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Progress in developments of dry coal beneficiation

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Abstract China's energy supply heavily relies on coal and China's coal resource and water resource has a reverse distribution. The problem of water shortages restricts the applications of wet coal beneficiation technologies in drought regions. The present situation highlights the significance and urgency of developing dry beneficiation technologies of coal. Besides, other countries that produce large amounts of coal also encounter serious problem of lack of water for coal beneficiation, such as American, Australia, Canada, South Africa, Turkey and India. Thus, dry coal beneficiation becomes the research hot-points in the field of coal cleaning worldwide in recent years. This paper systematically reviewed the promising research efforts on dry coal beneficiation reported in literature in last 5 years and discussed the progress in developments of dry coal beneficiation worldwide. Finally, we also elaborated the prospects and the challenges of the development of dry coal beneficiation.

Keywords Dry coal beneficiation · Air dense medium fluidized bed · Density segregation · Vibrated fluidized bed

1 Introduction

China's energy supply is heavily reliant on coal and this situation will last for decades to come. Now, China is the largest coal producer and consumer in the world. In 2012, China's coal production is up to 3.66 billion tons and coal consumption accounts for 68.4 % of its energy consumption. Thus, in order to improve energy efficiency and ensure the security of energy supply, China must increase the beneficiation ratio of run-of-mine coal. In 2013, the Chinese government released its toughest plan so far to combat air pollution, *Air Pollution Prevention Plan of Action*, in an effort to ease mounting public concern over air quality. In this plan, it is clearly pointed out that the beneficiation ratio of run-of-mine coal will be improved to more than 70 % till 2017 and apparently, a lot of continued efforts must be made to achieve this goal.

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Meanwhile, more than 70 % China's coal reserves in regions of Northwest China and North China and unfortunately, these regions are almost dry and have prolonged coal weather each year, which puts many obstacles to the deployment of wet beneficiation technologies for coal cleaning. Thus, it is imperative to develop efficient dry coal beneficiation technologies. Besides, other countries producing large amounts of coal also encounter serious problem of lack of water for coal beneficiation, such as American, Australia, Canada, South Africa, Turkey and India. Thus, in recent years, dry coal beneficiation technologies have progressively become the research hot-points in the field of coal cleaning worldwide and a lot of promising research efforts have been reported in literature.

Overall, in the section of dry coal beneficiation, the most significant properties of coal that facilitate the separation process are density, shape, friction, electricity, and magnetite. According the different beneficiating mechanisms, dry coal beneficiation reported in recent literature are mainly classified into the following five categories: (I) air dense medium fluidized bed separation with/without external force field, (II) fluidized bed separation based on the difference of settling velocity, (III) compound dry separation, (IV) triboelectrostatic separation and (V) magnetic separation. These five categories of technologies have their own advantages respectively in processing certain coal or yielding clean coal product with certain quality. Generally speaking, technologies belong to the categories (I), (IV) and (V) usually have high separation efficiency but high operational cost, which are suitable for producing high-quality clean coal. In contrast, technologies in categories (II) and (III) don't need additional dense medium or power and usually have larger capacities and low processing cost, but low separation efficiency due to the original limitation of separation mechanism. These technologies are suitable for producing steam coal. Besides, the electrostatic separation technologies and the magnetic separation technologies have high requirements for coal properties and certain degree of dissociation, thus, the handling capacities are limited. Considering these limitation, these two types of beneficiation technologies are only used in very special purpose. In the following sections, the representative research works in terms of the aforementioned technologies in the last five years are reviewed in detail and finally, we discuss the prospects and the challenges of the development of dry coal beneficiation.

2 Dry beneficiation with fluidized bed

Dry beneficiation of coal with an air dense-medium fluidized bed (ADMFB) uses a pseudofluid system of the mix of dense medium (such as magnetite powder) and fine coal powder as the separating medium and, within it, the feed coal conducts the sink-float processes based on Archimedes' principle. The light and heavy particles separate from each other by the separating density with light particles floating and heavy particles sinking (Chen and Yang 2003; Luo and Chen 2001; Luo et al. 2002a, 2003, 2007). The ADMFB separation differs in principle from pneumatic separating devices (using air as separating medium) such as air-tables and has comparatively high E values (Luo and Chen 2001).

