based on the operating experiences obtained at the plant, the K-Fuel® process was redesigned in 2008 by Bechtel Power Corporation. This enhanced K-Fuel® process design offers significant process, economic, and environmental improvements and it is now the template for Evergreen's business development activities in the USA and abroad [38,39].

The K-Fuel® process is capable of reducing moisture content of low rank coals by more than 50%. In addition, the mercury content of coals can be effectively removed by the K-Fuel® process resulting in a significant reduction in Hg emissions from power plants. The K-Fuel® treated coals were test burned in several US power generation facilities and the results confirmed the improved combustion efficiency and reduced emissions. Evergreen Energy is now actively working to commercially deploy this technology globally. In 2010, Evergreen Energy reached an agreement with a Chinese company to establish a joint venture, which signed a letter of intent with a large Chinese utility and chemical producer to explore ways in which the K-Fuel® technology could be applied at an inland coal chemical facility that was under development. In 2011, Evergreen Energy signed agreements with an Australian mining company WPG Resources to set up a joint venture to develop and deploy the K-Fuel® technology throughout Australia [17,33].

4.6.2 Continuous Hydrothermal Dewatering (CHTD)

Continuous Hydrothermal Dewatering (CHTD) has been developed by an Australian company, Exergen, and it has been successfully demonstrated at pilot scale on coals from Australia and other international locations. The basis of the CHTD technology is a vertical autoclave that uses gravitational head pressure and a small amount of energy to transform the molecular structure of lignite for the removal up to 80% of its moisture content. The use of gravitational pressure and high heat recovery design results in achieving greater than 60% reduction in water content for Victorian lignite, by using a less than 2% of the coal's energy. A schematic process flow of CHTD is shown in Fig. 30.

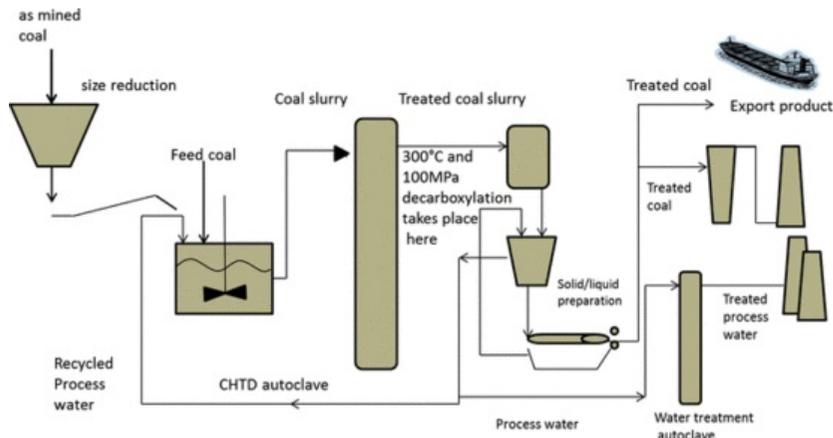


Fig. 30 CHTD process [40].

Efficient heat and pressure recovery is utilized in the process and the decarboxylation of lignite is achieved. Heat recovery greater than 90% is possible due to the efficient autoclave design. 10 MPa and 300 °C are applied upon a lignite slurry for a period of a few minutes. The molecular structure of the coal is altered in these conditions and the pores within the coal particle collapse making it unable to hold much moisture. The coal changes from being hydrophilic (water attracting) to hydrophobic (water repelling), allowing the water to be removed from the coal more easily. The chemical transformation of the coal reduces its ability to carry moisture, making it also less likely to absorb atmospheric moisture as its equilibrium moisture content is lowered. The water is extracted from the coal in a liquid state, producing a coal with higher energy density. Furthermore, the CHTD process also contributes in the coal removal from some impurities, resulting in a coal with improved combustion characteristics. For example, soluble inorganics are separated from the coal with the water. Up to 60% of sodium is removed, reducing the power station maintenance costs associated with boiler slagging. Dense components of the ash (such as quartz) may be removed from the coal slurry, leading to reduced wear on power station equipment. As an additional benefit, the water extracted from the coal can meet up to 40% of the make-up requirement for power station cooling. Exergen claims that the CHTD process is simple, continuous with a small footprint and can be readily up-scaled to a feed rate of thousands of tonnes per hour [40].

Having successfully proved the CHTD concept in its 4 t/h pilot plant, Exergen has been working on scaling up to a 50 t/h demonstration plant and after that Exergen plans to build a 4000 t/h commercial-scale facility adjacent to a new 30 Mt/y lignite mine in Latrobe Valley (LV), Australia that is under development by Exergen to upgrade LV lignite for export [33,40].

4.6.3 Hot Water Drying (HWD)

The HWD process, developed by researchers at the Energy and Environmental Research Center (EERC) of the North Dakota University, uses high temperature and high pressure to dry a coal in a water medium. In the HWD process, which is presented in Fig. 31, ground wet coal is treated at temperatures beginning from 240 °C under the corresponding saturated steam pressure for less than 10 min. CO₂, which is released during decarboxylation, leads to expansion of the micropores and expulsion of moisture from the coal. Devolatilized tars/oils, which are hydrophobic, remain on the coal surface in the pressurized aqueous environment. This presumably produces a uniform coating that seals the micropores, preventing moisture reabsorption, which is a major advantage of the process. Because the coating retains most of the low-rank coal's volatile matter, high energy recovery and excellent combustion performance can be obtained. The developers claim that alkali cations, a major source of boiler fouling, associated with the carboxyl groups, are released in the aqueous phase in the process and are removed during the final mechanical dewatering step.

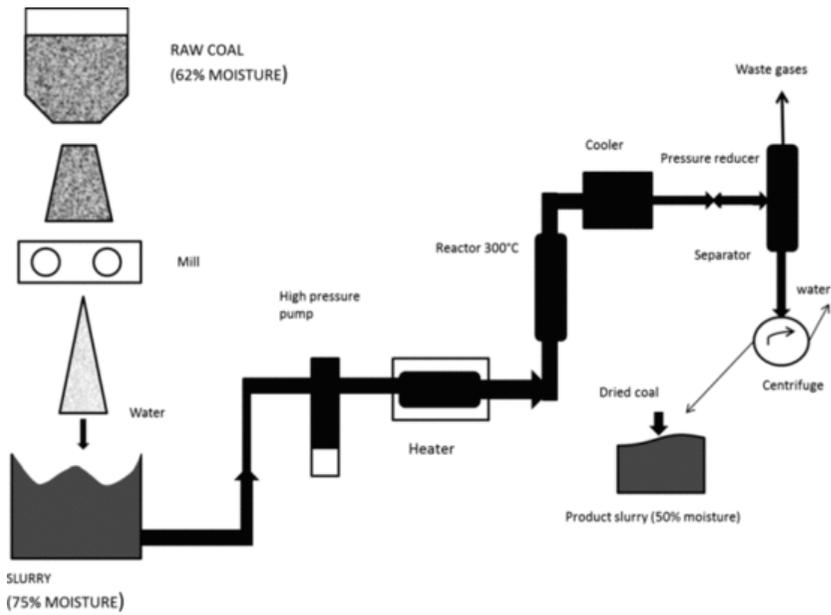


Fig. 31 Hot Water Drying concept [41].

The technical feasibility of HWD has been demonstrated in a 7.5 t/d pilot plant at the EERC with low rank coals from around the world. Costs of dewatering will vary with coal grade and location. It appears that a successful commercial low rank coal drying processes is linked to the immediate dried low rank coal utilization and not storage. When stored, the products from most drying systems can have stability problems, which result in excessive fine dust and spontaneous heating [28,33].

