M3TC Report
M3TC/TPR/2011/02

Drying of low-rank coal (LRC) – A review of recent patents and innovations

Prepared by: H. Osman, S.V. Jangam*, J. D. Lease and Arun S. Mujumdar

Minerals, Metals and Materials Technology Centre (M3TC)

Supervisor: Prof. A. S. Mujumdar, M3TC and ME Department,
National University of Singapore

August 2011

Drying of low-rank coal (LRC) – A review of recent patents and innovations

H. Osman, S.V. Jangam[*]*, J. D. Lease and Arun S. Mujumdar*

Minerals, Metals and Materials Technology Centre (M3TC),
Department of Mechanical Engineering,
Blk-EA, 06-15, 9, Engineering Drive 1, National University of Singapore, Singapore
e-mail: mpejsv@nus.edu.sg

---

* **Correspondence:** Dr. Sachin V. Jangam, Department of Mechanical Engineering & Minerals, Metals and Materials Technology Centre (M3TC), Blk-EA, #06-15, 9, Engineering Drive 1, National University of Singapore, Singapore-117576, email: mpejsv@nus.edu.sg

Abstract

Despite being geographically dispersed, abundant, and accounting for almost half of the world's coal reserves, low-rank coals (LRC) find limited use due to their high moisture content and high propensity for spontaneous combustion. Reducing the moisture content of low-rank coal enhances its heating value and reduces transportation costs, thus increasing its economic value. In addition, dried low-rank coals have been proven to improve plant efficiency, enhance safety, and reduce greenhouse gas emissions. Although numerous technologies for coal drying already exist, it is often challenging, if not impossible, to find one that is cost-effective in all aspects. When selecting a dryer for coal upgrading applications, factors such as particle size/size distribution, throughput, energy consumption, material handling capabilities, safety, carbon footprint, capital and operating costs, return on investment, etc. are important considerations. This paper provides an overview of the patent literature along with the archival literature that deals with drying of coal as well as biomass which is relevant to coal drying.

Keywords: Low rank coal; upgrading; innovation; patents; design; dryer selection; energy efficiency; safety; carbon footprint.

1. INTRODUCTION

Low rank coals (LRCs), also referred to as lignites or brown coal, account for more than 50% of the world coal reserves. Their applications, however, are limited due to their low heating value and spontaneous combustion property. LRCs contain very high amount of moisture, rendering low energy output and low fuel efficiency compared to high-rank coals. For example, moisture content in Victorian brown coal can be as high as 66%[1], whereas Silesian anthracite may contain as little as 0.6%.[2] Understanding the composition of water in coal facilitates the effective removal of coal moisture. Table 1 lists the different states of moisture that exists in coal and the corresponding method for its removal.[3]

Table 1. Different types of moisture in coal and typical methods for removal.

Category	**Location**	**Common name**	**Removal method**
Interior adsorption water	Micropores and microcapillaries within each coal particle.	Inherent moisture	Thermal or chemical
Surface adsorption water	Particle surface	Inherent moisture	Thermal or chemical
Capillary water	Capillaries in coal particles	Inherent moisture	Thermal or chemical
Interparticle water	Small crevices found between two or more particles.	Surface moisture	Mechanical or thermal
Adhesive water	Film around the surface of individual or agglomerated particles.	Surface moisture	Mechanical or thermal

Evaporation of coal water during the combustion of LRC reduces the net energy output and efficiency of a plant, and increases stack gas flow. Bulk transportation of LRC is expensive due to the significant amount of water; its self-ignition property increases difficulty in handling and storage due to safety reasons; and its low friability render blending operations and pneumatic transportation less effective.

LRC does however, have certain advantages over black coal. Among these the most noticeable are low mining cost, high reactivity, a high amount of volatiles, and low amount of pollution-forming impurities such as sulfur, nitrogen and heavy metals[4]. High moisture content makes drying of LRC an essential component in any upgrading or utilization process. For example, drying of LRC can result in major savings in transportation costs. According to Lucarelli[5], a coal producer can save \$0.19/GJ of energy on storage and handling and transportation costs if LRC is dried from 35% to just 25% moisture content, while the savings on logistics costs could be as high as \$7 million per year for a 600 MW plant. Increased calorific value of dried LRC also warrants higher market value. Other benefits include increased plant efficiency, smaller coal utilization equipment, reduced risk of spontaneous combustion, and lower greenhouse gas (GHG) emissions through clean coal technologies (CCT). Further, the largely untapped and widely distributed resource has enormous potential as a competitive clean energy source.

LRC presents a fire hazard if necessary measures are not taken to prevent the spontaneous combustion of the material. One way of preventing unwanted ignition of coal during drying is by utilizing a drying medium that has low oxygen content. Superheated steam (SHS) is one of such medium. Use of superheated steam, however, involves enormous capital expenditure due to the cost associated with the construction and running of the steam system. Another way of preventing the spontaneous combustion of coal is by employing indirect heat treatment using indirect dryers thereby minimizing the direct contact of LRC with oxygen-rich drying medium. Dried LRC is also susceptible to self-ignition when exposed to excessive moisture; this tendency increases as particle size gets smaller.[6] Hence, there is a need to properly store dried LRC for the sake of safety and also to minimize re-adsorption of moisture so that the lower moisture in the dried coal can be maintained. Various methods to minimize moisture re-adsorption exist and have been discussed by Jangam et al.[7] However, it remains to be seen if such methods are cost-effective when massive amount of coal is involved.

Loss of volatile organic compounds (VOC) as a result of drying LRC at high temperatures is another issue that must be addressed. The loss of useful volatile matter from LRC reduces its calorific value while at the same time increases the risk of fire from the combustion of VOCs. Drying at lower temperature or by using a slight vacuum environment can minimize the loss of VOCs. However, these approaches result in a lower rate of drying.

The cost involved in drying of LRC is another important consideration. In the attempt to upgrade a relatively low-value fuel, a comprehensive techno-economical study must be carried out beforehand to ensure that the effective cost of producing dried LRC does not exceed the market value of commercial coal with the same calorific value. Although numerous commercial scale dryers exist, not all are suitable for drying LRC. The diverse nature of LRC found worldwide requires that the LRC dryer be fine-tuned according to the bulk properties of the specific LRC to be handled to ensure optimal dryer performance. The diverse properties of LRC are evident from Table 2, which summarizes key characteristics of LRCs from major worldwide producers.[8-17] It should be noted that the moisture content of LRC as well as its other properties vary over a wide range depending on its origin; hence the choice of dryer for LRC application is not a universal one.

Table 2. Typical characteristics of LRC of different origins.

Region	**Calorific value (MJ/kg)**	**Moisture, %**	**Fixed Carbon, %**	**Volatile matter, %**	**Sulfur, % daf**	**Ash, % db**
Australia[8]	5–14	44–71	65–70	25–30	0.1–5	0.5–13
Bulgaria[9]	5–14	14–62			3–11	28–58
China[10]		14		46		8
Czech Republic[9]	9–19	6–55			0.7–9	7–44
Germany[9]	7–12	12–51	17–20	52–62	0.4–4	5–11
Hungary[9]	6–15	19–48			0.8–5	18–40
Indonesia[11,12]	21–23	15–22	37–40	37–41	0.5–4	2–8
Poland[9]	7–22	9–55			0.5–7	8–40
Spain[9]	12–17	13–24			3–12	14–70
Turkey[13]	20–28	6–20	29–46	45–56	1.8–14	3–20
USA[14-17]						
Montana	24–25	37	31	25	0.48	7
North Dakota	16	34–44	25–33	24–30	0.2–1.4	4–8
Texas	15	32	26	28	0.7	14
Wyoming	17–22	21–37	30–41	27–36	0.2–1.2	4–12

There is a need for careful and systematic evaluation of dryer designs to maximize the efficiency, cost-effectiveness, and safety of a drying equipment selected for a specific LRC application. As this article focuses on the drying of coal—with special emphasis on LRC—we will review patents filed within the last 25 years in the US, Europe and Japan. Although the primary interest is towards patents that are relevant to drying of coal, patents which do not explicitly specify coal as its target subject but which have potential for coal applications are also considered.

2. DRYING OF LRC

Numerous variations of dryers exist in the market, making the selection of a suitable dryer for a specific application a highly challenging task. In most cases, no two dryers are exactly the same since they were designed for very specific functions. When selecting or designing a dryer for LRCs, special care must be taken to ensure that the process is not only economical, but also safe.

Drying methods and processes can be classified in many ways. Dryers can be of batch or continuous type, or can be grouped according to how heat is transferred to the wet material. Here, dryers are grouped according to their physical design and the principle of operation. The reader is asked to refer to Mujumdar[18] and Kudra[19] for more details. It is noteworthy that dryer selection is also affected by geographical location, value of the product, safety considerations and the scale of operation. Also, downstream processing and utilization of coal can have important bearing on the selection of the dryer type.

For coals with lower moisture content (e.g. anthracite and bituminous coal), drying is still an important step since freshly mined coals, regardless of rank, are usually washed to remove contaminants. Careful consideration of the physical form of the feed is critical in any dryer design, because properties of coals such as particle size and size distribution, moisture content vary.

In the following discussion we have classified the dryer designs according to its most salient features. The designs are extracted from both patent literature and recent academic archives. It is important to note that unlike the archival literature, the patent literature does not provide scientific or engineering data or techno-economic analysis. The patents may include claims that are not independently verified. A patent can be nullified if it is challenged on the grounds that it provides in-adequate data or is based on previously published work.

3. ROTARY DRYERS

The rotary dryer is the most established dryer type and one of the most common for general applications. A basic design of a rotary essentially consists of an insulated cylindrical shell that is mounted on rollers and rotates at a very low speed. Rotary dryers allow direct and/or indirect contact between the drying medium and the wet particles, although the former is more common in industry.

In direct dryers, the wet material is in direct contact with the drying medium. Direct heat transfer is usually provided by a hot gaseous medium blown into the vessel from the gas inlet. For drying of

LRC, the drying medium must be free of oxygen to prevent combustion. Flue gases or heated air are the most common drying medium and in principal suitable for LRC application. However, there are reports of fires and explosions from oxygen contacting hot coals especially during start-up and shut down from such a system.[20] To avoid such accidents, one must ensure that the coal is sufficiently cooled before exposure to the environment. Other suitable mediums include superheated steam and nitrogen, which will be discussed later.

Gas can flow in the direction of feed progression (parallel flow), or in the opposite direction (counter-flow). Although counter-current flow offers higher thermal efficiency, parallel flow prevents the overheating of dry lignite near the outfeed.

Drying based on showering of particles

Rotary dryers designed for continuous processing are usually slightly inclined so that as the main vessel rotates, feed material progresses from the higher end of the vessel to its lower end. In such a system, the particles are conveyed by repetitive lifting and falling action provided by the circumferentially mounted flights and the force of gravity. The periodic lifting and showering of the material creates a curtain of particles through which hot gas flows. This agitation leads to higher efficiencies, increased heat transfer rate, and reduced processing time compared to stationary units. Thus, feed material is heated and dried as it progresses through the dryer.

Flights are one of the key components in rotary dryers. Besides enhancing the mixing of particles, flights also prevent particles from sticking to the dryers' wall and avoid formation of 'dead zones' which can result in poor heat transfer. Particle flow patterns and showering depends on the flight profile, the feed material, and the speed of rotation. The showering of particles produces dust which poses a fire hazard if excessive. With coal, risk of dust explosion is even greater. With this in mind, a desirable flight profile is one which minimizes particle attrition by mixing coal particles very gently yet effectively. Flight design in rotary dryers has been studied quite extensively.[21,22] However, the authors have yet to find research works focusing on the effect of flight design on particle attrition or heat and mass transfer. Nevertheless, one can expect that raining down solids near 180° of rotation results in more attrition compared to releasing the solids at lower angles.

Innovative flight designs have been disclosed by many inventors. Butler[23] and Dillman[24] described cost-effective solutions for altering flow patterns using modular and adjustable flights.