2.1 Separation with air dense medium fluidized bed

China University of Mining and Technology (CUMT) has carried out numerous research works on ADMFB separation in the last about 30 years and developed a series of dry beneficiation techniques for coal cleaning including the bubbling fluidized bed (Luo and Chen 2001; Luo et al. 2002a; Zhao et al. 2011a, 2011b), the vibrated fluidized bed (Luo et al. 2008; Yang et al. 2013a), and the magnetically fluidized bed (Fan et al. 2001, 2002, 2003; Luo et al. 2002b). Zhao et al. (2010) carried out systematic studies experimentally and numerically on fluidization characteristics of air dense medium fluidized bed with fine magnetite powder and pointed out that the increase of superficial air velocity will significantly improve the bed activity, but meanwhile, deteriorate the uniformity and stability of fluidization. Therefore, the superficial air velocity no more than 2.0 u_{mf} (minimum fluidization velocity) is suggested for coal beneficiation. In addition, a method of numerical simulation of the fluidization of ADMFB was proposed to study the bubbling characteristics and the particles motions and the simulation results were consistent with the experimental results, as shown in Fig. 1.

Furthermore, Zhao et al. (2011) established a modularized industrial-scale ADMFB separation system with a capacity of 40–60 t/h, as show in Fig. 2. This system uses the steel structure instead of the recent reinforced concrete structure, leading to a reduction of the construction coast, the area and the number of workers by 60 %, 75 % and 80 %, respectively. The separation results show that this modularized system can effectively separate 50–6 mm coal with an E value in the range of 0.05–0.07.

Luo et al. (2013) studied the effect of a secondary gas-distribution layer on the fluidization characteristics of an

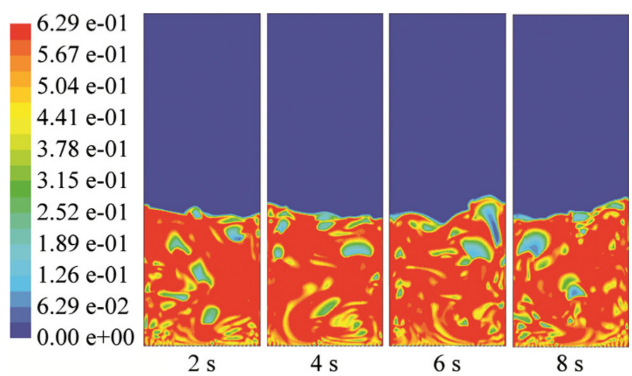

Fig. 1 Bubbling and particles motions observed by numerical simulation of ADMFB (Zhao et al. 2010)

Fig. 2 Modularized industrial-scale ADMFB separator

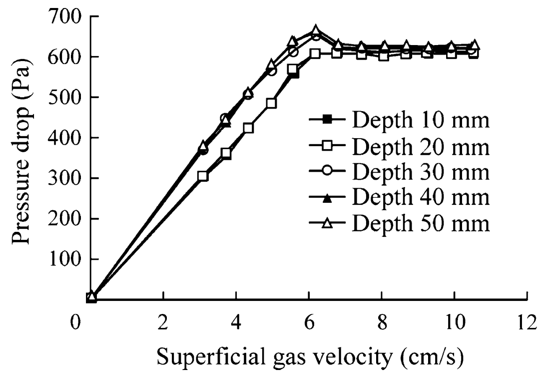

Fig. 3 Fluidization curves of an ADMFB with different secondary layer depth (Luo et al. 2013)