4.6.4 The Catalytic Hydrothermal Reactor Technology (Cat-HTR)

An Australian company Ignite Energy Resources Pty Ltd (IER), is developing the catalytic hydrothermal reactor technology which is designed to convert low value lignite and modern biomass into non-conventional crude oil and various upgraded coal products. The Cat-HTR technology uses water at or near supercritical temperatures and pressures, together with proprietary catalyst systems to selectively de-polymerize and de-oxygenate lignite and convert it into various higher density energy fuels and high grade clean coal products. A diagram of Cat-HTR process is shown in Fig. 32. The company has not disclosed much factual information; therefore details of the technology remain uncertain.

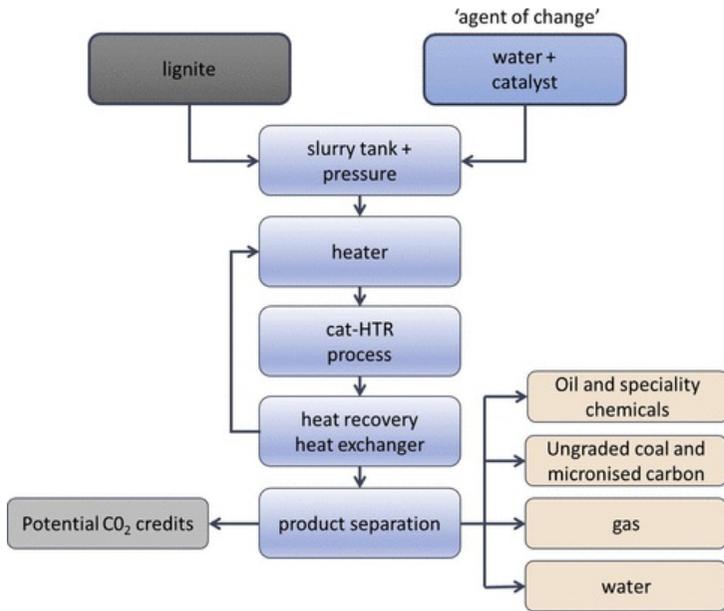


Fig. 32 Cat-HTR process diagram [42].

A pilot scale Cat-HTR plant with a capacity of 4000 t/y has been in operation since mid-2008. Based on the pilot test results, IER claims that Cat-HTR has the capability to convert 1.3 t of as-mined lignite (assuming 50% moisture) into up to one barrel of non-conventional crude oil and up to 0.34 t of high grade micronised coal.

In 2010, IER signed a hosting agreement with TRUenergy, a Victorian-based utility company and subsidiary of China Light & Power, to build a commercial Cat-HTR demonstration plant at TRUenergy's site at Yallourn and to supply upgraded fuel products to TRUenergy's existing lignite fired power station [33,42].

4.7 Mechanical thermal expression (MTE)

The MTE technology was developed in the mid 1990s and it combines the use of pressure and temperature to effectively remove the moisture content of lignite. Significantly lower pressures (<12 MPa) and temperatures (<200 °C) are required. The elevated temperature softens the coal in order to reduce the mechanical pressure required for dewatering. In the MTE process, raw lignite is first treated in saturated conditions heated at a level of 150–200 °C and at a saturation pressure (0.5 to 2 MPa) in order to prevent evaporation. A mechanical pressure of around 6 MPa is then applied to squeeze the water out of the lignite. A schematic of MTE process design is shown in Fig. 33.

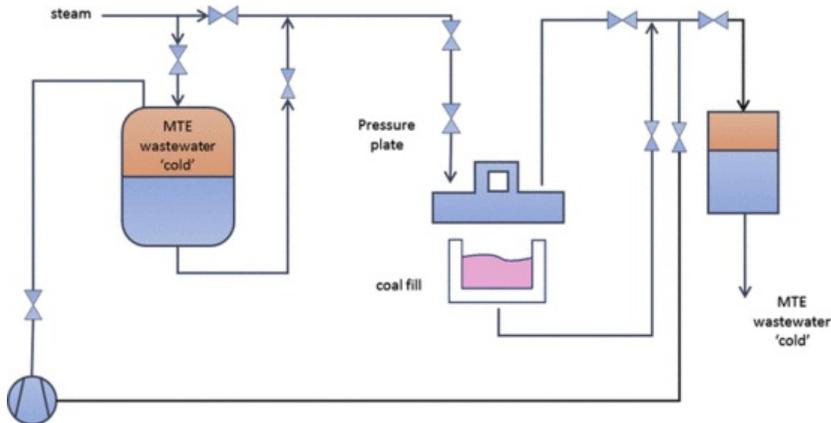


Fig. 33 MTE process design [4].

There has been active development of this technology in both Germany and Australia. In Germany, RWE in collaboration with other companies has undertaken the development of the MTE technology. Successful trials at laboratory- and pilot-scale using batch process have been performed. (We would like to include the following citations at this point, if possible (adjust numbering of references and in-text citations properly): [1 C. Bergins, Kinetics and mechanism during mechanical/thermal dewatering of lignite, *Fuel*, 82 (2003) 355-364. [1 C. Bergins, Mechanical/thermal dewatering of lignite. Part 2: A rheological model for consolidation and creep process, *Fuel*, 83 (2004) 267-276. [1 C. Vogt, T. Wild, C. Bergins, K. Strauß, J. Hulston, A.L. Chaffee, Mechanical/thermal dewatering of lignite. Part 4: Physico-chemical properties and pore structure during an acid treatment within the MTE process, *Fuel*, 93 (2012) 433-442. [1 C. Bergins, J. Hulston, K. Strauß, A.L. Chaffee, Mechanical/thermal dewatering of lignite. Part 3: Physical properties and pore structure of MTE product coals, *Fuel*, 86 (2007) 3-16.]) A further development step toward commercial implementation of the MTE process involved the conversion of the discontinuous pilot press to quasi-continuous fully automatic operations, with a throughput of approximately 1.6 t/h of dried lignite. While testing the MTE technology, various aspects of this technology have been tested including (a) the feeding of the MTE press with coal under quasi-continuous conditions, (b) the treatment of the raw lignite, and (c) the subsequent dry lignite treatment. The cost-effectiveness and energy efficiency of dewatering lignite using the MTE process has become evident through the various project phases. After completion of this development, a 25 t/h MTE demonstration plant was constructed at RWE's Niederaussem power plant and was commissioned at the end of 2001. At the beginning of 2002 RWE took over the demonstration plant but work was subsequently discontinued. RWE has chosen the WTA process for further development (Please also insert this citation if possible and adjust properly the numbering of in-text citations and references. C. Bergins, K. Strauss, Advanced processes for low rank coal drying and dewatering in high efficient power plants, *International Journal of Global Energy Issues*, 28 (2007) 241-263. [30,39].)

In Australia, the Cooperative Research Centre for Clean Power from Lignite (CRC Lignite) worked to develop the MTE process suitable for Victorian lignites. The development plan involved the construction of a 20 t/h pilot plant in 2005 to 2006. The CRC's MTE process used a different configuration involving some features distinctly different from those of the German process. In the CRC's process, the coal was fed as a slurry, which was preheated using energy extracted from the hot product coal and hot expressed water. The preheated coal slurry was then heated under pressure in a heating chamber to the required process temperature by saturated steam. The hot slurry from the heating chamber directly entered the compression cylinder under gravity. Dewatering occurred through both axial and circumferential filter surfaces. The circumferential filter surface, a feature of the CRC's process, appeared to be more effective in dewatering than the axial surfaces. This improvement meant that the dewatering in the CRC's process was not as dependent on particle size distribution as was in the German process.