Essentially, these inventions make use of flights to change the drum profile such that by adjusting the flights as the throughput varies, one can control the baghouse temperature within the range that permits its safe operation. For feed materials that are sticky and clumpy, Christensen[25] disclosed a flight design that effectively functions as passive rakes that have stirring, lifting, and breaking elements to prevent the particles from being kneaded into large clumps and causing instability to the vessel. However, such problem will not occur in the drying of lignite particles which are naturally non-cohesive. This design is more suited for drying of sludge or press-cake, and may be more applicable in coal pelletization or briquetting processes.

Such internal elements can help improve the flow of the drying material in the vessel and thus help enhance the volumetric heat and mass transfer coefficients. The patents in general do not provide adequate technical data, however; and the effectiveness of these various design changes is hard to assess and compare in concrete terms.

Drying with aeration

In conventional rotary dryers, convective heat and mass transfer between drying gas and the wet material occurs mostly during the showering of lifted particles since the rolling bed (dead zone) only contributes around 5%.[18] Without lifters or flights, rotary dryers are highly inefficient drying equipment. There are however, two types of rotary dryer that operate without the lifting and showering principle, yet offer high efficiencies and small footprint per unit capacity compared to the conventional kinds. These dryers use aeration as a key feature in their drying operation.

The first of these aeration-based rotary dryers is the well-known Roto-Louvre dryer which has been commercialized mainly for food, chemicals, and minerals processing.[26] In the Roto-Louvre dryer, hot air or gas is blown into the rolling bed of solids through a tapered assembly of overlapping plates. This dryer has found application in lignite drying and is able to provide relatively high drying rates due to the intimate gas-particle contact within the large bed area. For drying of coal, an inlet gas temperature of 480 °C and exhaust gas temperature of 80 °C produces coal at a relatively low temperature of approximately 50 °C with moisture reduction from 18% to 4%.[27] With air velocity through the bed of solids typically between 0.5–1.5 m/s, there is very little tendency to dust. As opposed to lifting and showering in normal rotary dryers, the rolling of particle bed in the Roto-Louvre dryer provides very gentle mixing, thereby reducing particle attrition significantly.

Generally, the Roto-Louvre dryer is physically smaller than the conventional rotary dryer of the same capacity due to its capability for high drying rate.[28] The downside is that the dryer is more costly due to its complex internal structure, has a lower heat efficiency, and is difficult to scale-up.[29]

The other aeration-based rotary dryer is the Yamato dryer. Unlike the Roto-Louvre dryer which passes drying gas from underneath the rolling bed, the Yamato dryer injects air right into the middle of the bed through a series of tubes branching off from a central tube which is positioned parallel to the axis of the drum.[30] Kudra and Mujumdar[19] reported that more intimate gas-to-particle contact in the Yamato dryer results in high heat transfer and drying rates without causing too much particle attrition. The Yamato dryer also offers a 50% size reduction over conventional rotary dryers, which is a tremendous improvement. The advantages of the Yamato dryer are in many ways similar that of the Roto-Louvre dryer. However, it is to be noted that the Yamato dryer is less complex and hence easier to fabricate compared to the Roto-Louvre dryer.

Drying with unconventional flow of solids

Livingston et al.[31] patented a triple-pass rotary dryer design which consists of three concentric hollow cylinders that rotate at the same speed, and are in communication with each other through apertures near the end of the cylinders. Wet particles are introduced into the system through the material inlet port and progresses to the outlet by means of pressure gradient and assisted by the tumbling action from rotation of the drying vessel. The solids are conveyed through three regions, beginning from the space between the outer shell and the first inner tube, and then proceeding to the space between the first inner tube and the second inner tube, and then finally passing through the innermost tube where material before the solids are discharged (refer to Fig 1a). It is claimed that the multi-pass system provides good gas-particle mixing and longer residence time compared to a conventional single-pass rotary dryer with similar operating parameters and external dimensions. No testing data is provided, however.

More recently, Livingston[32] disclosed in a patent a novel rotary dryer which incorporates the impinging stream principle. 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 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. 1b.

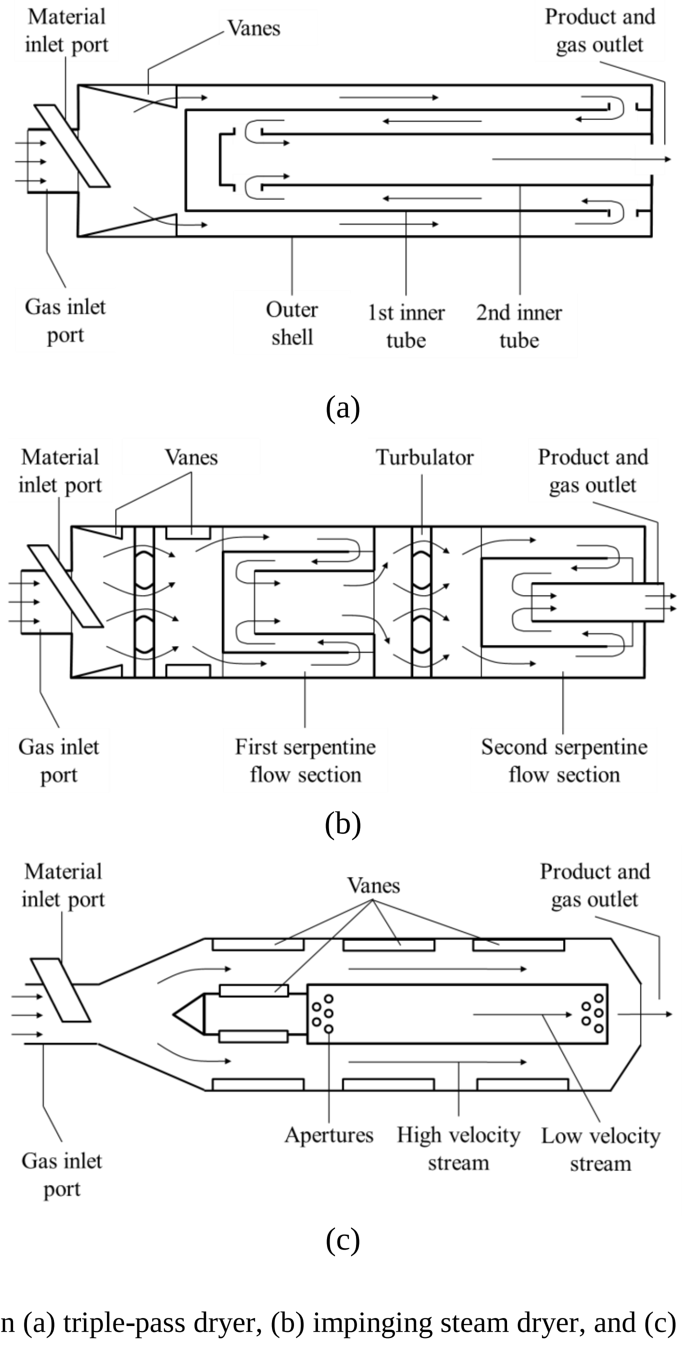

FIG. 1. Particle flow in (a) triple-pass dryer, (b) impinging steam dryer, and (c) single-pass dryer with perforated core.

A single-pass rotary dryer disclosed by Duske[33] avoids the added cost and complexity of the multi-pass dryers described above (refer to Fig. 1c). The Duske dryer is claimed to be an improved version of the conventional single-pass design in the sense of offering superior drying characteristics without adding significantly to the length of the dryer. Flights aligned in a ramp-like manner forces the solids against the gas flow, increasing residence time. The inclusion of a perforated core and lifters serves to impede the flow of material and provide a showering effect to improve heat transfer rate and thermal efficiency. Residence time of particles that enter the perforated core is further increased since the core provides a drying space of low gas velocity away from the direct flow of gas.

There is much technical literature to indicate that impinging streams can yield very high heat and mass transfer rates. All the above patents are novel in their own right and may be more suitable for low density materials or powder. For larger and heavier solids, the need for high pressure drop will add to operational costs. Moreover, the high velocity gas streams can result in too much particle attrition, which is not a desired outcome from the drying of LRC. While truly novel, these patents involve designs that are rather complex and probably more expensive to build and maintain. Its cost-effectiveness needs to be proven independently possibly in academic laboratories both experimentally and via mathematical modeling. Indeed, this design and variations thereof may be good research projects for academic R&D.

Rotary-tube (indirect) drying

Indirect drying can be achieved in a number of ways. Most commonly, an indirect rotary dryer consists of a jacketed shell through which steam or other heating medium flows. At any one time, a very small fraction of solids are 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 accomplished 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 [34].

Akira et al.[35] have disclosed a rotary-tube dryer in which the tubes carry coal rather than steam. Wet feed enters the inclined tubes under the influence of gravity, and 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, regulate the flow of coal being dried and ensure 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 and controlling the rotation speed of the dryer. The coal-in-tube dryer, should produce lesser dust compared to the steam-tube dryer since the tumbling action in the former is not as pronounced. A number of the coal-in-tube dryer has since been manufactured by Kawasaki Heavy Industries with evaporation rates between 6.7 tons/hr and 13.1 tons/hr, and unit throughputs between 95 tons/hr to 420 tons/hr.[36] No reports are available on the flow behaviour of the particulates through the tubes.

Combination of direct and indirect heating

Alexander et al.[37] disclosed an example of an indirect-direct dryer in a patent that describes a cylindrical rotary drum enclosed in a furnace-like cavity with integrated burners. The drum consists of a heater section and a burner section. The pre-heater section is located upstream, near the material inlet, and extends over approximately one-third of the vessel length. The burner section is located downstream near the product discharge and extends over the remaining length of the vessel; see Fig. 2. This dryer design is somewhat different from other rotary dryers in its class in two major ways:

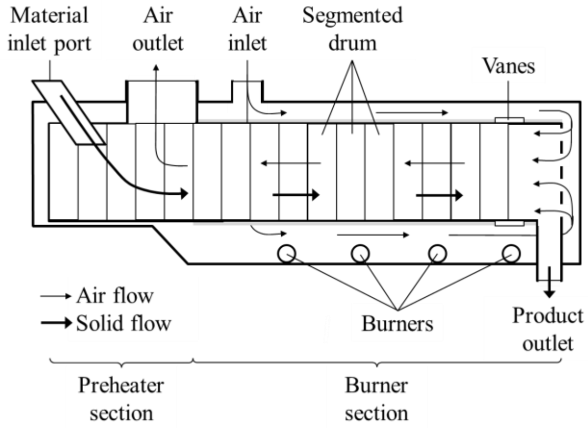

FIG. 2. Simplified schematic of an indirect-direct dryer.

First, heating of the wet product is achieved both directly and indirectly; indirect heating is achieved by using hot combustion gas to heat the drum sections from their exterior surfaces, while direct heating is achieved by driving the same gas into the vessel from proximate end of the burner section.

Second, a multiplicity of stainless steel fins are mounted on the outer surface of the shell and oriented such that fins on the pre-heater section serve to agitate the surrounding air, while fins on the burner section serve to move air downstream and into the vessel. This arrangement not only facilitates the external heating of the drum, but also produces a hot gas stream that results in counter-flow direct heating of the feed material.

4. FLUIDIZED BED DRYERS (FBD)

Fluidized bed drying is ideal for a wide range of particulate or granular solids and has found widespread usage in various industries, including those dealing with chemicals, pharmaceuticals and bio-chemicals, food and dairy products, and polymers. This is mainly due to very high heat and mass transfer rates as a result of vigorous gas-solid mixing. Fluidized bed dryers can compete successfully with more conventional dryer types (e.g. rotary, tunnel, conveyor) in the drying of powders, granules, agglomerates and pellets, with particles averaging between 50–5000 µm. Both heat sensitive and non-heat sensitive products can be dried using one or more of the FBD variants, among which, the most common are: Batch FBD, Well-Mixed Continuous FBD (WMFBD), Plug-Flow FBD (PFFBD), Vibrated FBD (VFBD), Mechanically-Agitated FBD, Centrifugal FBD, and Spouted Bed Dryers (SBD). Each variant design has its strengths and weaknesses and their implementation is highly dependent on feed and product requirements. Other advantages include smaller foot print, relatively lower capital and maintenance cost, and ease of control. However, FBD is not without its limitations. Among the major issues in fluidized bed drying are high power consumption, increased gas handling requirements, high tendency to cause product attrition, and low flexibility in terms of feed type (size and shape) that can be handled. Here we will focus on novel designs that have potential for drying LRC.