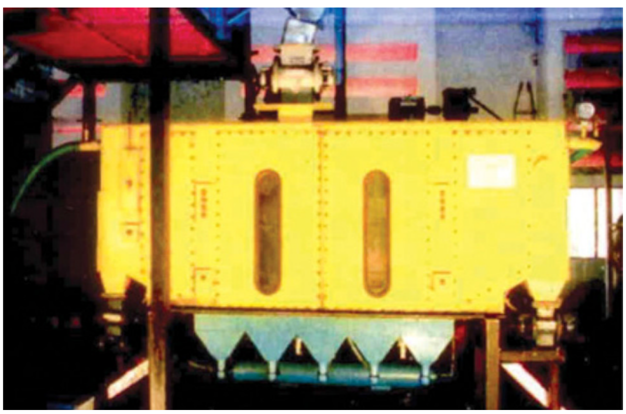

Fig. 4 Continous ADMFB separator for beneficiating Indian high ash coal (Sahu et al. 2011)

ADMFB for dry coal beneficiation and the experimental results show that the secondary layer with an optimal depth of 30 mm can significantly reduce the variance in both the bed pressure drop and the bed density, leading to an improvement in the fluidization quality, as shown in Fig. 3. It is also pointed out that the secondary layer can divide large bubbles passing through the region into small bubbles and can increase the pressure drop of the gas distributor. This work will provide a foundation for the design of the discharge structure of the bed and for calculating the capacity of the bed.

In similarity with China, India is heavily dependent on coal for meeting its energy requirements in economic development (Sahu et al. 2011). In these years, many research works on using the ADMFB separation for Indian coal cleaning have been done by Indian scholars. Sahu et al. (2009, 2011, 2013) used an ADMFB separator to beneficiate India high ash coal with a size range of −25 + 6 mm and studied the stability of fluidization to make an expansion bed with a nanobubbling condition. It was pointed out that the stability of the fluidized bed had a significant effect on sharp separation between clean coal and gangue. A continuous ADMFB separator with a capacity of 600 kg/h was established, as shown in Fig. 4. The separation results show that the ash content is reduced from 40 % in feed coal to around 32 %–35.5 % in clean coal product with a 60 %–72 % yield and the separation efficiency E value is 0.12.

Mohanta et al. (2011, 2012, 2013a, b) had made many efforts to optimize the operational parameters and the feed coal properties in order to achieving an optimum beneficiation performance of an ADMFB separator. It was pointed out that when the feed coal size is below 15 mm, the size effect on sharpness in separation becomes significant and the E values decrease faster. The experimental results indicate that for processing finer coal of size less than 15 mm, the ADMFB separator does not offer any real performance advantages better than the traditional process like heavy-medium cyclone and water-only cyclone. They also carried out a detailed investigation to examine the interdependencies among these parameters and their interactional effect on the separation performance of an ADMFB separator. The optimization results show that the optimum conditions were: superficial air velocity from 18.94 to 20.42 cm/s, bed height from 25.94 to 29.36, and coal to magnetite weight ratio of 0.02. A correlation for the theoretical prediction of minimum fluidization velocity was proposed in the following:

$$u_{\mathrm{mf}} = \frac{\mu}{d_{\mathrm{p}}\rho_{\mathrm{f}}}\left(\sqrt{(41.96)^2 + 0.049\mathrm{Ar}} - 41.96\right)$$

where u_{mf} is the minimum fluidization velocity; μ, d_{p} and ρ_{f} are the air viscosity, the particle diameter and the air density, respectively; Ar is the Archimedes number. The predictive adequacy and reliability was evaluated by adopting a statistical analysis approach on the data available in the literature and the results indicate that this new correlation is useful and accurate for predicting the minimum fluidization velocity and designing an ADMFB.

Researchers in University of Alberta in Canada (Prashant et al. 2010; Azimi et al. 2013a, b) have also done many works on ADMFB separation. Prashant et al. (2010) studied the effect of operating parameters such as the type of media, fluidizing velocity and separating time on beneficiation performance investigated under both batch and continuous ADMFB separators which are demonstrated in Figs. 5 and 6 respectively. The separation results show that the ash content of −6 + 2 mm feed coal is reduced from 25 % to 10 % with a yield of 80 %.