The CRC Lignite reported on the successful trial of the CRC's MTE process for drying lignite and concluded that this technology could provide a low cost, energy efficient process for partial drying (down to around 30% moisture) at the large scale required for power plant feed. The CRC Lignite found the MTE less expensive than HTD or WTA process and capable of removing more than 70% of the water from the lignite from Victoria and South Australia, resulting in huge CO₂ savings when the dry coal is burnt in a power station [39,4].

The liquid water removed from coal by HTD and MET processes carries with it both organic and inorganic matter. The large volumes of acidic, salty and organic-rich product water present a major concern in terms of wastewater treatment difficulties and costs for disposal or reuse of the product waters. The overall viability of the processes will depend on the availability of a simple and energy-efficient water remediation strategy. Investigations into ways of treating the wastewater from HTD and MET processes were carried out by several researchers [43,44] and more work in this area is needed [33].

4.8 Emerging techniques

4.8.1 Screw conveyor dryer (SCD)

The screw conveyor dryer (Fig. 34) consists of a jacketed conveyor in which material is simultaneously heated and dried as it is conveyed [45]. The heating medium is usually hot water, steam, or a high-temperature heat transfer medium such as pot oil, fused salt, or Dowtherm heat transfer fluid. The flights and shaft may be hollow, through which the heating medium flows to provide greater heat transfer area with minimum space requirements. Screw conveyors, due to their versatility in gentle handling, can be used for drying a large variety of solid particles ranging from free-flowing to relatively less free-flowing ones and from fine powders to lumpy, sticky, and fibrous materials [45].

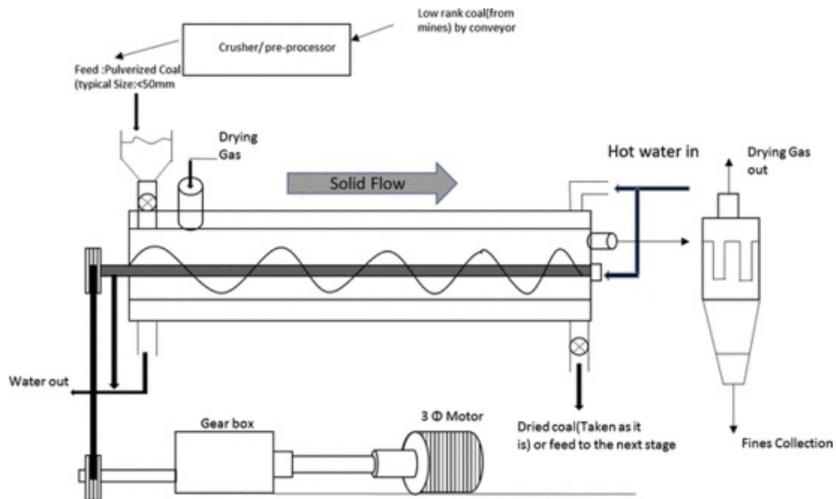


Fig. 34 Screw conveyor dryer for LRC drying [1].

Among advantages of the screw conveyor (SC) dryer are (a) their applicability for indirect heating, (b) their small size compared to other systems (c) their high thermal efficiency, etc.

This type of dryer provides a very high heat transfer area-to-volume ratio compared to other dryers.

The possibility of a fire hazard reduces when screw conveyor dryer with indirect heating is used. With the use of superheated steam, nitrogen, or vacuum for moisture, the system can render the drying process 100% safe.

There is also the option of setting up the screw conveyor dryer in a multistage drying system. A higher performance can be achieved when the set-up is properly optimized through either a two-stage screw conveyor drying system or a SC dryer followed by some other dryer type such as vibrated bed dryer [1].

4.8.2 Microwave drying

Microwave drying (MW) is well known for its advantages, such as volumetric heating, faster drying rates, and possibility of using intermittent exposure of wet solids to microwaves. Recently, microwave drying has been applied for drying of low-rank coal. The CoalTek process, developed by CoalTek Inc. and the Drycol Process, developed by DBAGlobal (Milton, Queensland, Australia) is based on the use of microwave for coal quality improvement.

4.8.2.1 CoalTek process Developed and commercialized by a Georgia-based company, CoalTek Inc., this is a microwave-based process which removes moisture, ash, sulfur, and mercury from low rank coals and transforms them into cleaner burning fuels with an energy content increased by as much as 50%. This low temperature process is applicable to both thermal and metallurgical coal, and is capable of removing moisture while preserving the key metallurgical properties of coking coals. Typically, 40–50% moisture removal is achievable. It is claimed that all CoalTek by-products are captured, filtered and separated, meeting environmental standards. CoalTek has not revealed its technology so details of the process are still unknown. CoalTek opened its first commercial processing facility in Calvert City, Kentucky, USA in 2006 and the plant's initial capacity of 120 kt/y will be expanded in the future. There are also plans to build additional CoalTek plants in China and USA [33].

4.8.2.2 Drycol process Several other coal drying technologies are experiencing an ongoing development. One coal drying process being developed by DBAGlobal Australia Pty, Ltd., with the trade name Drycol process uses the controlled application of microwave radiation, to dry coal (Fig. 35). Coal feed stock is first separated into fine grade coal and one or more larger grades. The fine coal is loaded onto a conveyor and conveyed continuously through a microwave-energized heating chamber for drying. The fine grade coal is dried sufficiently so that when it is recombined with the larger grade coals, the moisture content of the aggregate coal is within a target moisture content range.

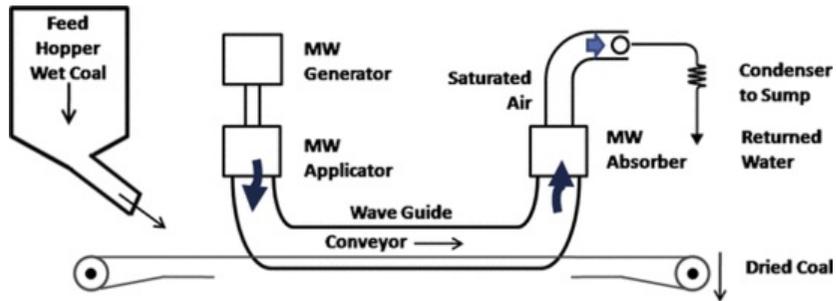
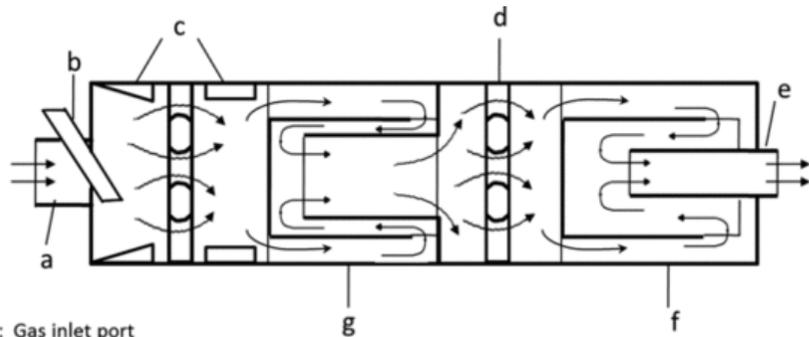


Fig. 35 DRYCOL process [42].

A 15 t/h plant has been operated to commercially dry coal from a 28% moisture content to a final of 12% [46]. It was reported that MW drying was much faster than the conventional coal drying. Further, it results in reduction of impurities such as sulfur, potassium, and phosphorous. However, the presence of impurities can result in hot spots, and high dielectric losses for coal can also result in fire hazards during drying. Further, it is difficult to comment on the cost involved for handling a large amount of coal. Intermittent MW drying is a possible option to remove moisture efficiently during the final stages of coal drying [1].