Multi-stage FBD

Multi-stage dryers are suitable for drying solids which cannot withstand high temperatures. By heating up moist drying air in between stages, the absorption capacity of the drying air can be maintained. Dunlop et al.[38] proposed a two-stage drying process involving two fluidized bed dryers. In the first stage, raw coal with size up to 5 cm is heated at a temperature of 150–290 ºC in fluidizing air velocity of 1.2–2.4 m/s, removing 40–60% of its moisture. In the second stage of the process, coal from the first stage is heated at a temperature of 290–350 ºC in fluidizing air velocity of 2.4–3.7 m/s until the moisture content is reduced to less than 1%. Entrained particles and water are removed from the exhaust air after passing through a cyclone and condenser. Clean and relatively dry exhaust is then recirculated by blending with heated air. A single-stage FBD processing normally require gas velocities of 5.5 m/s or more, resulting in excessive entrainment of the fluidized bed and may distort the fluidization of the bed. Further, the multi-stage process enables the use of lower inlet gas temperatures or lower fluidizing gas velocities compared to single-stage systems.

Holmberg and Ahtila[39] compared the performance of a 4-stage drying system with an equivalent single-stage system for the drying of wood chips. Their study concluded that the specific primary energy consumption (kJ/kgH_2O) of the multi-stage system was reduced by more than 10% compared to a single-stage system with the same inlet temperature of drying air. In addition, requirements for fresh air are significantly reduced, reducing fan capacity and lowering capital and operating costs. A multi-stage FBD therefore offers tremendous savings in the energy costs of drying. With possibility to use secondary energy from a plant facility as the drying energy, the overall efficiency of the plant can be further improved. Of course data for wood chips cannot be directly transferred to coal particles but the basic concept is sound and most likely to apply.

Multi-level FBD

Stone[40] patented a novel circular vibratory FBD (CVFBD) which features two drying decks positioned one above the other in a drying vessel. Wet solids effectively go through two drying stages; in the upper deck, moist hot gas emerging from the lower deck preheats the wet feed causing some moisture to evaporate. After sufficient time has elapsed, the heated and partially dried solids on the upper deck are dropped to the lower deck where more intensive drying takes place. It was claimed that the CVFBD offers twice the capacity of similar-sized single deck dryers with only a slight increase in heater and fan sizes. The patent literature does not provide any detailed quantitative information. However, the authors believe that the CVFBD has been commercialized for a wide range of applications including the drying of coal, purportedly able to reduce moisture content of solids to less than 1% at 49 ºC.[41]

Pulsed FBD

The FBD designs discussed above along with other conventional FBD possess several limitations that can be listed as follows [42]:

- A need for high pressure drop requires more pumping cost

- Spherical and cubic particles are more favorably fluidized
- Pressure drop and fluidization requirements restrict the size of the fluidized bed vessel
- Particle size and distribution is highly restricted
- Prone to bed instability and reduced transfer characteristics due to aggregative fluidization or channeling
- Attrition of friable materials such as lignite

To offset the negative effects of the last two constraints, Kudra et al.[43] proposed a pulsed fluidized bed dryer (PFBD) that uses two gas flow velocities. The lower flow velocity keeps the whole bed in an expanded state at all times, while the higher flow velocity fluidizes the specific areas in a sequentially pulsating manner such that a traveling wave of variable orientation is formed in the bed. Fig. 3 shows schematic diagrams of the above dryer. Particle entrainment due to excessive gas flows and the formation of dead zones, which result from non-uniform fluidization, is common to both conventional and new FBD designs. A number of studies have shown that pulsed fluidization can improve the fluidization quality as it eliminates the problem of channeling and slugging. Pulsed fluidization also offers the additional benefit of reduced energy consumption compared to conventional FBD. According to a study by Prachayawarakorn et al[44] , the specific energy consumption of a PFBD is 0.19 MJ/kgH_2O compared to 0.33 MJ/kgH_2O using a conventional FBD. Of course these numbers depend on the operational conditions for the two systems which are not specified. Li et al.[45] reported that pulsating fluidized beds result in reduced bubble size and better gas-particle contact, and went further to conclude that a pulsating frequency of 40 Hz produces normal fluidization.

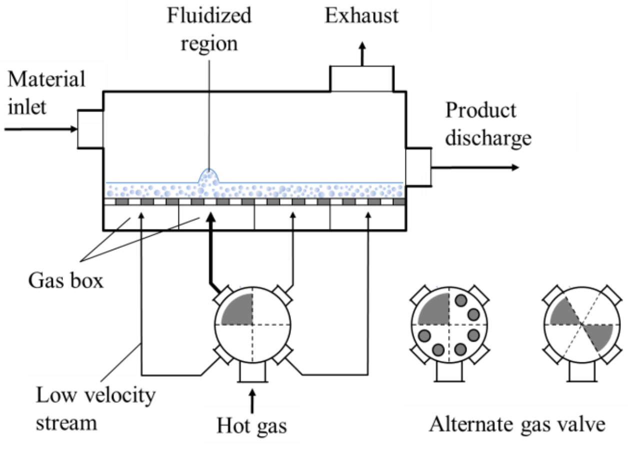

FIG. 3. Schematic diagram of a pulsed fluidized-bed dryer

FBD with immersed heater

Excellent gas-particle contact in fluidized bed dryers 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 heat transfer (gas flow) with conduction heat transfer (immersed heaters). 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.[46]

It is to be noted that the heat transfer coefficients depends strongly 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.[47] 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.

Fluid bed dryers

Other variations of the fluidized bed dryer have also been patented. These include plug flow drying of coal in inclined fluid bed drying system[48], vibrated fluid bed drying of fine coal particles[49], and spouted fluidized bed granulating and drying of slurry.[50] Although numerous designs based on the fluid bed concept exist, more designs continue to surface in fully disclosed patents. However, not all will find widespread implementation due to factors such as cost and scalability, but mostly due to the concern for reliability of new, untested designs. The performance of fluidized beds, usually characterized by the quality of fluidization, depends highly on the size and shape of the feed particles, which is apparent in coal drying. To facilitate fluidization of the bed, the most straightforward way is to grind and sieve raw coal before feeding into the drying vessel. Fluidization quality can also be improved by employing mechanical vibrations, agitation or pulsating flow of fluidizing gas, as described above.

5. MICROWAVE DRYERS

There are extensive reviews in the archival literature on various aspects of microwave drying and dryers. Several handbooks also cover the basic principles and major applications in diverse industries.[51-53] In view of their potential for application in various industries it is not surprising that many patents have been issued covering various aspects of microwave (MW) drying. However this paper will not cover other industrial application areas, which include sintering of metals and ceramics, thawing of meats etc.

Tremendous interest in the utilization of microwave energy in drying applications is evident from the number of patents filed (more than 1500) for MW-related dryers in the past two decades. Such overwhelming interest is understandable considering the advantages MW-related drying systems offer over conventional ones. Conventional drying methods employ surface heating, and are generally a slow process since the rate of heat transfer from the surface to the core of the material is dependent on the process conditions, particle size, and material properties. In microwave heating, volumetric heating is achieved and energy is preferentially transferred to moisture in the material without the need to heat the material first, resulting in shorter drying time. Capital and operating costs due to use of the highest form of energy (electricity) in microwave drying remain an impediment despite its technical advantages. It has been reported that the use of MW for coal can also result in local overheating and can have safety concerns which needs to be studies before selecting this dryer for coal application.[7,54]

Stand-alone MW dryers

Learey et al.[55] patented a method of drying coal using microwave frequencies of 915 MHz or 2450 MHz, and involves the grading of raw coal according to size—fine, medium, and coarse. Referring to Fig. 4, fine grade coal will go through a series of one or more dryers to be sufficiently dried, such that the aggregate moisture content of the mixture, consisting of fine, medium and coarse grades, is reasonably within the target range. This is based on the assumption that smaller particles contain a greater amount of moisture, hence providing the greatest potential in aggregate moisture reduction. Medium and coarse grades may or may not go through any dryer. This inventor claimed that the microwave heating chamber design facilitates uniform heating of coal below 90 ºC through microwave power and conveyance speed controls.

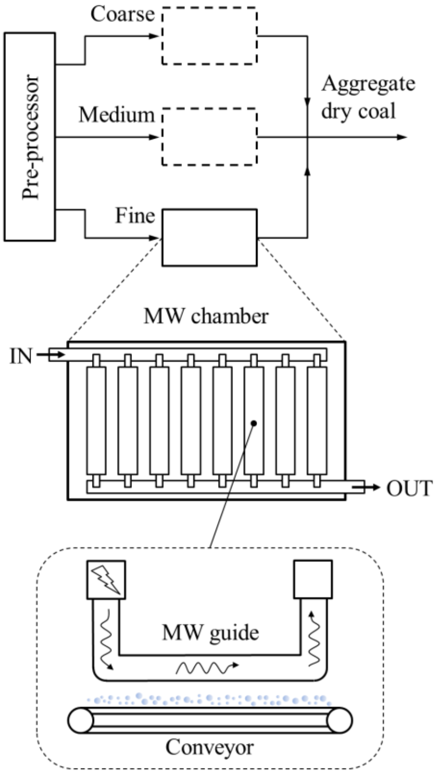

FIG. 4. Process for achieving target aggregate coal moisture content using microwave energy.

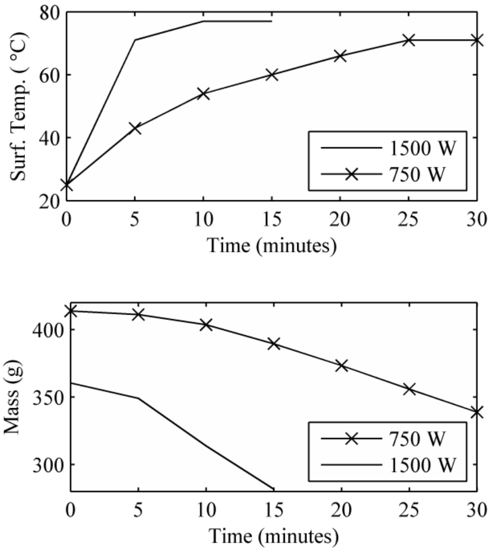

FIG. 5. Drying characteristics of Yantis lignite in microwave dryer.

Latchum[56] disclosed a method of drying lignite using microwave energy in a controlled manner. Photometric sensors were used to monitor surface moisture of lignite as it is transported into the microwave chamber by means of a conveyor belt of 1.5–3 meters wide, and 30–60 meters long. A controller programmed to process input signals from sensors ensures that the impedance presented to the MW generators is constant to avoid damage to various components. Such arrangement also ensures that surface moisture is present throughout most of the drying period, and prevents product breakage due to rapid withdrawal of water. In addition, overheating of product is avoided since the temperature is set below 105 °C. The performance of the dryer at microwave power levels of 750 W and 1500 W is illustrated in Fig. 5.

In a very comprehensive patent document, Weinberg et al.[57,58], described a rigorous control method that supposedly has the capability to selectively alter coal properties. At the start of the process, information about the coal is gathered. This information includes location of origin, purpose of usage (e.g. electricity generation, steel production), desired product properties, tonnage, handling procedures required (e.g. grinding, screening), and properties of the raw coal samples. All this information provides the system with fine control over the material being processed such that dried coal with very specific moisture content, colorific value and sulfur content is produced at the output, notwithstanding the characteristics of raw coal fed into the system. It is not known if such a system has since been implemented but it will be interesting to see its effectiveness via independent studies. As noted by the inventors, the variability of coal even from a single coal mine can be very large, let alone coal obtained from worldwide sources. Thus, if such a system were to be manufactured, it would probably involve a very significant amount of capital.

In most MW drying applications, the feed is usually not stationary. This is because MW heating is known to be uneven, and tends to form regions of underexposure and overexposure, commonly referred to as cold-spots and hot spots respectively. By keeping the material in constant motion relative to the MW-guides, more even heating can be achieved. This relative movement is usually achieved by placing the material on a rotating plate or conveyor, and passing it under the MW-guides.[55-57] The use of reciprocating ram has also been suggested by Hein et al.[59,60] for moving viscous mixtures through the microwave chamber. For processing of coal, this may not be the most efficient mode of conveyance. Since fossil-fuel generated electricity has a very high carbon footprint, use of high quality energy source generally results in very high life cycle costs due to carbon emissions and the high potential to attract carbon tax being implemented in many countries.