Azimi et al. (2013a, b) used an ADMFB to separate low-rank coals in Canada and carried out a detail study of the factors including superficial air velocity, residence time, and bed height affecting the beneficiation performance of a

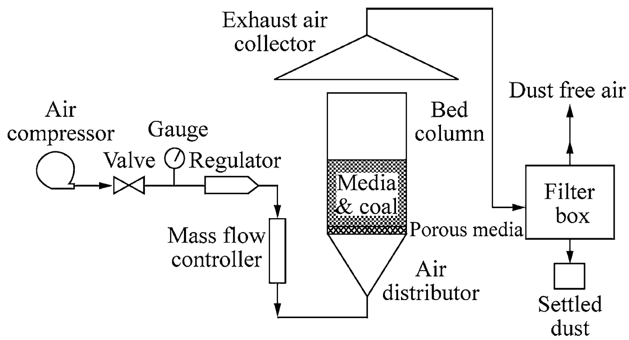

Fig. 5 Schematics of a laboratory batch ADMFB separator (Prashant et al. 2010)

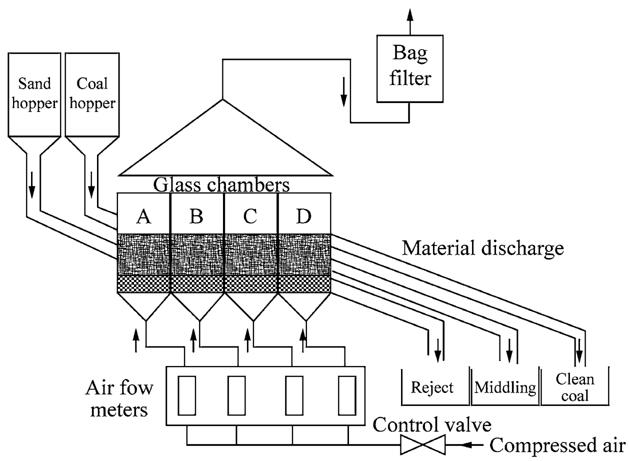

Fig. 6 Schematics of a laboratory continuous ADMFB separator (Prashant et al. 2010)

low-ash lignite coal. The experimental results show that the optimum operating condition is superficial air velocity of 15 cm/s, residence time of 90 s and bed height of 15 cm and in this condition, the beneficiation results revealed that higher ash removal (23 %) and recoveries (86 %) are obtainable with a clean coal ash content, recovery, and separation efficiency of 10.6 %, 95.63 %, and 15.29 %, respectively. In addition, it was also pointed out that feeding more coal to ADMFB resulted in higher organic material recovery and lower ash content of the product and system separation efficiency.

2.2 Separation with vibrated fluidized bed

The conventional ADMFB separation is not available recently to separate fine coal smaller than 6 mm in size because of low separation efficiency and difficult in dense medium recovery and product purification. Luo et al. (2008) introduced the vibration energy into conventional ADMFB for separating dry fine coal particles and systemically studied the vibrational energy transmission, the interaction between vibration and air and the separation performance of vibrated air dense medium fluidized bed (VADMFB). The results show that the bubble formation in a VADMFB is efficiently restricted to small bubbles due to the cutting effect derived from the horizontal vibration component and the extruding effect from the vertical vibration component. An empirical correlation of the critical vibration frequency above which the bubble can be restrained and broken was proposed:

$$f > \left(\frac{6Q}{\pi}\right)^{-1/5} g^{3/5}$$

where f, q and g are vibration frequency, air flow rate and gravitational acceleration, respectively. The synergy between vibration and air make the fine coal bed can be fluidized with both micro-bubbles and a uniform bed density. The separation results show that the VADMFB has a good separation performance for −6 mm fine coal under optimal operating conditions with an E value of 0.07.