4.8.3 Impinging stream drying

Impinging stream dryers – ISDs (Fig. 36) are novel alternatives to flash dryers for particulate materials with very high drying loads. Nevertheless, studies on ISD are still partial or limited to very few applications. In these type of dryers the intensive collision of opposed streams creates a zone that offers very high heat, mass and momentum transfer rates [47]. Drying air and wet solids enter concurrently from the gas inlet port and the material inlet port, respectively. Vanes in the upstream region of the rotating vessel facilitate the mixing of gas and particles in preparation for pneumatic transport of particles through the vessel. As the gas–particle mixture progresses downstream, it encounters two drying sections, each comprising of an upstream turbulator and a downstream serpentine flow section. Mixing of the gas–particle mixture is intensified as the gas–particle mixture flows through the turbulator, increasing the heat transfer rate. The serpentine flow section increases particle residence time while keeping the dryer relatively compact. A schematic diagram for this drying system is illustrated in Fig. 36. Hence, rapid removal of surface moisture is possible. Other advantages of impinging dryers are their smaller size and high robustness due to the absence of any moving parts. However, the design of such a system is very important; in particular, the feeding arrangement and the design of the impinging pipes affect the value of volumetric heat transfer coefficient and in turn the water evaporation rate [14]. Recently, Choicharoen et al. [47] carried out performance evaluation of an impinging dryer with okara as an ideal material and concluded that ISD gives a very high volumetric heat transfer coefficient and the performance depends on the aforementioned parameters. All these advantages of ISD allow one to consider it as a possible option for drying LRC provided that it can handle high throughputs, which can be a main limitation. Another limitation could be the scale of velocities used [1].



- a: Gas inlet port
- b: Material inlet port
- c: Vanes
- d: Turbulator
- e: Product and gas outlet
- f: Second serpentine flow section
- g: First serpentine flow section

Fig. 36 Impinging steam dryer [14].

4.8.4 Novel fluidized bed dryer

Fluidized bed dryers have been traditionally used for coal drying using various heating mediums such as air, flue gases, and superheated steam [8,48]. There have been numerous attempts to improve the performance of FBDs for coal, by applying either an indirect heating approach to the solid bed and/or using high pressure steam as a heating medium (in case of superheated steam drying). However, the size and shape of the particles to be handled is a major parameter which decides the quality of fluidization and ultimately determines the performance of fluidized beds. Fluidization is important during coal drying because the particles can be highly irregular in shape, which results in channeling and slugging of the bed. The quality of fluidization can be improved either by mechanical vibrations, agitation, or a pulsating flow of fluidizing gas [8]. Vibrated beds have been widely used for different applications and recently agitated bed dryers have emerged as a better option because they can provide better performance due to indirect heating of the bed. In the case of pulsating fluidized beds, the fluidization velocity pulsates with time in the form of regular or irregular patterns [49]. Many studies have shown that pulsed fluidization can improve the fluidization quality because it eliminates the problem of channeling and slugging.

Li et al. [49] reported that pulsating fluidized beds result in reduced bubble size and better gas–particle contact. Hence, some difficult-to-dry materials can be easily handled. Li et al. [49] have also carried out a theoretical study of the hydrodynamic behavior of these dryers using a two-fluid model for three pulsating frequencies of 0.4, 4, and 40 Hz.

It was concluded that 40 Hz resulted in normal fluidization. In addition, the bed expansion was greater in pulsating FBDs with low bed fluctuation rates, which means improved fluidization quality. Therefore, such types of FBDs can replace traditional FBDs for coal applications and can be considered as a better option for the development of more efficient drying systems [1].

4.8.5 Superheated steam dryer

Superheated steam dryers (Fig. 37) use superheated steam as a drying medium, which is fed directly into the dryer and not through tubes or other heat exchangers as in indirect-fired dryers. The steam evaporates moisture from the material without condensing, as it remains above the saturation point and transfers only sensible heat (see Fig. 38).

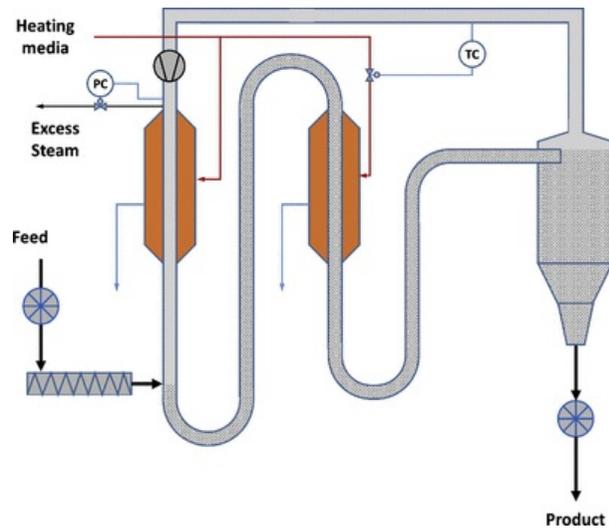


Fig. 37 Superheated steam dryer with pre-heater and secondary superheater [7].

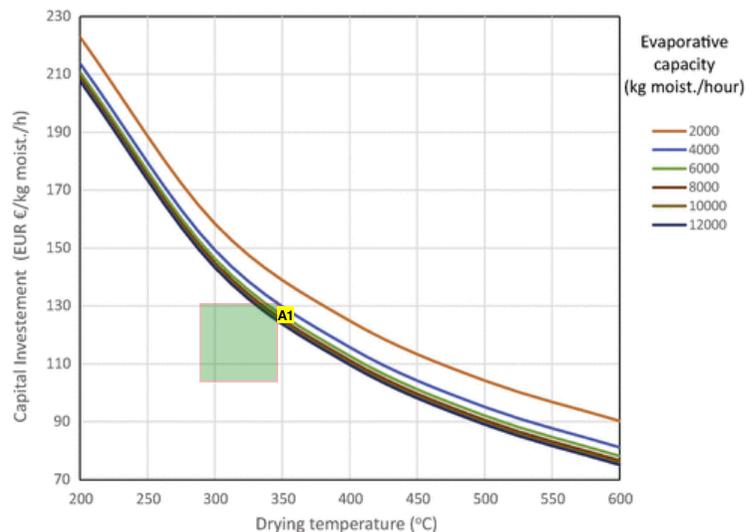


Fig. 38 Capital investment of dryers as a function of drying temperature with evaporation capacity as a parameter.

Annotations:

A1. Please remove this figure and transfer it below in paragraph 5.1, where indicated

A larger quantity of steam at a lower temperature and pressure exits the dryer than the corresponding values that enters it. A closed-loop operation of the superheated steam dryer can be adopted, where the low-pressure steam from the dryer is recirculated after being reheated. The heat of excess steam evaporated can be recovered to a large extent and used in other processes.

Although the concept of drying using superheated steam was conceived more than a century ago, serious interest in superheated steam drying (SSD) emerged only recently. Many benefits are associated with SSD which include, (a) reduced risk of spontaneous combustion [50,51], (b) increased drying rates, (c) better energy efficiency and finally improved grindability [17,52]. More benefits and limitations of SSD are summarized in Table 3. [\(Please remove Table 3 from its previous place and insert it in the following line\)](#)

Shaffer et al. [54] described a method for drying lignite (or other similar carbonaceous materials) using superheated steam and a centrifuge. One of the example processes given in the patent begins by first heating ground coal (15 °C, moisture content (MC) 34%) in hot water (95 °C), and placing the resultant coal (65 °C, MC 40%) in a centrifuge to remove the surface moisture. The mechanically dewatered coal (MC 34%) then proceeds into a sealed processor where it is heated by superheated steam to 245 °C in a pressurized environment. More steam is then injected into the vessel to increase the temperature to 260 °C at a pressure of 34 atm, resulting in the loss of more moisture. After cooling water is sprayed on the coal batch, it is finally taken to the centrifuge again to remove any remaining surface moisture. In general, the whole process was reported to reduce the aggregate moisture content of coal from 34% to 8% with a batch processing capacity of 34,000 kg.