MW-assisted Dryers

Advantages of MW heating can be accrued in one of three ways: as a pre-dryer, a booster dryer, or a post-dryer. When used as pre-dryer, volumetric heating due to MW quickly forces internal moisture to the surface, facilitating the optimal operation of a conventional dryer. In booster drying, microwave energy is added as the drying rate begins to fall off, thereby sustaining or even increasing the drying rate. When used as a post-dryer, the MW system greatly improves drying efficiency of the conventional dryer since the last one third of water is most difficult to remove by the conventional dryer alone.

For example, fluidized bed drying offers very high heat and mass transfer rates through excellent mixing and vigorous gas-particle interactions. However, the falling-rate period presents to most dryers increasing difficulty in drawing strongly-bonded internal moisture to the particle surface where it can be removed by convection.[61] On the other hand, such difficulty is not encountered in a microwave dryer since water is agitated at extremely high frequencies from within the particle itself, resulting in a very short drying time, albeit lower product quality due to uneven exposure and moisture stresses. MW-assisted fluidized bed drying overcomes the above limitations by providing rapid and uniform drying at high energy efficiency with a smaller footprint of the dryer.

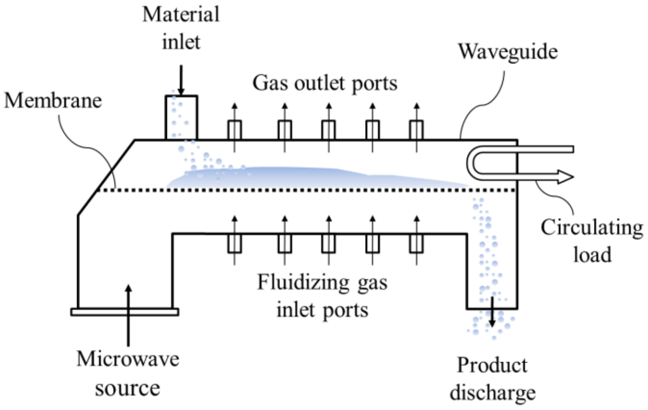

FIG. 6. Schematic diagram of a waveguide fluidized-bed dryer

Smith[62] described a fluidized bed dryer that is configured to work as a MW waveguide with fluidizing gas inlet and outlet ports (refer to Fig. 6). The ports are sized smaller than the wavelength of microwave to prevent microwave leakage to the external environment. As with most MW devices, not all microwave energy produced is absorbed by the material. To prevent excess reflected waves from damaging the microwave generator, water is circulated near the downstream end of the waveguide to absorb the remaining microwave energy. There are several drawbacks to this design: First, the design does not allow for the reflection of waves. Hence, microwave energy can only propagate in one direction, absorbed either by the material or by the circulating load (water). Further, the material to be dried must be placed near the center of the waveguide where the TE-10 mode microwave field is maximal. Since there is no material below the distributor plate, microwave propagating below the membrane is wasted. Hence, microwave energy is not efficiently used in this case.

Doelling[63] overcomes the inherent limitations of Smith's invention through design of a MW-assisted fluidized bed dryer that makes use of a retrofitted conventional fluidized bed dryer. In his invention, Doelling described an FBD vessel that allows reflected microwave of various orientations to fill the vessel cavity, thereby forming multi-mode standing waves—a direct contrast to unidirected, single-mode (TE-10) microwaves in Smith's invention. Further, the distributor plate not only serves its usual function as material support and fluidizing gas distributor, it also serves as a microwave screen to block microwaves from penetrating to regions below the plate. Since microwaves are highly confined to the fluidized bed region and within the vessel, a more efficient use of microwave energy can be realized. The use of MW with FBD was shown to improve drying rates by 2 to 4 times. In addition, a tuner for matching impedance between the microwaves generator and the product in the vessel leads to overall improvement in the flexibility of the system.

MW drying also produces clean coal with low-sulfur content using the ability to preferentially direct MW at pyrite (Fe-S) compounds in coal giving rise to localized thermodesulfurizing reaction between pyritic sulfur and other neighboring reactive compounds present in the solid.[64] The polarization of MW fields result in the breakage of the Fe-S bonds, releasing sulfur in the form of hydrogen sulfide (H_2S), sulfur carbonyl (COS) or sulfur dioxide (SO_2). Yang and Wu[65], and Rowson and Rice[66] studied the effect of a strong alkali on the desulfurization of coal. Their study concluded that the irradiation of pulverized coal in strong alkaline (KOH or NaOH) solutions successfully reduced sulfur content by as much as 70–80% without affecting coal structure and coking characteristics. For further discussion on MW-related drying, the reader is asked to refer to Schiffmann[67], Zhang et al.[54], and Constant[68]. For reasons already mentioned, it is important to carry out proper techno-economic and life cycle analysis when selecting appropriate dryers especially if there is heavy use of electricity.

6. SCREW CONVEYOR DRYERS (SCD)

When there is need for simultaneous conveying and heating or cooling, a screw conveyor can be easily converted to a dryer or heat exchanger by providing the necessary heat to the moving solids either directly or indirectly and by removing the evaporated moisture by gentle gas flow or by application of vacuum. Typically, a screw conveyor dryer consists of a jacketed vessel (generally cylinder or U-trough) in which material is simultaneously heated and dried as it is conveyed. The heating medium, usually hot water, steam, or any thermal fluid, may also flow through the hollow flights and shaft to provide high heat transfer area without the need for additional space or material.

Multi-stage SCD

One of the earliest descriptions of a multi-stage SCD for drying wet coals, lignite or other carbonaceous material is disclosed in a patent by Comolli[69], in which raw lignite is dried as it is conveyed through three jacketed screw conveyors (refer to Fig 7.). In the first stage, moist lignite is subjected to a surrounding temperature of 80–150 ºC essentially at atmospheric pressure to rapidly remove surface moisture to a critical moisture content of 8–12 %. Following the first stage, the partially dried lignite is passed through a pressure lock device to the second drying stage. The second stage is a slower drying rate stage which is isolated from the atmosphere through pressure lock devices (e.g. rotary valve) at the entry and exit, providing a mean for drying at sub or elevated pressures. At this stage, lignite is heated to 90-260 ºC and steam is introduced such that water vapor differential pressure between gas and solids is less than 0.5 atm. Rapid drying followed by slow drying drives low-volatility hydrocarbons to the surface of the particles and obstructing the pores, thereby minimizing moisture readsorption without the need for coating. The dried lignite is cooled in the third stage before final exposure to the atmosphere. Hence, this drying system provides relatively cool dry coal with attenuated spontaneous combustibility. A similar invention for drying of pellets is described by Okada.[70]

Dewatering using tapered-shaft screw conveyor

Maffet[71] described a mechanical dewatering method for peat and sludge using two or more independently rotated screw conveyors placed end-to-end within a porous cylindrical vessel. The first screw serve as a dewatering zone and consists of three sections, differentiated only by the diameter of the shaft, which gets progressively bigger with corresponding decrease in flight depth. As wet material travels downstream, it is pressurized causing water to be squeezed through the porous vessel wall with apertures sized between 12.5–250 µm. A further enhancement to this invention will be to break-up the dewatered material into loose solids and thermally dry the solids in a jacketed screw conveyor similar to those described by Comolli and Okada.

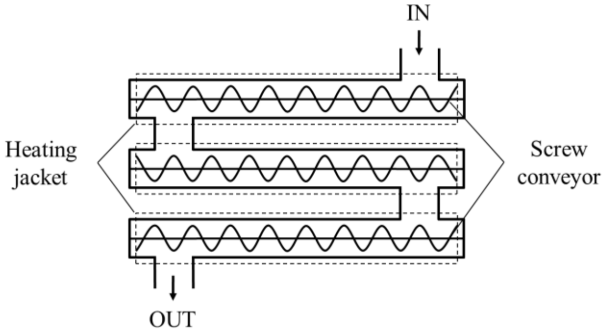

FIG. 7. Schematic diagram of a multi-stage screw conveyor dryer.

Performance characteristics

One of the noticeable benefits of a screw conveyor dryer with hollow flights and/or shaft is that it can be used for indirect heating of the particles. As discussed in earlier sections, indirect heating is highly desirable in drying of coal. Safety is further enhanced if superheated steam or nitrogen is used as the heating and/or drying medium. Moreover, SCD offers a relatively high heat transfer area-to-volume ratio compared to most of the other dryers.[72] Further, the rotation of the screw leads to better heat transfer coefficients due to continuous renewal of the heating surface and gentle mixing of solids. Waje et al.[72] found that the average value of the heat transfer coefficient to be in the range 45–102 W/m^2K. Improvements to thermal efficiency and power consumption can be achieved by operating the SCD at a higher degree of fullness and at higher temperatures. Drying rates can also be increased by operating the SCD in a low-pressure environment. Reduced pressure operation will also reduce the fire hazard due to spontaneous combustion by depleting availability of oxygen.

The screw conveyor dryer is essentially a modified screw conveyor system. Therefore successful implementation of the SCD not only depends on the target output properties of the processed coal, but also on the screw dynamics and physical attributes. Being a well-established mechanical tool, a wealth of knowledge in the form of handbooks and selection guides[73,74] are available to assist in identifying a suitable screw configuration for any application. To determine a suitable screw configuration, physical characteristics of the material to be handled such as flowability (related to angle of repose), abrasiveness (can be found in Moh's scale), and size must be known beforehand. Subsequently, the degree of fullness, volumetric feed rate, screw speed, screw size, power requirements, heat requirements, and length of screw can be determined. For a concise SCD design guideline, the reader can refer to Waje et al.[72]

Other innovations that are not directly applicable to coal drying, but may have potential for further exploration and adaptation are listed in Table 3, with references to their corresponding patent documents.[75-79]

Table 3. Screw conveyor devices for various applications.

Reference	**Purpose**	**Feature(s)**
Okada[70]	Drying of resin pellet.	Cascaded screw conveyor tubes, each jacketed by electric heating elements, offers multi-stage drying. Temperature and rotation speed of screw conveyors adjusted according to control data.
Gentry[75]	Fracturing and washing of crushed lignite in scew conveyor.	Two sections screw—helical and notch section—permits higher rotational speed with some improvements in cleaning, less lignite loss, and reduced water requirements.
Costarelli[76]	Drying of plastic materials through mechanical dewatering.	Water is expressed as screw conveyor compress solid near the tapered end of the housing. Blade breaks up compacted solid before discharge.
McCabe et al.[77]	Removing volatile components from a matrix (e.g. sludge, contaminated soil, etc)	Right-hand and left hand screw conveyors in parallel within housing where matrix is conveyed. Screw conveyors are heated by hot medium flowing through hollow shaft and flights.
Mentz[78]	Drying of minerals and ores.	Electric heating rings on outer surface of housing heat the drying chamber. Screw conveyor with cut and folded flights agitates conveyed solids.
Azuma[79]	Drying of waste containing water.	SCD with heating by combustion gas flowing through jacket and hollow screw conveyor shaft. The jacket is a double tube combustion chamber, with H_2 and O_2 (ratio 2:1) as combustion gas.

7. DRYING WITH SUPERHEATED STEAM

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: reduced risk of spontaneous combustion[80,81], increased drying rates, better energy efficiency and improved grindability.[82,83] More benefits and limitations of SSD are summarized in Table 4.[84]

Table 4. Advantages and limitations of SSD.[84]

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.

Shaffer et al.[85] 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 ºC, MC 34%) in hot water (95 ºC), and placing the resultant coal (65 ºC, 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 ºC in a pressurized environment. More steam is then injected into the vessel to increase the temperature to 260 ºC at a pressure of 34 atm, resulting in the loss of more moisture. After cool 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[86] 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 (refer to Fig. 8). Compared to hot air drying with conventional heat recovery process, the SHR-FBD process offers considerable overall cost savings despite 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. Table 5[87] compares the performance of a conventional dryer and a SHS dryer, as reported by the authors. The capital and energy costs associated with compression need to be carefully identified and evaluated.