Macpherson and Galvin (2010) and Macpherson et al. 2010, 2011) in the University of Newcastle in Australia introduced the Reflux Classifier, whose water-based version had been successfully employed in industry for gravity separation of −2 + 0.25 mm coal, into the field of dry coal beneficiation. This new Reflux Classifier uses sand (−335 + 125 micron) as a dense-medium and uses vibration at two distinct levels to improve fluidization stability, as shown in Fig. 7. There are two parts: a vibrated fluidized bed in the lower section and a device consisting of parallel inclined channels in the upper section. The addition of an incline above the fluidized bed provides a more stable system allowing for grater separation efficiency and

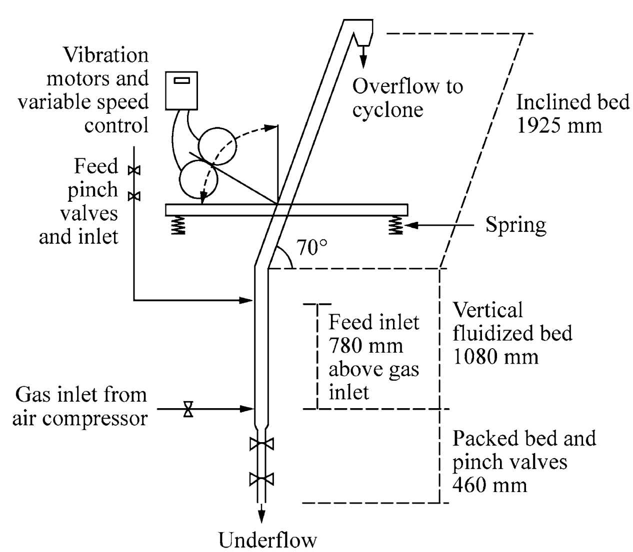

Fig. 7 Schematic diagram of the reflux classifier using air-sand dense-medium and vibration (Macpherson et al. 2011)

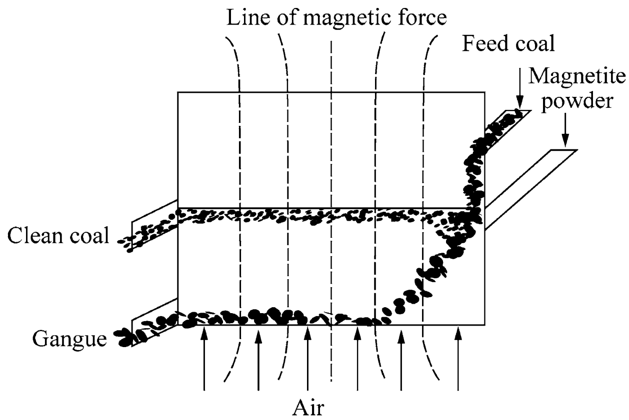

Fig. 8 Schematic diagram of the crossflow magnetically stabilized air dense medium fluidized bed (Song et al. 2012b)

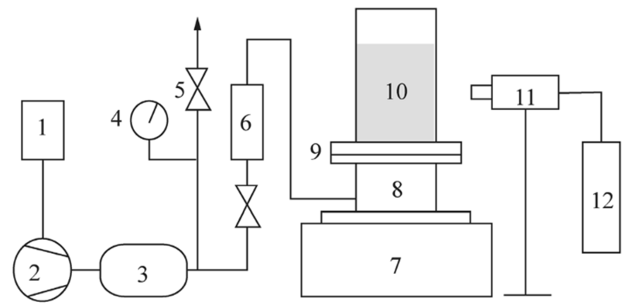

Fig. 9 Schematic diagram of the experimental apparatus (Yang et al. 2013b)

minimizing the effect of changing conditions. The density cut-point can be varied from 1,418 to 2,130 g/cm^3 by varying the underflow rate and the E value was within the range of 0.06–0.46 depending on particle size and gas rate.