Fushimi and co-workers [55] described a promising new technique to reduce energy usage in drying processes through self-heat recuperation (SHR) whereby exergy is recuperated through compression, heat exchange, and heat pairing for sensible and latent heat. This technology involves the superheating of water evolved from the heated wet sample, after which the superheated steam is compressed to further increase its temperature. Sensible heat from the superheated steam is then utilized to raise the temperature of moisture in the wet feed and evolved water. Compared to hot air drying with conventional heat recovery process, the SHR-FBD process offers considerable overall cost savings in spite of having a greater requirement for electrical energy. Results concluded that drying based self-heat recuperation uses 13.7% less energy compared to conventional drying techniques with heat recovery.

SSD requires less energy than hot gas dryer because there is no need to supply coal moisture with latent heat of vaporization. Because fire hazards are associated with spontaneous combustion of coal, such dangers are completely eliminated in the case of superheated steam drying, whilst the targeted moisture content can also be achieved in a very short time by using higher steam temperature.

In principle, any convection dryer can be converted into a SSD. Thus, superheated steam can be used in conjunction with flash dryers, fluidized bed dryers, spray dryers, impinging jets and stream dryers, and rotary dryers [14].

5 Dryer comparison

It is generally accepted that there is no universal dryer type suitable for every case but the choice of the dryer depends on the particular conditions and the intended application. Various drying methods have been discussed so far which

are essentially used for coal drying. A major objective for LRC upgrade and optimization is to minimize the overall energy consumption in LRC drying, while making the drying process cost effective. It should be noted that each drying method can still be further improved from a technical and economic point of view. The main characteristics and limitations which pose possibilities for various commercial drying improvements are presented in Table 4 [14].

Table 4 Advantages and limitations of dryers [1].

Dryer type	Advantages	Limitations
Rotary dryer	Drying along with disintegration; internal heating with coils; flue gas with low O ₂ as drying medium to eliminate fire hazard	High maintenance
Rotary tube dryers	Indirect heating; no fire hazard; good efficiency	Capital intensive
Fluidized bed dryer	Intensive drying due to good mixing	High pressure drop; attrition
Spouted bed dryer	Very good heat and mass transfer rates	Scale-up issues; limited particle size
Pneumatic dryers	Simple construction	Attrition
Screw conveyor dryer	Indirect heating can be applied; Reduced fire hazard when indirect drying is applied; small size; high efficiency due to high heat transfer area-to-volume ratio	Subject to wear due to moving parts, high maintenance cost
Microwave drying	Volumetric heating; faster drying rates; reduction of impurities	Hot spots resulting from the presence of impurities; fire hazards due to high dielectric losses; high cost involved for handling large amounts
Impinging stream dryers	Direct heating; good heat and mass transfer; small size; no moving parts	Limitation in handling high throughputs and the scale of velocities used
Various types using superheated steam	High thermal efficiency; no danger of fire or explosion; energy efficient	Suited for high capacity continuous operation; energy in exhaust should be usable elsewhere in plant

5.1 Technical characteristics

Conventional evaporative dryers (rotary, fluidized bed, flash etc.) use air or combustion gases as the drying media, with temperatures of about 700–900 °C at the dryer inlet and 60–120 °C at the outlet [28]. For coal drying, such high temperatures may lead to spontaneous ignition and loss of volatiles. As a result the use of such high temperature media is typically avoided unless the coal is used directly in a combustion process (e.g. mill drying in pulverized fuel boilers). Hence, in current practice indirectly heated rotary dryers have been a more common choice. Rotary dryers were also reported to have higher energy efficiency and lower energy consumption per unit mass of coal dried compared to other conventional dryers [1,28,48].

On the other hand, although the use of superheated steam reduces the odds for spontaneous self-ignition because of the absence of oxygen, the cost involved in such processes is high due to the complexity in design and operation of such dryers for very high throughput. At lower production rates steam drying is thought to be an expensive operation [1].

Typical values of the technical characteristics and specifications for the main types of dryers used for lignite, which play a major role at the dryer performance are (a) the specific energy consumption, (b) the dryer efficiency, (c) the operating range (drying temperature and moisture) and (d) the residence times achieved. Typical values are presented in Table 5.

Table 5 Typical range of design and performance specifications for various types of dryers.

	Rotary	Pneumatic (flash)	Fluidized bed/spouted
Specific consumption (MJ/kg-evaporation)	3.0–4.0 (It would be preferable to center the content of the cells containing numeric values in this and in the other tables, as they were in the submitted file.)	2.7–2.8	2.2 ^a –3.5
Drying efficiency (%)	50–75	75–95 ^a	70–90 ^a
Evaporation (t/h)	3–23	4.8–17	2–41
Drying medium temperature (°C)	200–600	150–280	160–280
Capacity (t/h)	3–45	4.4–16	1.5–25
Feed moisture (%)	45–65	45–65	45–65

Moist. discharge (%)	10–45	10–45	10–45
Typical residence time within dryer	5–10 min	0–10 s	5–10 min

^a With heat recovery.

Osman et al. [14] have performed a comparison of the capital and energy cost between conventional and superheated steam dryers, presented in the following table, Table 6.

Table 6 Economic comparison of conventional and SSD dryers.

	Conventional	Superheated steam dryer (SSD)
Capacity (kg/h)	15,000	15,000
Air/steam flow (kg/h)	335,000	241,000
Fan volume (m ³ /h)	415,000	290,000
Motor (kW)	900	630
Heat demand (MW)	15.5	9
Heat recovery (MW)	0	5.5
Capital cost (Euro)	1,350,000	2,850,000
Energy cost (Euro)		
w/o heat recovery	2,900,000	1,400,000
w/ heat recovery	–	560,000

The capital investment according to Mujumdar [8] can be calculated roughly from the following equation:

$$C = (M\&S\ Index) \left[30 + 36.74 \frac{W}{(17.77 + T)} \right] \tag{1}$$

where *C* is the installed cost (US\$ in the year of the M&S Index) covering the dryer and auxiliaries, including foundations and erection, but no secondary dust collectors or building; *M&S Index* is the Marshall and Swift All-Industry Equipment Cost Index; *W* is the evaporation capacity (kg moisture/h) and *T* is the inlet-gas temperature (°C) (see Table 7).

Table 7 (Please remove this table and transfer it below where indicated.) Capital cost and operating consumptions for the major types of dryers.

	Rotary dryer	Pneumatic (flash) dryer	Fluidized bed/spouted bed dryer	Superheated steam dryer
CAPEX	120–290 €/dry kg/h	260–680 €/dry kg/h	160–285 €/dry kg/h	235–315 €/kg water/h
Operating electrical. consumption	8–14 kW h/dry t	16–38 kW h/dry t	15–20 kW h/dry t	20–45 kW h/dry t

Considering (M&S index)₂₀₁₁ = 1536, the following diagram can be drawn, presenting the capital investment as a function of evaporation capacity and with the drying temperature as a parameter ranging from *T* = 200–600 °C (see Fig. 38). (Please transfer and include Figure 38 below this line.)

Bruce and Sinclair [56] have investigated the capital cost and operating consumptions for the major types of dryers (see Table 7). (Please insert Table 7 below this line)

Regarding the maintenance cost, this is assumed to be around 5% of the capital investment for simple systems and closer to 10% for complex systems with significant number of rotating or vibrating parts [8].