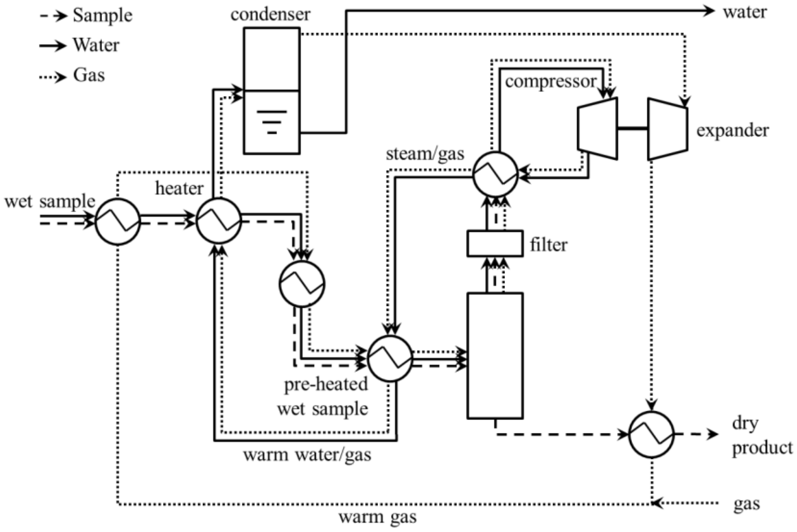

FIG. 8. Drying process based on self-heat recuperation technology.

The Koppelman process exemplifies use of SHS in drying of LRC in a pilot scale operation. Briefly, this process involves the pumping of a lignite-water slurry into a tubular reactor at 10 MPa. The mixture is then pyrolysed in steam at 540 ºC, producing gases having a calorific value of 15-19 MJ/m^3 which are collected and burned for power production. In a sample implementation of the process, lignite having a calorific value of about 16 MJ/kg was treated at 7–10 MPa and 400–675 ºC to produce upgraded lignite with a calorific value in the range 28–30 MJ/kg and with no tendency to reabsorb moisture.[29]

Table 5. Economic comparison of conventional and SSD dryers.[87]

	Conventional	**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 optimum pressure and drying time depend on the size of the LRC particle and the resulting moisture content of the dried particle depends on the steam pressure and temperature, the particle size and moisture content of the raw LRC. SSD requires less energy than hot gas dryer because there is no need to supply coal moisture with latent heat of vaporization. Pang and Pearson[88], and Defo et al.[89] independently performed experimental studies to investigate the application of the superheated steam drying at ultra-high temperatures and the results concluded that ultra-high temperature drying saves more energy while reducing drying time by up to ten times. Drying in SHS also increases the apparent density of the lignite by 15–20% due to shrinkage of the lignite particles on moisture removal. In addition, the decomposition of sulfur functional groups during steam drying process produces cleaner coal with high heating value.[90] Because fire hazards associated with spontaneous combustion of coal are completely eliminated in superheated steam drying, target moisture content can 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.[91,92]

8. INTEGRATED DRYING

Most applications that use SHD are usually integrated with other processes to fully utilize latent and sensible heat from the steam through some form of heat recovery techniques. GEA[93] reported that primary energy consumption of a SHD without any heat recovery consumes about 825 kWh/kg evaporated water. Between 70–90% of this energy can be recovered by using generated steam in another process, or by using Mechanical Vapor Recompression whereby at least 0.2 kWh of electricity can be produced per kg of the said evaporated water. Because SHD involve very high capital cost, this technique is more economically viable for adoption in large-scale power plants, or processes like WTA (fluidized bed drying with internal heat recovery).

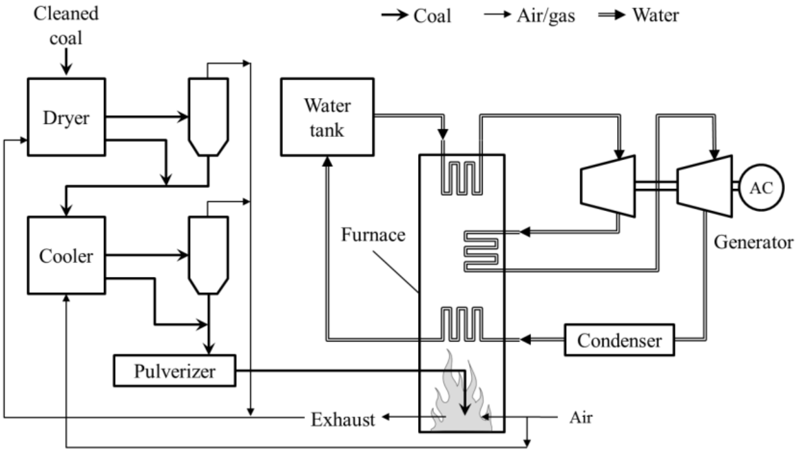

FIG. 9. Integrated processing, drying, and utilization of coal.

Integration of drying and power generation is most beneficial when the power plant is close to the coal mine eliminating the need for transportation and large storage facilities, thereby reducing logistics related costs. Bowling[94] invented a process whereby the preprocessing of coal (cleaning, sorting, grinding, drying, etc) and coal utilization in the form of electricity generation, are part of an integrated process. In this process, hot fuel gas produced in the gasifier is used to dry the incoming coal under pressurized environment. A small fraction of the flue gas returns to the dryer to dry more coal, while the remaining proceeds to the boiler to generate steam. A small faction of the generated steam is bled on its way to the turbines. The heat required for drying moist coal comes from a small fraction of the hot combustion gas and steam produced to drive the turbines for electricity generation; see Fig. 9.

A relatively recent coal utilization technology known as the Integrated Gasification Combined Cycle (IGCC) produces electricity from coal by gasification and subsequent combustion of the coal gas. Additional electricity is produced by the steam turbine driven by steam generated from the heat in the gas turbine exhaust. The IGCC plant offers an overall conversion efficiency of approximately 30% higher than a conventional steam power plant, with correspondingly lower CO_2 and pollutant emissions. Coupled with the use of cheap LRC and an efficient drying system, the full benefits of this promising technology can be realized. This was addressed by Rao and colleagues[95] in their patent which disclosed the process of the integrated drying and gasification combined cycle (IDGCC) plant. The drying component of this system uses high-pressure inert gas (e.g. Nitrogen) or high-pressure fuel gas produced from gasified coal heated by the cooling streams from the gasification units, to dry coal. Rao et al.[95] showed that this system produces 6.2% more power than a conventional plant. A comprehensive study by Levy and co-workers[96] studied the technical and economic feasibility of using power plant waste heat to dry lignite. This led to the implementation of two 600 MW coal-fired plant in North Dakota designed for a throughput of 998,000 kg per hour of wet lignite which has been in operation since 2009. For Latrobe Valley coals, the thermal efficiency were successfully raised to 38–40% using the IDGCC process, presenting a substantial improvement over the 29% efficiency achieve in the latest conventional units.[97] Currently, HRL Technology is constructing a 400 MW IDGCC plant close to the Loy Yang coal mine.[98]

9. INCREMENTAL MOISTURE REDUCTION

Ness et al.[99,100] developed a process, called DryFining Process, that uses waste heat to reduce the amount of moisture, sulphur, mercury, and ash. This aims to increase heating value of lignite while increasing power plant efficiency and reducing emissions. Their patent documents describe the process and the control as well instrumentation in great detail. The process involves the use a series of at least two fluidized bed dryers (FBDs) with internal heat exchangers, and implements low temperature drying of lignite in an incremental manner. FBD drying of coal is popular because it offers high heat and mass transfer rates. However, most conventional FBD processes employ high temperatures and in some cases pressures, and have high energy consumption. This increases the cost of producing dry lignite, making it economically unattractive. The use of waste heat from, for example, condenser cooling water, hot flue or stack gas, or spent process steam from turbine, as a heat source in the drying operation substantially reduces the operating cost. From sustainability standpoint it is important to utilize waste heat.

In the Ness et al. process, raw wet coal is crushed and screened to remove large particles and impurities as rocks and gravel prior to drying. Fluidizable and non-fluidizable particles are separated by fluidizing the material and utilizing the segregation and sorting capabilities of the modified FBD. Being larger or heavier than fluidized particles, the non-fluidizable particles sink to the bottom of the bed where they are automatically channelled to holding containers marked for return to mine. These rejected particles account for up to 25% of the feed stream, and may contain high levels of impurities such as nitrogen and sulphur. Thus, the removal of substantial amounts of sulphur, mercury, and ash is accomplished by density filtration. The inclusion of immersed heaters internal heat exchangers provide sufficient heat transfer, enabling minimum fluidization velocity of 0.8–1.4 m/s to be used. Tests have shown that raw lignite dried to 27–32% moisture at drying temperatures in the range of 90–150 °C provides optimum process conditions. The temperature of coal exiting the dryer is typically around 60 °C, which is well below the ignition temperature of dry lignite. There is still potential to recover some of its sensible heat and also to make storage of reactive coal safer.

Table 6. Performance summary of the DryFining system.[103]

	Prototype	Commercial
Coal flow rate reduction	2.0%	14%
Mill power reduction	3.3%	25%
Boiler efficiency improvement	0.37% Abs.	2.13% Abs.
Net unit heat rate improvement	0.37%	2.85%
NOX reduction	7.5%	> 20%
SOX reduction	1.9%	40%
Hg reduction	0.4%	40%
CO2 reduction	0.4%	4.0%

Their preliminary test results show that lignite can be dried, albeit by small increment, using a relatively low temperature air to reduce moisture content by about 6%. Test runs showed positive results with almost 2% increase in boiler efficiency, substantial reduction in fan size, 20% reduction in pulveriser power, 10% reduction in NO_X emissions, and 34% reduction in SO_2 emission.[101,102] Success of this test elevated the development status of DryFining to the prototyping stage with the construction of a 115 t/hr coal dryer in 2005. By 2006, performance testing showed approximately 25% moisture reduction (38.5% MC to 29.5% MC) in lignite with corresponding higher calorific value (HCV) improvement from 13.64 MJ/kg to 15.62 MJ/kg. The technology has already been commercialized with a full-scale coal drying system consisting of four drying modules, each capable of drying coal at 135 t/h, already in operation at Coal Creek station. Performance summary of the prototype coal drying system and the full-size commercial system is given in Table 6.[103]

The potential impact of this technology appears to be very significant, especially for nations that depend greatly on low rank coal or high moisture sub-bituminous coal to fulfill her industrial needs.

10. SOLVENT DISPLACEMENT

Treatment of coal and coal fines in a variety of organic liquids, as a means of enhancing the stability of coal, while reducing energy requirements during drying has been around since 1926. One example is hot oil drying whereby raw coals are dried in hot oil after which most of the oil is recovered, a method also known as fry drying and used extensively for foods and sludge drying. Oil that is absorbed into the coal pores supposedly results in greater stability of the processed coal.[104]

Apart from oil, drying of coal in other hydrocarbons has also been demonstrated with success. Murphy[105] described a two-fold improvement in drying time when methanol was used as the drying liquid. Similarly, Cantu et al.[106] described the use of alcohols with 1–3 carbon atoms to facilitate the drying of coal.

Grounded coal immersed in hot molten paraffin (104–163 ºC) was also shown to be another effective dehydration method. Dean[107] showed that coal treated from such a process displayed a dramatic increase in calorific value (originally 22,300 kJ/kg, upgraded up to 34,900 kJ/kg), low final moisture content (around 3%), and inhibited rehydration due to paraffin displacement of water in coal cavities.

Drying in organic solvent was found to be less energy intensive than conventional evaporative means since the latent heat of vaporization of volatile solvents is significantly lower than that of water.[108] Nevertheless, some thermal energy is still required for heating and the solvent recovery processes—which could be energy intensive. An attempt to further reduce this energy requirement is described by Yoon et al.[109] through a process that claims to spontaneously displace surface moisture under sufficient pressure, with little or no heating, and using a gas that can be converted into a non-polar, hydrophobic liquid (e.g. butane). This concept is illustrated in Fig. 10.