2.3 Separation with magnetically stabilized air dense medium fluidized bed

Song et al. (2012a, b) in China University of Mining & Technology studied the continuous separation of $-6 + 0.5$ mm fine coal by using a crossflow magnetically stabilized air dense medium fluidized bed (MSADMFB) with the 0.074–0.045 mm magnetite beads as dense medium, as shown in Fig. 8. The fluidization results show that the range of steadily operational air velocity in MSADMFB is broader than that in a conventional ADMFB when they are at stable fluidization. The external magnetic field compels the magnetic grains to form parallel magnetic chains following the magnetic induction lines, which enlarge the bed voidage and form uniform air channels. Air bubbles cannot be produced when the air flows through the channels. Thus, a MSADMFB comparatively has a more stable bed density and smaller pressure fluctuation. The separation results show that the cross-flow MSADMFB can achieve successfully the separation of fine coal of $-6 + 0.5$ mm with a E value in the range of 0.068–0.095. It is also pointed out that the separation efficiency turns worse gradually with the decrease of the size of the fine raw coal.

3 Fluidization beneficiation without dense medium

For fine coal dry beneficiation, the fluidization separation using dense medium has several problem need to be solved, including the efficient recovery of fine dense medium and the purification of product. Meanwhile, the complex process and the relatively high operational costs due to the recovery and loss of dense medium also present great obstacle on the industrial applications of the fluidization separation with dense medium. Thus, some recent studies on fluidization beneficiation without artificial dense medium have been carried out in order to provide an efficient and economical solution for fine coal cleaning.

3.1 Vibro-fluidization beneficiation based on density segregation

Yang et al. (2013a, b) introduced the density segregation phenomenon in the field of gas–solid fluidization into the research on fine coal dry beneficiation and adopted a vibrated fluidized bed to foster the formation of fluidization environment that intensifies density segregation within the bed of fine coal, leading to an effective fine coal beneficiation performance. Figure 9 demonstrates the schematic diagram of the experimental apparatus and Fig. 10 depicts the separation mechanism. Particles in the region of a bubble having considerable lower solid volume fraction than the surrounding bulk phase conduct sink-float processes and particles with higher density tend to sink preferentially over the lighter particles, which leads to local density segregation. Thus, after the function of periodic bubbling, the local density segregation evolves the density segregation of total bed, leading to stratification of the particulate bed with the layers of clean coal, middling and gangue distribute along the bed height from top to bottom. The experimental results show that the operational parameters including superficial air velocity, vibration intensity, bed height and fluidizing time have significant influences on the segregation performance. The separation results show that the probable error E values of $-6 + 3$ and $-3 + 1$ mm fine coal separated in a continuous separation system using a vibrated fluidized bed are 0.19–0.225 and 0.175–0.195, respectively, indicating that the fine coal separation in a vibrated gas-fluidized bed system is useful to and more effective for fine coal cleaning.

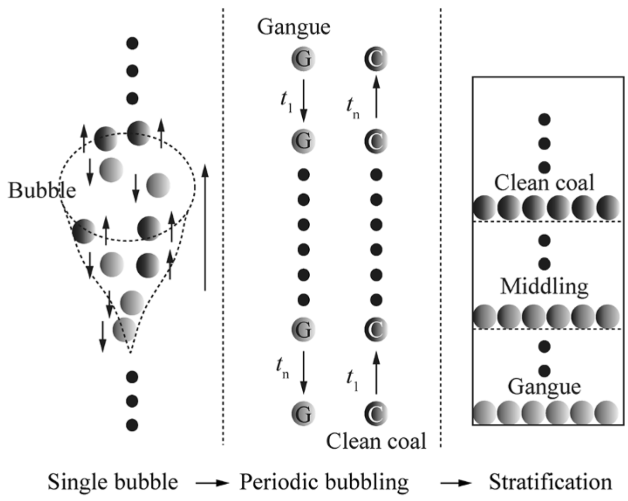

Fig. 10 Separation mechanism of vibro-fluidization beneficiation based on density segregation (Yang et al. 2013a)