Recently, a technoeconomic comparison has also been performed between predrying technologies on retrofit cases of lignite-fired power plants as well as on new build power plants [32].

Comparing the fluidized bed drying concepts the pressurized variant operated by Vattenfall (PFBD) could be 7–10% cheaper potentially as compared to the atmospheric variant in the retrofitting case of an existing power plant. From the pilot plant results, the power plant efficiency has been proved to potentially increase by several percentage points and the CO₂ emissions to decrease by up to 5–10% [32].

In the case of the WTA concept, a total investment of €50 million was required for the erection and operation of the prototype WTA dryer at Niederaussem as reported in 2009 [32]. Significant reduction in the dryer size and the investment costs of the WTA fine grain drying concept have appeared in comparison with the coarse grain drying concept). The specific investment costs of the entire WTA pre-drying system have been reduced by 60% to 70 €/kW, compared to those for WTA coarse grain drying, due to size reduction of the dryer, ESP and fluidization blower, vapor recompressor and other supplementary equipment optimization (Fig. 39) [32].

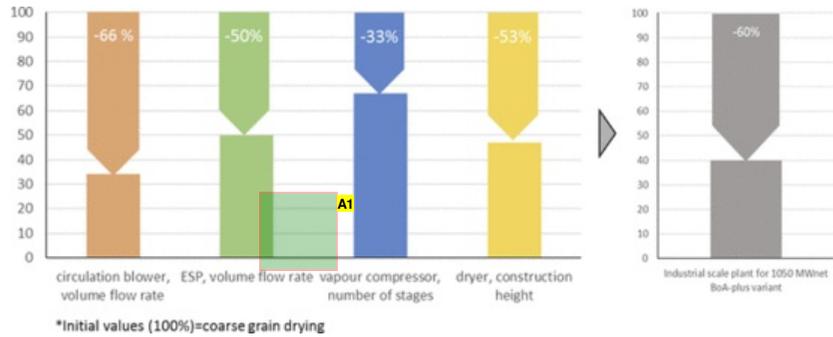


Fig. 39 Significant reduction in the dryer size and investment costs of the WTA fine grain drying concept [32].

Annotations:
 A1. We can provide a better quality picture for this figure. It is attached as Figure39.png

When comparing the WTA and PFBD fluidized bed drying concepts, the investment costs of the PFBD concept which uses coarse grains were found higher than those of the WTA fine grain concept. In particular they were 3.2 times higher than those for the Frechen WTA-2 plant and 1.9 times higher than those for the Niederaussem WTA-2 plant [32].

Regarding the DryFining™ concept, Great River Energy disclosed in a recent report that the investment costs of the first commercial installation amounted to 240 \$/kW_{net}, with a potential reduction down to 80–100 \$/kW net for future retrofit installations [57]. Other site-specific costs and owners' costs need to be added to calculate the total capital costs for future retrofit projects. The cost of O&M for the dryers at Coal Creek Station were estimated at 0.35 \$ per wet tonne of lignite processed or 350,000 \$/y for an 113 t/h dryer. But other expenses due to fuel, auxiliary power consumption and other O&M costs were reduced through the use of pre-drying at both units by more than \$20 million annually [32].

A case study of the efficiency improvement of power plants using the DryFining™ concept, along with post-combustion CO₂ capture has been performed, with the Loy Yang A Power Station as a reference. The results of the investigation are presented in Table 8.

Table 8 Summary of the thermodynamic modelling results and comparison of the pre-drying and post-combustion CO₂ capture cases [32].

System configuration	Base	Case 1	Case 2	Case 3	Case 4	Case 5
Base plant	X	X	X	X	X	X
PCC plant		X	X	X	X	X
Coal drying			X	X		X
Plant optimization				X	X	X
Air cooled						X
Power generation summary	kW	kW	kW	kW	kW	kW
Main steam turbine generation	568,960	530,810	527,700	528,840	549,390	528,840

Expander generation				5320	3130	5320
Total gross power generation	568,960	530,810	527,700	534,160	562,620	534,160
Net power generation	521,380	446,460	445,840			
Net power output reduction	—	74,920	75,540	69,000	53,110	68,900
Gross plant efficiency, %	31.46	29.35	30.74	31.12	30.53	31.12
Net plant efficiency, %	28.82	24.68	25.97	26.36	25.88	26.36
CO ₂ capture summary	Base	Case 1	Case 2	Case 3	Case 4	Case 5
CO ₂ captured, t/d	—	5000	5000	5000	5000	5000
CO ₂ produced, t/d	14,831	14,831	14,081	14,081	14,854	14,081
CO ₂ emitted, t/d	14,831	9831	9081	9081	9854	9081
Gross specific emissions, kg/kW h	1.086	0.772	0.717	0.708	0.743	0.708
Net specific emission, kg/kW h	1.185	0.917	0.849	0.836	0.877	0.836
Electricity output penalty, kW h/t CO ₂	—	419.89	274.70	233.60	284.36	233.60

Note: The actual PCC plant auxiliary load and hence the total plant auxiliary load for Cases 4 and 5 will be either equal or less than the figures shown. For the purpose of this study a detailed assessment of the PCC auxiliary load has not been carried out.

An increase of the plant efficiency by 1.3 percentage points to 25.97% through pre-drying can be seen from the comparison between Case 1 and Case 2. However, this efficiency gain came with reduced power output of 0.6 MWe. The coal drying plant also reduced the CO₂ emissions significantly by 0.75 t/d or 0.068 kg/kW h net and the penalty of reduced power output due to CO₂ capture, from 419.89 kW h/t CO₂ in Case 1 to 274 kW h/t CO₂ in Case 2 [32] (see Table 9).

Table 9 (Please move this table below, where indicated) Evaluation of dryer types.

	CAPEX (1 for highest, 5 for lowest cost)	OPEX (1 for highest, 5 for lowest cost)	Capacity range (1 for shortest, 5 for widest range)	Final moisture content (1 for highest, 5 for lowest)	Heat recovery opportunity (1 for highest, 5 for lowest opportunity)	Fire hazard avoidance (1 for lowest, 5 for greatest avoidance)
<i>Category 1: Convective thermal dryers</i>						
1. Rotary-tube dryers						
(a) Direct	5	5	5	4	5	4
(b) Indirect	4	5	5	4	5	5
2. Fluidized-bed dryers (FBD)	4	3	4	4	5	5
3. Pneumatic (flash) dryers	2	4	3	5	5	4 ^a –5 ^a
4. Mill type dryers	N/A ^b	5	5	N/A	N/A	4
<i>Category 2: New dryers operating with a high velocity air flow stream for grinding/drying</i>						
1. Windhexe technology	N/A	N/A	N/A	N/A	N/A	N/A
2. DevourX mill	N/A	N/A	N/A	N/A	N/A	N/A
3. LamiFlo™ system	N/A	5	5	N/A	N/A	5

<i>Category 3: Hydrothermal dewatering (HTD)</i>						
1. K-Fuel®	N/A	N/A	N/A	N/A	N/A	N/A
2. Continuous Hydrothermal Dewatering (CHTD)	N/A	N/A	1 ^c	N/A	5	N/A
3. Hot Water Drying (HWD)	N/A	N/A	1 ^c	N/A	5	5
4. Catalytic Hydrothermal Reactor Technology (Cat-HTR)	N/A	N/A	1 ^c	N/A	N/A	N/A
5. Mechanical thermal expression (MTE)	5	N/A	4	3	N/A	5
<i>Category 4: Emerging techniques</i>						
1. Screw conveyor dryer (SCD)	N/A	N/A	N/A	N/A	N/A	5
2. Microwave drying						
(a) CoalTek process	N/A	N/A	2	N/A	N/A	N/A
(b) Drycol	N/A	N/A	2	4	N/A	3
3. Impinging stream drying	N/A	N/A	N/A	N/A	N/A	N/A
4. Superheated steam dryer	3	2	N/A	5	5	5

^a Depending on the drying medium (5 for steam, 4 for any other medium containing oxidizing agent).