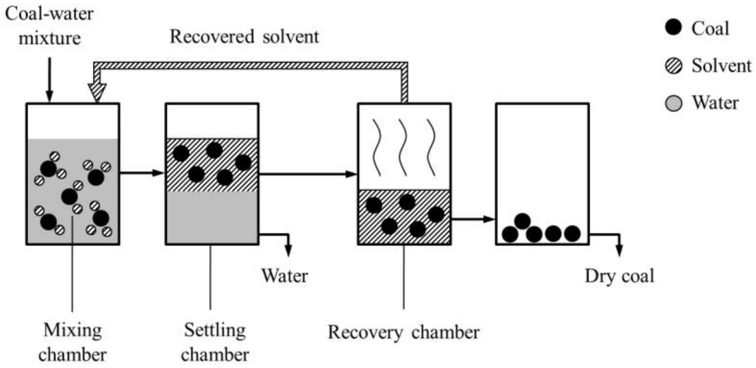

FIG. 10. Dewatering of coal through solvent displacement of water.

Another displacement drying technology has been proposed and developed by Kanda et al.[110,111] This is based on displacing water in high moisture coals with a highly volatile, low latent heat organic solvent that can be separated from the solid easily and also separated from water by flash distillation. In this case, they propose the use of liquefied dimethyl ether (DME) at ambient temperature. DME has properties that make it an ideal water extractant. At normal conditions DME can “dissolve” about 8% by weight of water. DME is a good fuel that burns safely along with coal if there is any residual. With a normal boiling point of only -24.8 °C and a vapor pressure of 0.59 MPa at 25 ºC, DME can be removed from coal very easily to obtain coal with as much as 95% water removal. DME from a DME-water mixture can be vaporized by decompression. DME vapors are cooled and compressed before reusing for drying. Multi-stage compression and multi-stage distillation are proposed for higher process efficiency. Kanda et al. estimated the energy consumption for dewatering of low rank coal is about 1100 kJ/kg—which is less than 50% of the latent heat of vaporization of water and several-fold more efficient than conventional thermal drying of coal.

Superheated steam drying can result in better energy consumption values but at higher overall costs. Since the process requires a considerable amount of capital expenses and also uses electricity for compression; the overall economic potential yet to be determined. The concept of displacing water with low latent heat solvents is not new. It has been proposed and tested for drying of plastic components, textiles, etc, but not yet successfully commercialized to the authors’ knowledge. The recovery of solvent by cost-effective means remains the main concern. Considerable pilot scale tests and techno-economic studies are needed before this process can be considered for commercial application.

11. BRIQUETTING

Briquetting of coal stems from the need to reclaim stockpiles of coal fines left over from screening, grinding, drying and other processes. Coal particles that are too small have negligible economic value as they cannot be shipped without re-agglomerating them to a larger size. For example, some of the processes for synthetic fuels cannot use coal particles smaller than one-quarter mm. Apart from the convenience of size, briquetting of coal can also minimize moisture re-adsorption, and increase calorific value as well as the density of the agglomerate.

Process

In a typical briquetting process (refer to Fig. 11), lignite containing 48–70% water is crushed to 0.01–3 mm particles which are then dried to about 12–15% moisture content. The dried coal particles are then densified using an extrusion press (or some other briquetting device) at low to high pressures to form hard compacts with a calorific value comparable to that of high rank coals.[97] In some cases, additives are blended prior to agglomeration to increase the pH of the coal and improve the strength of the densified product.[112] The actual process flow and operating conditions of a briquetting process may vary depending on the properties of the raw material, the desired characteristics of the product, and the equipment used.

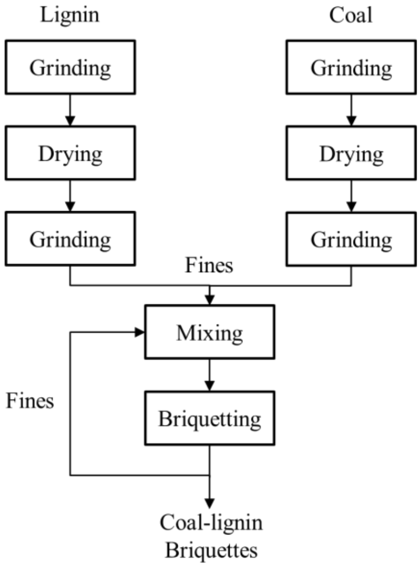

FIG. 11. Process flow for production of coal briquettes using lignin.

Johns et al.[113] patented a densified brown coal (DBC) process in which raw lignite is kneaded into a plastic mass which can be easily extruded into pellets. The process begins by shear attrition the freshly mined lignite to 5–10 µm particles, forming a coal slurry of plastic quality with no water addition. Applied shearing stress releases water from the cellular structure of the coal, forming smooth and wet plastic mass after about 1–1.5 hours of kneading. Next, the slurry is extruded under modest pressure to produce cylindrical pellets of convenient dimensions. Finally, the pellets are air-dried at room temperature forming hard and dense coal pellets with high crushing strength. For pellets made from Loy Yang coal, the crushing strength is reported to vary between 2.8–8.6 MPa depending on the lithotype, extrusion pressure, kneading time, and the presence of additives. Addition of fine sodium carbonate (Na_2CO_3) and attrition of coal particles to greater extent has been claimed to substantially increase the crushing strength of the pellets.

The Coldry process patented by Wilson[114] presents a further development to the DBC process. The patent document describes a brown coal upgrading system similar to the DBC process outlined above. It is suggested that the plastic mass is formed using a sigma-type kneading machine operating at relatively low speeds of 20–40 rpm, followed by extrusion at 1.5–2.5 MPa using a single screw extruder to produce moist pellets containing 55–65% water. The moist pellets are then conditioned for 25–50 minutes on a mesh conveyor which goes through a series of conditioning chambers where heated air atabout 60 ºC is blown. The conditioning removes surface moisture and sufficiently strengthens the pellets for subsequent handling and drying operations. Finally, the pellets are dried for 1–3 days in a specially-designed column dryer[114] to yield pellets with high crushing strength. The key difference between the DBC and Coldry processes is the use of drying equipment in the latter. Note that the drying times are rather long. No data are available about the energy consumption for pelletizing and then drying.

Use of a binding agent

The use of various binders such as tar, pitch, petroleum residues, humic acid, PVC, atactic polypropylene, plastic waster, wood pulp waster liquor, molasses, biomass, starch, lime, clay, ceramic, etc, have been reported in both patent and archival literature.[115,116] In the past, excessive use of heavy oil as binder in coal briquettes resulted in briquettes with poor grindability, leading to higher grinding costs at coal-fired power plants. This was addressed in a patent document by Yamamoto et al.[117] who outlined a coal briquetting process that coats the external surface of the briquettes with oil without using excessive oil to bind the particles within the briquette. It is not clear if the oil will infuse into the particle.

Lignin and cellulose in biomass can also be used as binders as they exhibit binding property when heated or hydrolysed. White[116] described the production of coal briquettes by spraying a biomass binder on the coal fines followed by mixing at 150–200 ºC. He reports that the use of a suitable biomass binder produces coal pellets that are around 28–94 % stronger than ‘pure’ coal pellets. It is to be noted that the binder material is produced from the liquefaction of biomass at temperatures of 230–370 ºC and pressures of 1.3–20 MPa in the absence of air. Thus, the use of the biomass binder produced from an energy intensive process increases the overall cost and energy consumption in producing coal briquettes.

In view of the above limitations, Malhotra[118] described a coal briquetting process that makes use of lignin in biomass as binder without the need for liquefaction. In this process the lignin and coal particles are separately ground and dried—to around 17% and 13% moisture by weight, respectively, and ground again until the particles are sized approximately 1–2.5 mm. The grinding and drying process raises the temperature of the coal-lignin mixture (approximately 2:3 ratio) to around 90 ºC, eliminating the need for further heating during extrusion by a roller press at a pressure of 13.7–24.1 MPa. At these conditions, the resulting briquettes were reported to have about 12% moisture by weight, a heating value of 15–20 MJ/kg, and density of 1700 kg/m^3.

The use of a binding agent prevents the compressed material from returning to its original form. The softening of binding agents at elevated temperatures and its subsequent hardening upon cooling result in hard and compact agglomerate that do not break easily. However, the strength of the briquette is largely dependent on the properties of the raw materials, the amount of binder added, and the process conditions.

Equipment

Several types of equipment for coal and biomass densification exist, with technologies ranging from very simple to very complex devices. The equipment vary in terms of physical size, operating pressure and temperature, power, throughput, feeding device, manual or automatic operation, etc. In general, there are five main types of briquetting equipment: piston press, screw press, roll press, pellet press, and manual press.[119]

In a screw extruder press, the biomass is extruded continuously by a screw through a heated tapered die. The wear of parts in contact with extrusion material is less in a piston press compared to the wear of the screw and die in a screw extruder press due to less relative motion between contact parts and extrusion material in the former. In addition, the piston press generally requires less power than a screw press of similar capacity. However, screw presses are known to produce superior quality and uniform-sized briquettes at a continuous rate compared to the relatively brittle briquettes produced by the piston press technology.

Advantages and limitations

Briquetting of coal and coal-biomass mixture offers many advantages. Firstly, the densification of loose coal/biomass residues converts unwanted material into a product with high economic value. Compared to high rank coal, brown coal is typically a relatively clean fuel with less sulfur and ash contents[112] (refer to Table 7). When densified, brown coal briquettes are a stable fuel that is uniform in size and quality, and provides a heating value that is comparable to black coal. Coal briquettes generally yield high thermal efficiency upon combustion and produce less CO_2, SO_2 and fly ash. The compacting of loose lignite reduces transportation cost, and enables handling and storage of solid fuel with minimal breakage.

Table 7. Comparison of brown coal and black coal with densified brown coal from Morwell (Victoria) seam.[112]

	Brown coal Morwell, Vic	**Black coal Tarong, Qld**	**Densified brown coal**
Moisture	59.3% wb	5.2% adb	15.9% adb
Volatile matter	49.2% wb	29.7% db	48.9% db
Fixed carbon	48.85% db	40.9% db	49.15 db
Ash	2.4% db	29.4% db	2.4% db
Total sulfur	0.3% db	0.42% db	0.3% db
GSE	27.2 MJ/kg daf	31.98 MJ/kg daf	27.2 MJ/kg daf
NWSE	8.4 MJ/kg	21.3 MJ/kg	22.0 MJ/kg adb
Bulk density	1130 kg/m^3		1200–1700 kg/m^3

Combination of LRC and biomass in the production of briquettes yields strong briquettes without the need for costly binders. Moreover, biomass is easily available at low cost, making the production of LRC briquettes both sustainable and profitable. Briquetting also allows the processed LRC to be safely stored and transported without the concern of spontaneous combustion since densification of loose coal particles substantially reduces its exposure to the environment. Furthermore, an additional step can be taken to eliminate moisture readsorption in briquettes such as coating with oil or other hydrophobic compounds.

The manufacturing cost remains one of the main obstacles towards large-scale adoption of coal briquettes in power generation. Cost is largely attributed to the power requirements of the briquetting system and to the cost of the binder material. As we have outlined above, the briquetting process involves grinding, drying and extrusion of the agglomerate. These procedures can consume enormous amounts of energy. The use of binders is necessary to produce briquettes of sufficient strength but add to the cost of producing the briquettes. Eliminating the use of binders altogether is possible but must be compensated by compacting or extrusion at very high pressures around 138 MPa.[120] More R&D is needed to reduce energy-intensity of briquetting and to make a systematic comparison of alternative processes.

12. COMPARISON OF DRYERS

Various drying methods have been discussed so far which are essentially used for coal drying. As discussed earlier, no universal choice is available for coal dewatering because of various reasons pointed out in the aforementioned discussion. Table 8 discusses various commercial drying techniques reported for coal drying, their salient features and possibilities of improvement. It should be noted that there exists lot of scope to optimize each drying method and make it more sustainable. It is necessary to minimize the overall energy consumption in LRC drying and make the drying cost effective in order to make LRC competitive to high grade coals. Hence more innovative needs to be evaluated besides just improving the drying system. This may include use of hybrid dryers, over-drying a part of coal and then mixing it with a wet coal which ultimately can achieve a certain acceptable moisture level. The use of renewable energy sources such as solar and wind energy for coal drying at the mine site can make it more sustainable and more attractive.