^b Although there are currently no available data for the CAPEX of mill drying, it has to be noted that, unlike the other pre-drying technologies, mill drying cannot be considered to impose an extra cost in pulverized lignite power plants, since mills have to be included anyway for pulverization of the fuel.

^c currently the capacity of the pilot plant is low, potentially it could reach high values if future plants with higher capacity are implemented.

Finally, a table containing an evaluation of all the described dryers by using some key factors with a scale from 1 to 5 for each factor is presented below [\(see Table 9\)](#). [\(Please move table 9 below this line\)](#):

6 Conclusions

The drying of lignite is essential in order to improve the net calorific value of lignite along with other main characteristics, and to ensure an efficient operation of lignite power plants. The selection of a proper drying technology among a number of different dryer options is crucial for achieving this goal. As mentioned before, several dryer options may be suited for each case and the choice of the suitable dryer for every case depends on the particular conditions of each specific application.

A detailed description for each of the main types of dryers used for lignite drying has been performed in this report. Each of the listed dryer types has particular advantages and disadvantages, which have been briefly presented. The decisive key factors upon the choice of the most suitable dryer are (a) the capital and operational cost, (b) the achievable capacity range along with (c) the final moisture content, (d) any available sources of heat, or alternative uses of heat, and (e) the avoidance of excessive material temperatures for the prevention of thermal degradation and avoidance of fire or explosion hazards.

All these parameters contribute in the performance of the dryer and consequently in the overall efficiency of a lignite power plant. Therefore they should be taken into account for any further optimization of the drying process and in particular the decrease of the associated energy production cost in the lignite power plant industry.

According to common practice, the rotary indirect drying method, the mill drying as well as the fluidized bed drying concept are the most prominent for lignite drying with a high efficiency and low fire hazards. Therefore, they have been distinguished as the most applicable cases for pulverized coal-firing power plants so far and they have been commercialized in large industrial scale. Among the other afore-described technologies investigated, i.e. the hydrothermal dewatering techniques, the new dryers operating with high velocity air and any emerging techniques are currently operating either at a pilot scale or a commercial scale for applications other than fossil fuel blends (coal and/or lignite), including those of food, paper and pulp, biomass, etc.

The main difficulties that must be overcome and the aspects that have to be taken into account for the development and scale-up of drying technologies involve both technical and economic parameters. These parameters include (a) the capital cost (CAPEX) and operating cost (OPEX), (b) the specific consumption, (c) the dryer efficiency, (d) the operating range (drying temperature and moisture), (e) the residence times, and (f) the level of difficulty in retrofitting and integration of the drying technology in existing retrofitted power plants. Last but not least the fire hazard during the process as well as the storage and transport, and any associated environmental emissions originating from the pre-drying system operation should be as well considered as influencing parameters for the selection of any of the drying concepts. Cost-effective solutions taking into account all these parameters are being established, according to the on-going research and current development operations in drying technology.

Acknowledgments

The authors gratefully acknowledge the financial support of the General Secretariat for Research and Technology/Ministry of Education and Religious Affairs through the "Bilateral Research & Technology Cooperation Greece-Germany 2013-2015" Program/Grant Nr. ΓΤΕΤ GER_2597 (COALEEP Project – <http://www.coaleep.com/>).

References

[1]

S.V. Jangam, M. Karthikeyan and A.S. Mujumdar, A critical assessment of industrial coal drying technologies: role of energy, emissions, risk and sustainability, *Drying Technol* **29** (4), 2011, 395–407.

[2]

<https://www.energy-charts.de/energy.htm>.

[3]

The role of coal in EU power generation. European Association for Coal and Lignite (EURACOAL), 14.05.2013; 2011.

[4]

Wibberley L et al. Techno-economic assessment of power generation options for Australia. Technology assessment report 52. Queensland, Australia; 2006. p. 252.

[5]

J. Brammer and A. Bridgwater, Drying technologies for an integrated gasification bio-energy plant, *Renew Sustain Energy Rev* **3** (4), 1999, 243–289.

[6]

Equipment testing procedure: continuous direct-heat rotary dryers: a guide to performance evaluation. Chicago: American Institute of Chemical Engineers (AIChE); 2004.

[7]

C.J. Roos, C. Northwest and A. Center, Biomass drying and dewatering for clean heat & power, 2008, Northwest CHP Application Center.

[8]

A.S. Mujumdar, Handbook of industrial drying, 2006, CRC Press.

[9]

Dryer Handbook. APV Company, APV Crepaco; 1980.

[10]

R. Wimmerstedt and B. Linde, Assessment of technique and economy of biofuel drying, 1998, Vaermeforsk; Stockholm, Sweden.

[11]

H. Holmberg and P. Ahtila, Evaluation of energy efficiency in biofuel drying by means of energy and exergy analyses, *Appl Therm Eng* **25** (17–18), 2005, 3115–3128.

[12]

P. Rofouieeraghi, Biomass gasification integrated into a reference Canadian Kraft mill, 2012, Ecole Polytechnique; Montreal, Canada, p. 109.

[13]

C.E. Bill, Rotary steam tube dryer, *Ind Eng Chem* **30** (9), 1938, 997–999.

[14]

H. Osman, et al., Drying of low-rank coal (LRC)—a review of recent patents and innovations, *Drying Technol* **29** (15), 2011, 1763–1783.

[15]

D. Allardice and B.C. Young, The utilisation of low rank coals, *Aust Coal Rev* 2000, 40–46.

[16]

Desai D, Clayton S, Hoadley A. Drying of brown coal using a superheated steam rotary dryer. In: The proceedings of the 5th Asia–Pacific drying conference. p. 179–84.

[17]

A. Suwono and Hamdani, Upgrading the Indonesian's low rank coal by superheated steam drying with tar coating process and its application for preparation of CWM, *Coal Preparat* **21** (1), 1999, 149–159.

[18]

O. Hoehne, et al., Drying of lignite in a pressurized steam fluidized bed—theory and experiments, *Drying Technol* **28** (1), 2009, 5–19.

[19]

Lechner S, Höhne O, Krautz HJ. Pressurized steam fluidized bed drying (PSFBD) of lignite: constructional and process optimization at the BTU test facility and experimental results.

[20]

H. Groenewold and E. Tsotsas, Drying in fluidized beds with immersed heating elements, *Chem Eng Sci* **62** (1–2), 2007, 481–502.

[21]

C. Gutfinger and N. Abuaf, Heat transfer in fluidized beds, In: P.H. James and F.I. Thomas, (Eds.), *Advances in heat transfer*, 1974, Elsevier, 167–218.

[22]

Klutz HJ, Moser C, Block D. WTA fine grain drying—module for lignite-fired power plants of the future. In: VGB power tech, Essen, Germany; 2006.

[23]

E. Nshimiyimana, Application of Windhexe dehydration technology for producing β -carotene rich flours from sweetpotatoes, 2012, Food Science Department, North Carolina State University; Raleigh, North Carolina.

[24]

F. Buschsieweke, Dampfwirbelschichttrocknung von Braunkohle, brown coal drying in a steam fluidized bed, 2006, Universität Stuttgart, [in German].

[25]

Godfrey B. Recent developments in innovative drying technologies. In: International symposium on the sustainable use of low rank coals, The Department of Primary Industries (DPI), Melbourne, Australia, 27–30 April 2010. p. 31.

[26]

H.-S. Kim, et al., Fluidized bed drying of Loy Yang brown coal with variation of temperature, relative humidity, fluidization velocity and formulation of its drying rate, *Fuel* **105**, 2013, 415–424.

[27]

Levy E et al. Use of coal drying to reduce water consumed in pulverized coal power plants; 2005. p. Medium: ED.

[28]

M. Karthikeyan, W. Zhonghua and A.S. Mujumdar, Low-rank coal drying technologies—current status and new developments, *Drying Technol* **27** (3), 2009, 403–415.

[29]

C. Defu, Lignite drying and upgrading technology and its application to power generation system, Power Point presentation, 2013, Department of Thermal Engineering, Xi'an Jiaotong University.

[30]

Bergins C. ~~Science and technology of the mechanical thermal dewatering; 2008~~. [Science And Technology Of The Mechanical/Thermal Dewatering. Habilitation Thesis. Technical University Dortmund. 2005.](http://hdl.handle.net/2003/25771)

[http://hdl.handle.net/2003/25771.](http://hdl.handle.net/2003/25771)

[31]

Klutz H-J et al. Development status of WTA fluidized-bed drying for lignite at RWE Power AG; 2010. p. 2. <<http://www.rwe.com/web/cms/mediablob/en/606202/data/183490/2/rwe/innovations/power-generation/coal-innovation-centre/fluidized-bed-drying/Development-status-of-WTA-fluidized-bed-drying-for-lignite-at-RWE-Power-AG-Article-taken-from-Kraftwerkstechnik-Sichere-und-nachhaltige-Energieversorgung>>.

[32]

N.S. Dong, Techno-economics of modern pre-drying technologies for lignite-fired power plants, 2014, IEA Clean Coal Centre.

[33]

Q. Zhu, Update on lignite firing, 2012, IEA Clean Coal Centre.

[34]

Habermann M et al. Supercritical lignite-fired boiler for RWE's new 1,100 MW unit. In: Proceedings of the 12th annual POWER-GEN Europe conference and exhibition: POWER-GEN Europe, 2004, PennWell Corporation, Essex, UK, 25–27 May 2004. Barcelona, Spain.

[35]

Bergins C, Leisse A, Rehfeldt S. How to utilize low grade coals below 1000 kcal/kg? In: POWER-GEN Europe; 2014.

[36]

Carvalho M. Combustion technology for a clean environment. In: Selected papers for the proceedings of the third international conference, Lisbon, Portugal, July 3–6, 1995. Taylor & Francis; 2002.

[37]

Technology overview; 2011. <<http://www.lfpumping.com/downloads.php>>.

[38]

Burton T. K-Fuel® technology application to upgrade lignite & subbituminous coal. In: 2011: IBC's coal upgrading and conversion conference, Singapore, 26–29 April 2011. Singapore: IBC Asia (S) Pte Ltd. p. 18.

[39]

H. Katalambula and R. Gupta, Low-grade coals: a review of some prospective upgrading technologies, *Energy Fuels* **23** (7), 2009, 3392–3405.

[40]

Exergen. A major innovative in clean coal technology. Melbourne, Victoria, Australia: Exergen Pty Ltd.; 2009. p. 7.

[41]

C.Z. Li, Advances in the science of Victorian brown coal, 2004, Elsevier Science.

[42]

B. Godfrey, Recent developments in innovative drying technologies. Power Point presentation, 2010, Brown Coal Innovation Australia.

[43]

C.J. Butler, A.M. Green and A.L. Chaffee, Remediation of mechanical thermal expression product waters using raw Latrobe Valley brown coals as adsorbents, *Fuel* **86** (7–8), 2007, 1130–1138.

[44]

H. Nakagawa, et al., Hydrothermal dewatering of brown coal and catalytic hydrothermal gasification of the organic compounds dissolving in the water using a novel Ni/carbon catalyst, *Fuel* **83** (6), 2004, 719–725.

[45]

S.S. Waje, B.N. Thorat and A.S. Mujumdar, An experimental study of the thermal performance of a screw conveyor dryer, *Drying Technol* **24** (3), 2006, 293–301.

[46]

G. James, Microwave for coal quality improvement: the Drycol project, 2008, DBAGlobal; Milton, Queensland, Australia.

[47]

K. Choicharoen, S. Devahastin and S. Soponronnarit, Performance and energy consumption of an impinging stream dryer for high-moisture particulate materials, *Drying Technol* **28** (1), 2009, 20–29.

[48]

W.G. Willson, D.A.N. Walsh and W. Irwinc, Overview of low-rank coal (LRC) drying, *Coal Preparat* **18** (1–2), 1997, 1–15.

[49]

Z. Li, et al., Investigation of flow behaviors and bubble characteristics of a pulse fluidized bed via CFD modeling, *Drying Technol* **28** (1), 2009, 78–93.

[50]

E.F. Faber, et al., A technoeconomic compression of air and steam drying, *Drying* **86**, 1986, 588–594.

[51]

Mujumdar AS. Superheated steam drying: principles practice and potential for use of electricity; 1990.

[52]

G.D. Bongers, W.R. Jackson and F. Woskoboenko, Pressurised steam drying of Australian low-rank coals: part 1. Equilibrium moisture contents, *Fuel Process Technol* **57** (1), 1998, 41–54.

[53]

Van Deventer H. Industrial superheated steam drying. TNO report 2004; 2004. p. 239.

[54]

Shaffer DB. Upgrading carbonaceous materials, USA; 2010.

[55]

C. Fushimi, et al., Novel drying process based on self-heat recuperation technology, *Drying Technol* **29** (1), 2010, 105–110.

[56]

D.M. Bruce and M.S. Sinclair, Thermal drying of wet fuels: opportunities and technology, 1996, H.A. Simons Ltd..

[57]

C. Dene, Dry integrated emissions control technology options – technical update, 2013, Electric Power Research Institute; California, USA, p. 14.

Highlights

- Report of different types of dryers, both evaporative and non-evaporative.

- Comparison of technical characteristics of main dryer types.
 - Report of existing drying applications in large power plants.
-

Queries and Answers

Query: Your article is registered as a regular item and is being processed for inclusion in a regular issue of the journal. If this is NOT correct and your article belongs to a Special Issue/Collection please contact aravind.kumar@elsevier.com immediately prior to returning your corrections.

Answer: It is correctly registered.

Query: Please confirm that given name(s) and surname(s) have been identified correctly.

Answer: The names and surnames have not been identified correctly, they should be vice versa. For example, for the first author, Nikolopoulos is the surname and Nikos is the first name. This also applies for all the authors.

Query: The country name has been inserted for the affiliation 'b'. Please check, and correct if necessary.

Answer: Yes, it is correct. Thank you for noticing.

Query: Please check the edits made in affiliations 'a and c', and correct if necessary.

Answer: Ok, they are correct.

Query: Please check the hierarchy of the section headings.

Answer: Hierarchy of the section headings is ok.

Query: Please note that Figs. 15, 17, 18, 27, 38 and Tables 2, 7, 9 were not cited in the text. Please check that the citations suggested by the copyeditor are in the appropriate place, and correct if necessary.

Answer: Figure 17 and 18 are correctly cited. Figures 15, 27 and 38 should be transferred according to the corresponding comments. Tables 2, 3, 7 and 9 should be also transferred, according to the corresponding comments in the text

Query: Please check the removal of symbol '†' from Ref. [39].

Answer: It's ok.

Query: The decimal comma has been changed to a decimal point in Table 8. Please check, and correct if necessary.

Answer: It is correct.