Table 8. Scope of improvement for innovative dryers.

Dryers	**Features**	**Scope of improvement**
Rotary dryers		

Yamato	Aeration of particle bed using air blown in through pipes	New designs of flights Use of internal heat exchangers Improvement in hot air injection system Model-based control
Roto-Louvre	Aeration of particle bed using air blown in through Louvres	
Triple-pass	Serpentine flow of particles through three concentric shells.	
Impinging stream	Complex internal elements to achieve impingement-like flow of particles	
Single-pass with core	Internal flights designed for long particle pathway in high velocity gas stream. Core provides a region of low velocity to increase residence time.	
Steam-in-tube	Indirect drying of solids by contact with heated tube walls.	
Fluidized bed dryers		
Multi-stage	Drying in stages using two or more FBDs in series.	Improve the quality by mechanical means such as agitation, vibration, pulsation etc for particles from Geldart 'C' and 'D' type Use of combined heat transfer modes Improve gas distribution system, better design of gas chamber and distribution plate
Multi-level	Drying in stages using a single FBD with multiple levels.	
Pulsed	Involves the expansion of bed using a lower gas velocity, and pulse fluidization of bed using higher gas velocities.	
With immersed heater	Immersing a heater or heat exchanger in the bed region.	
Microwave dryers		
Conveyor-type	Passing of solids through a series of MW chambers	Mainly cost reduction by converting maximum MW energy into heat Minimize losses Possibility of using renewable energy source at mine site to generate MW
Use with FBD	Irradiating solids in FBD with MW energy.	
Screw conveyor		
Multi-stage dryer	Drying in stages using two or more SCDs in series.	Use of variable screw pitch Use of paddles in between two flights for better mixing Providing more heat transfer area per unit length of the screw
As a dewatering tool	Use of tapered shaft screw conveyor to express water out of sludge material.	

Self-heat recuperation	Recuperating of exergy from superheated steam to reduce energy usage of drying processes.	Minimizing the compression cost in order to make it more attractive Minimizing the use of non-condensable by using vibrated bed dryer or similar
Integrated Drying	Integration of drying process with electricity generation through the use of plant waste heat for drying of lignite.	
Solvent displacement	Using hydrocarbons (e.g. DME) to displace water from coal followed by solvent recovery.	Developing more efficient solvent recovery processes

13. FINAL REMARKS

Conventional coal drying techniques pose a number of limitations. Firstly, complexity of the drying operation may translate into high capital and operating cost. For example, many drying systems make use of a multiplicity of heat exchangers, cyclones and condensers. Second, many systems, especially those that use steam or inert gas as drying medium, utilize large boilers and compressors to achieve high operating pressures and temperatures. This arises from the need to obtain high drying temperatures amidst high heat loss and poor heat exchange rates. Finally, conventional coal drying techniques produce substantial amounts of coal fines due to weakened coal structure caused by removal of water. Presence of excessive coal fines poses risk to safety, pollutes the environment, demanding substantial resources for its suppression. It is always important to calculate the bottom-line and the cost-effectiveness of any drying system selected. Since drying is a mean of upgrading LRC so that it can be sold at a higher price, it is important to calculate *a priori* the economic benefit accrued due to reduced transportation cost and increased market value a result of improved calorific value. Sulfur content and ash content of the LRC have important consequence on the market value as well.

Despite numerous types of available dryers, literature on the design, scale-up and techno-economic aspects of LRC drying is still sketchy and difficult to compare on a consistent basis. Industry-academia interaction and testing at pilot scale at mine sites is essential to make a major improvement in LRC drying technology as suggested by Mujumdar.[121] Scale up of dryers from lab or even pilot size equipment is difficult. In the case of LRCs the diverse properties of coals makes testing at pilot scale imperative in the development of new technologies that are efficient and safe as well as cost-effective.

REFERENCES

1. Li, C.Z. Advances in the science of Victorian brown coal. Elsevier Science, 2004.
2. Bratek, K.; Bratek, W.; Gerus-Piasecka, I.; Jasieńko, S.; Wilk, P. Properties and structure of different rank anthracites. Fuel 2002, 81(1), 97-108.
3. Karthikeyan, M.; Zhonghua, W.; Mujumdar, A.S. Low-rank coal drying technologies-current status and new developments. Drying Technology **2009**, 27(3), 403-415.
4. Willson, W.G.; Walsh, D.; Irwinc, W. Overview of low-rank coal (LRC) drying. International Journal of Coal Preparation and Utilization **1997**, 18(1), 1-15.
5. Lucarelli, B. Benefits of drying Indonesian low rank coals. Cleaner Coal Workshop, Vietnam, August 19-21, 2008.
6. Karthikeyan, M. Minimization of moisture readsorption in dried coal samples. Drying Technology **2008**, 26(7), 948-955.
7. Jangam, S.V.; Karthikeyan, M.; Mujumdar, A.S. A critical assessment of industrial coal drying technologies: role of energy, emissions, risk and sustainability. Drying Technology **2011**, 29(4), 395-407.
8. Perry, G.J.; Allardice, D.J.; Kiss, L.T. The chemical characteristics of Victorian brown coal. In The Chemistry of Low-Rank Coals; Schobert, H.H., Ed.; ACS Publication, 1984; 3-14.
9. Sondreal, E.A.; Mann, M.D.; Weber, G.W.; Young, B.C. Advanced power assessment for Czech lignite. Technical report. Energy & Environment Research Center, University of North Dakota, 1995.
10. Tian, D.; Liu, X.; Ding, M. CS2 extraction and FTIR & GC/MS analysis of a Chinese brown coal. Mining Science and Technology (China) **2010**, 20(4), 562-565.
11. Umar, D.F.; Usui, H.; Daulay, B. Change of combustion characteristics of Indonesian low rank coal due to upgraded brown coal process. Fuel Processing Technology **2006**, 87(11), 1007-1011.

12. Xu, R.; He, Q.; Cai, J.; Pan, Y.; Shen, J.; Hu, B. Effects of chemicals and blending petroleum coke on the properties of low-rank Indonesian coal water mixtures. Fuel Processing Technology **2008**, 89(3), 249-253.
13. Küçükbayrak, S.; Kadioğlu, E. Effect of pyrolysis on the proximate and ultimate analysis of lignite. Thermochimica Acta **1989**, 155, 1-6.
14. Ruppert, L.F.; Kirschbaum, M.A.; Warwick, P.D.; Flores, R.M.; Affolter, R.H.; Hatch, J.R. The US Geological Survey's national coal resource assessment: the results. International Journal of Coal Geology **2002**, 50(1-4), 247-274.
15. Smith, K.L.; Smoot, L.D. Characteristics of commonly-used US coals-Towards a set of standard research coals. Progress in Energy and Combustion Science **1990**, 16(1), 1-53.
16. Ferguson, J.A.; Rowe, M.W. Calorific value of lignites from proximate analysis. Thermochimica Acta **1986**, 107, 291-298.
17. Osvalda, S.; Piero, S.; Sabato, M. The influence of heat treatment and weathering on the gasification reactivity of Montana lignite. Proceedings of the Twenty-Seventh Symposium (International) on Combustion, 2-7 August, Boulder, Colorado, 1998; 2991-2999.
18. Mujumdar, A.S.; Devahastin, S. Classification and selection of industrial dryers. In Mujumdar's Practical Guide to Industrial Drying; Devahastin, S., Ed.; Exergex Corp.: Montreal, Canada, 2000.
19. Kudra, T.; Mujumdar, A.S. Special drying technologies. In Advanced Drying Technologies; Kudra, T., Mujumdar, A.S., Eds.; CRC Press: Boca Raton, Florida, 2009; 427-462.
20. Wilver, P.J.; Brumbaugh, C.A. Thermal drying of low rank coals using the fluid bed method. Proceedings of the 13th Biennial Lignite Symposium, 21-23 May, Bismarck, North Dakota, 1985.
21. Krokida, M.; Marinos-Kuoris, D.; Mujumdar, A.S. Rotary drying. In Handbook of Industrial Drying; Mujumdar A.S., Ed.; CRC Press: Boca Raton, Florida, 2007; 151-171.
22. Revol, D.; Briens, C.L.; Chabagno, J.M. The design of flights in rotary dryers. Powder Technology **2001**, 121(2-3), 230-238.
23. Butler, T.G. Method and apparatus of rotatable drum dryer with flights releasably secured in different orientations, U.S. Patent 5515620, 1996.

24. Dillman, B.A. Apparatus and method for controlling the flow of material within rotary equipment, U.S. Patent 6726351, 2004.
25. Christensen, J. Rotary dryer and associated drying plant, U.S. Patent 5197204, 1993.
26. FMC Technologies, Roto-Louvre Dryer. Available at: http://www.fmctechnologies.com/en/MaterialHandlingSolutions/Technologies/DryingandCooling/RotoLouvre/RotoLouvreDryer.aspx (accessed 2011).
27. Erisman, J.L. Roto-louvre dryer. Industrial & Engineering Chemistry **1938**, 30(9), 996-997.
28. Sambamurthy, K. Drying. In Pharmaceutical Engineering; New Age International: New Delhi, India, 2007; 295-328.
29. Schobert, H.H. Beneficiation of lignite. In Lignites of North America; Elsevier Science: Amsterdam, The Netherlands, 1995; 451-504.
30. Yamato, Y. Aeration-type rotary dryer, U.S. Patent 5996245, 1999.
31. Livingston, J.T.; Livingston, A.D. Rotary drum dryer, U.S. Patent 5555639, 1996.
32. Livingston, A. Rotary impinging stream dryer, U.S. Patent 7155841, 2007.
33. Duske, W.P.; Hogue, R.T.; Koesli, K.J. Single pass rotary dryer, U.S. Patent 5746006, 1998.
34. Bill, C.E. Rotary steam tube dryer. Industrial & Engineering Chemistry **1938**, 30(9), 997-999.
35. Akira, N.; Keiichi, K.; Takeshi, W.; Huminobu, O.; Yoshiaki, H.; Katsuhisa, M. Coal moisture control process, EU Patent EP0370144, 1988.
36. Kawasaki Heavy Industries. Coal-in-Tube dryer. Available at: http://www.khi.co.jp/english/kplant/business/industry_infra/industry/charcoal.html (accessed 2011).
37. Alexander, D.J.; Sindelar, R.A. Combined direct and indirect rotary dryer with reclaimer, U.S. Patent 5305533, 1994.
38. Dunlop, D.D.; Kenyon, L.C. Process for drying coal, U.S. Patent 7537622, 2009.
39. Holmberg, H.; Ahtila, P. Comparison of drying costs in biofuel drying between multi- stage and single-stage drying. Biomass and Bioenergy **2004**, 26(6), 515-530.
40. Stone, L.H. Circular vibratory fluid bed dryer, U.S. Patent 6829840, 2004.
41. Kason Corporation. Technical Library - Fluid bed dryer-screener system. Available at: http://www.kason.com/TechnicalLibrary/index.php?sType=1&ArticleID=551 (accessed 2011).

42. Kudra, T.; Mujumdar, A.S. Drying in pulsed fluidized bed. In Advanced Drying Technologies; CRC Press: Boca Raton, Florida, 2009; 77-88.
43. Kudra, T.; Gawrzynski, Z.; Glaser, R. Pulsed fluidised bed, U.S. Patent 5918569, 1999.
44. Prachayawarakorn, S.; Tia, W.; Poopaiboon, K.; Soponronnarit, S. Comparison of performances of pulsed and conventional fluidised-bed dryers. Journal of Stored Products Research **2005**, 41(5), 479-497.
45. Li, Z.; Su, W.; Wu, Z.; Wang, R.; Mujumdar, A.S. Investigation of flow behaviors and bubble characteristics of a pulse fluidized bed via CFD Modeling. Drying Technology **2010**, 28(1), 78-93.
46. Groenewold, H.; Tsotsas, E. Drying in fluidized beds with immersed heating elements. Chemical engineering science **2007**, 62(1-2), 481-481.
47. Gutfinger, C.; Abuaf, N. Heat transfer in fluidized beds. Advances in Heat Transfer **1974**, 10, 167-218.
48. Cha, C.Y.; Merriam, N.W.; Boysen, J.E. Inclined fluidized bed system for drying fine coal, U.S. Patent 5087269, 1992.
49. Ladt, M.A. Method of drying fine coal particles, U.S. Patent 4444129, 1984.
50. Legros, R.; Chaouki, J.; Bi, X.T.; Macchi, A.; Ratnani, K. Spout-fluid bed dryer and granulator for the treatment of waste slurries, U.S. Patent 5913588, 1999.
51. Ishii, T.K. Handbook of Microwave Technology Applications; Academic Press: San Diego, California, 1995.
52. Jones, P.L.; Rowley, A.T. Diaelectric dryers. In Industrial Drying of Foods; Baker, C.G.J., Ed.; Springer: The Netherlands, 1997; 157-177.
53. Fu, Y.C. Fundamentals and industrial applications of microwave and radio frequency in food processing. In Food Processing: Principles and Applications; Smith, J.S., Hui, Y.H., Eds.; Wiley-Blackwell: Ames, Iowa, 2004; 79-100.
54. Zhang, M.; Tang, J.; Mujumdar, A.S.; Wang, S. Trends in microwave-related drying of fruits and vegetables. Trends in Food Science & Technology **2006**, 17(10), 524-534.
55. Learey, T.R.; Drozd, J.M. Microwave drying of coal, U.S. Patent 7666235, 2010.
56. Latchum, J.W.J. Apparatus and method for drying solid materials, U.S. Patent 4567340, 1986.

57. Weinberg, J.L.; Ginther, N.E.; Aten, J.A.; Wang, R.T. Pre-burning, dry process methodology and systems for enhancing solid fuel properties, U.S. Patent 7901473, 2011.
58. Weinberg, J.L.; Ginther, N.E.; Aten, J.A.; Wang, R.T.; Drozd, M.J. Methods and system for enhancing solid fuel properties, U.S. Patent 20070295590, 2007.
59. Hein, W.; Granger, B. Tilting microwave dryer and heater, U.S. Patent 20080282573, 2008.
60. Hein, W.; Granger, B. Microwave dryer, U.S. Patent 20050082283, 2005.
61. Souraki, B.A.; Andres, A.; Mowla, D. Mathematical modeling of microwave-assisted inert medium fluidized bed drying of cylindrical carrot samples. Chemical Engineering and Processing: Process Intensification **2009**, 48(1), 296-305.
62. Smith, F.J. Microwave fluidized bed dryer, U.S. Patent 3528179, 1970.
63. Doelling, M.K. Microwave assisted fluidized bed processor, U.S. Patent 4967486, 1990.
64. Weng, S.; Wang, J. Exploration on the mechanism of coal desulfurization using microwave irradiation/acid washing method. Fuel processing technology **1992**, 31(3), 233-240.
65. Yang, J.K.; Wu, Y.M. Relation between dielectric property and desulphurization of coal by microwaves. Fuel **1987**, 66(12), 1745-1747.
66. Rowson, N.A.; Rice, N. Desulphurisation of coal using low power microwave energy. Minerals Engineering **1990**, 3(3-4), 363-368.
67. Schiffmann, R.F. Microwave and diaelectric heating. In Handbook of Industrial Drying; Mujumdar A.S., Ed.; CRC Press: Boca Raton, Florida, 2007; 286-304.
68. Constant, T.; Moyne, C.; Perre, P. Drying with internal heat generation: Theoretical aspects and application to microwave heating. AIChE Journal **1996**, 42(2), 359-368.
69. Comolli, A.G. Drying and passivating wet coals and lignite, U.S. Patent 4249909, 1981.
70. Okada, K. Resin pellet dryer, Euro Patent EP1553369, 2004.
71. Maffet, V. Mechanical dewatering process utilizing a non-uniform screw conveyor, U.S. Patent 4380496, 1983.
72. Waje, S.S.; Thorat, B.N.; Mujumdar, A.S. An Experimental Study of the Thermal Performance of a Screw Conveyor Dryer. Drying Technology **2006**, 24(3), 293-301.
73. Forcade, M.P. Screw Conveyor 101. Goodman Conveyor Company, 1999.
74. Fayed, M.E. and Skocir, T.S. Mechanical Conveyors. CRC Press, 1996.
75. Gentry, C.C. Apparatus and method for beneficiation of lignite. U.S. Patent 4448678, 1984.

76. Costarelli, E. Screw drier particularly for plastic materials, U.S. Patent 4520724, 1985.
77. Mccabe, M.M.; Dowd, B.S. System and method for removing a volatile component from a matrix, U.S. Patent 5216821, 1993.
78. Mentz, J.W. Horizontal dryer having a screw conveyor and ring electrical heating elements, U.S. Patent 5531034, 1996.
79. Azuma, K. Screw conveyor system of drier for waste containing water, Japan Patent JP2001165572, 2001.
80. Faber, E.F.; Heydenrych, M.D.; Seppa, R.V.I.; Hicks, R.E. A technoeconomic compression of air and steam drying. Drying **1986**, 86, 588-594.
81. Mujumdar, A.S., Superheated steam drying: principles practice and potential for use of electricity, Report No. 817, U 671. Canadian Electrical Association, 1990.
82. Suwono, A. Upgrading the Indonesian's low rank coal by superheated steam drying with tar coating process and its application for preparation of CWM. International Journal of Coal Preparation and Utilization **1999**, 21(1), 149-159.
83. Bongers, G.D.; Jackson, W.R.; Woskoboenko, F. Pressurised steam drying of Australian low-rank coals: Part 1 Equilibrium moisture contents. Fuel processing technology **1998**, 57(1), 41-54.
84. van Deventer, H.C. Industrial superheated steam drying. TNO 2004. Available at: http://gasunie.eldoc.ub.rug.nl/FILES/root/2004/3337003/3337003.pdf (accessed 2011)
85. Shaffer, D.B. Upgrading Carbonaceous Materials. USA Patent 20100005710, 2010.
86. Fushimi, C.; Kansha, Y.; Aziz, M.; Mochidzuki, K.; Kaneko, S.; Tsutsumi, A; Matsumoto, K; Yokohama, K; Kosaka, K; Kawamoto, N. Novel drying process based on self-heat recuperation technology. Drying Technology **2011**, 29(1), 105-110.
87. SPE Dieffenbacher Group, Superheated steam dryer. Available at: http://www.dieffenbacher.de/en/wood-based-panel-division/fiberboard-lines/frontend/hot-steam-fiber-dryer.html (accessed 2011).
88. Pang, S.; Pearson, H. Experimental investigation and practical application of superheated steam drying technology for softwood timber. Drying technology **2004**, 22(9), 2079-2094.
89. Defo, M.; Fortin, Y.; Cloutier, A. Modeling superheated steam vacuum drying of wood. Drying technology **2004**, 22(10), 2231-2253.

90. Rozgonyi, T.G.; Szigeti, L.Z. Upgrading of high moisture content lignite using saturated steam. Fuel processing technology **1985**, 10(1), 1-18.
91. Dieffenbacher, Superheated Steam Flash Dryer. Available at: http://www.dieffenbacher.de/en/dieffenbacher-group/group-wood-based-panel-division/schenkmann-piel-engineering-germany/products/superheated-steam-flash-dryer.html (accessed 2011).
92. GEA Niro, The pressurized steam fluid bed dryer system. Available at: http://www.niro.com/niro/cmsdoc.nsf/webdoc/ndkk5hvee2 (accessed 2011).
93. GEA Barr-Rosin, Superheated steam drying. Available at: http://www.barr-rosin.com/products/super-heated-steam-drying.asp (accessed 2010).
94. Bowling, C.M. Method for producing dried particulate coal fuel and electricity from a low rank particulate coal, U.S. Patent 5137539, 1992.
95. Rao, A.D.; Goodland, D.C. Integrated drying of feedstock feed to integrated combined-cycle gasification plant, U.S. Patent 5953899, 1999.
96. Levy E.K.; Sarunac N.; Bilirgen H.; Caram H. Use of coal drying to reduce water consumed in pulverized coal power plants – Final report. Lehigh University, 2006.
97. Allardice, D.; Young, B.C. The utilisation of low rank coals. Australian Coal Review **2000,** 40-46.
98. HRL Loy Yang IDGCC. Available at: http://www.zeroco2.no/projects/mulgrave (accessed 2011).
99. Ness, M.A.; Coughlin, M.P.; Wheeldon, J.M.; Johnson, A.M. Control system for particulate material drying apparatus and process, U.S. Patent US7987613, 2011.
100. Ness, M.A.; Coughlin, M.P.; Levy, E.K.; Sarunac, N.; Wheeldon, J.M. Apparatus and method of separating and concentrating organic and/or non-organic material, USA Patent US7540384, 2009.
101. Ness, M., Lignite fuel enhancement: incremental moisture reduction program phase 1 Feb 2002 status report. Available at: http://www.nd.gov/ndic/lrc/lrcinfo/fy00-xxxvi-101.pdf (accessed 2011).
102. Ness, M., Lignite fuel enhancement: incremental moisture reduction program phase 2 Oct 2003 status report. Available at: http://www.nd.gov/ndic/lrc/lrcinfo/fy03-xlix-121.pdf (accessed 2011).

103. Bullinger, C. Case study: implementing coal drying. First International Symposium on the Sustainable Use of Low Rank Coals, Melbourne, Victoria, April 27-30, 2010.

104. Pikon, J.; Mujumdar, A.S. Drying of coal. In Handbook of Industrial Drying; Mujumdar A.S., Ed.; CRC Press: Boca Raton, Florida, 2007; 993-1016.

105. Murphy, C.L. Drying of lignite using non-aqueous solvents, U.S. Patent 4014104, 1977.

106. Cantu, T.S.; Williams, M.C. Alcohol/heavy liquid drying of coal, U.S. Patent 4498246, 1985.

107. Dean, M.W. Method for dehydrating wet coal, U.S. Patent 5815946, 1998.

108. Kudra, T.; Mujumdar, A.S. Displacement drying. In Advanced Drying Technologies; CRC Press: Boca Raton, Florida, 2009; 307-314.

109. Yoon, R.; Luttrell, G.H. Method for dewatering fine coal, U.S. Patent 5458786, 1995.

110. Kanda, H.; Makino, H. Energy-efficient coal dewatering using liquefied dimethyl ether. Fuel **2010**, 89(8), 2104-2109.

111. Kanda, H.; Makino, H.; Miyahara, M. Energy-saving drying technology for porous media using liquefied DME gas. Adsorption **2008**, 14(4), 467-473.

112. Johns, R.B.; Chaffee, A.L.; Harvey, K.F.; Buchanan, A.S.; Thiele, G.A. The conversion of brown coal to a dense, dry, hard material. Fuel Processing Technology **1989**, 21(3), 209-221.

113. Johns, R.B.; Chaffee, A.L.; Cain, D.A.; Buchanan, A.S. Upgrading solid fuels, U.S. Patent 4627575, 1986.

114. Wilson, D. Dryer, drying method and drying paint, U.S. Patent 20070294911, 2004.

115. Zhang, X.; Xu, D.; Xu, Z.; Cheng, Q. The effect of different treatment conditions on biomass binder preparation for lignite briquette. Fuel Processing Technology **2001**, 73(3), 185-196.

116. White, D.H. Pelletizing and briquetting of coal fines using binders produced by liquefaction of biomass, USA Patent 5916826, 1999.

117. Yamamoto, S.; Nagata, K.; Tanimichi, J.; Takebe, Y. Coal pellets production, U.S. Patent 4420445, 1983.

118. Malhotra, R. Coal particles briquette where the binder is lignin and methods and systems of preparing the same, U.S. Patent 20100154296, 2009.

119. Hood A.H. Biomass briquetting in sudan: a feasibility study. USAID, 2010. Available at: http://www.fuelnetwork.org/index.php (accessed 2011).

120. Vorres, K. Lignite and brown coal. In Kirk-Othmer Encyclopedia of Chemical Technology. John Wiley & Sons, 2010; 1-29.

121. Mujumdar, A.S. Editorial: development of new industrial drying technologies. Drying Technology **2011**, 29(11), 1249-1250.