3.2 Dry jigging

The air jig is a deep-bed separator that deploys the difference in hindered settling velocity of particles with different density, which is analogous to the proved wet jig. Air is supplied into the jig in two forms: a continuous flow and a superimposed pulsated airflow that provides the impetus for stratification and consolidation trickling. Sampaio et al. (2008) employed dry jigging to beneficiate Candiota coal in Brazil. This coal is low rank and can't be treated by any wet beneficiation technologies. The separation results show that the sulfur content reduces from 2.33 % in feed coal to 1.08 % in clean coal, providing a cheaper way than washing combustion gases. The detailed separation results are given in Fig. 11. Charan et al. (2011) used air jig manufactured by Allmineral Company in Germen to beneficiate Indian high-ash non-coking coals which contain high amounts of mineral matter. The first commercial air jig with a capacity of 50 t/h was installed and commissioned to separate −40 + 5 mm high-ash coals with an ash content of 40 %. The separation results show that a clean coal product with an ash content of 33 % was produced.

4 Compound dry beneficiation

Recently, researchers have studied and developed some innovative dry coal beneficiation technologies depending on not only the density difference, but the difference of other properties including coefficient of friction and shape. This compound dry beneficiation enhances the stratification process of coal and gangue in many aspects and leads to a stable and efficient separation performance.

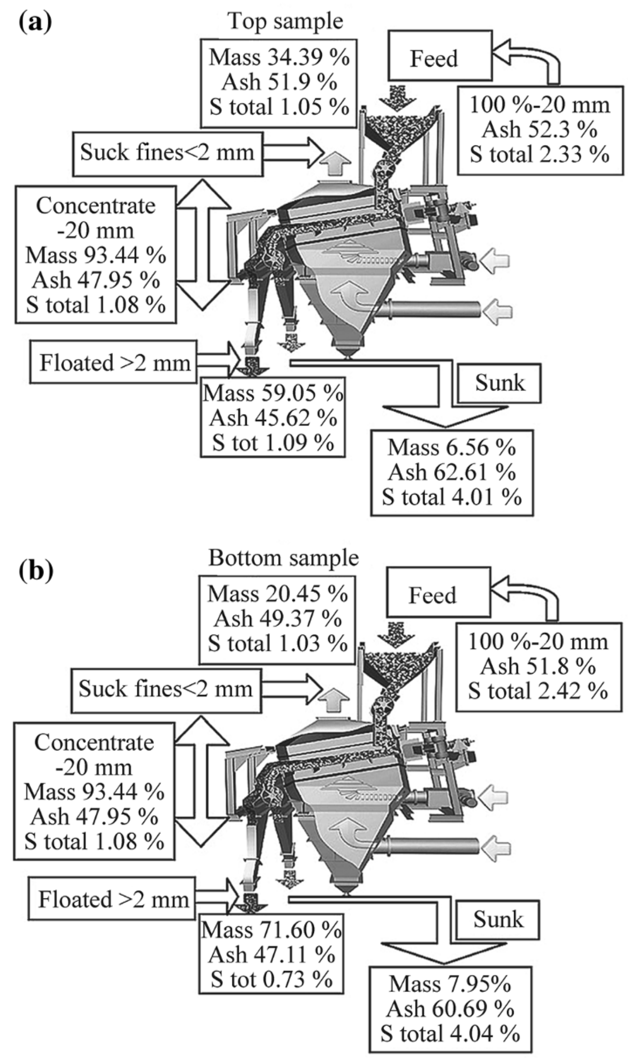

Fig. 11 Detailed separation results of air jig studied by Sampaio et al. (2008)

4.1 FGX dry separator

The FGX dry separator is firstly developed by China's researchers and already has several hundred commercial installations. It consists of a perforated separating bed, a vibrating mechanism, and a hanging support mechanism, shown as in Fig. 12. The deck vibration frequency, longitudinal deck angle, feeder frequency, and baffle plate height all have significant effects on the separation performance. Coal particles conduct the spiral flip motions under the synergy of vibration and air flow. The lighter particles rise to the top of the particulate layer and are collected in the front section of the separating bed as the clean coal product. Meanwhile, the heavy particles stay in the bottom of the particulate layer and keep contact with the bed. Thus, with the function of vibration and riffles fitted on the bed, these heavy particles move forward to the narrow section of the

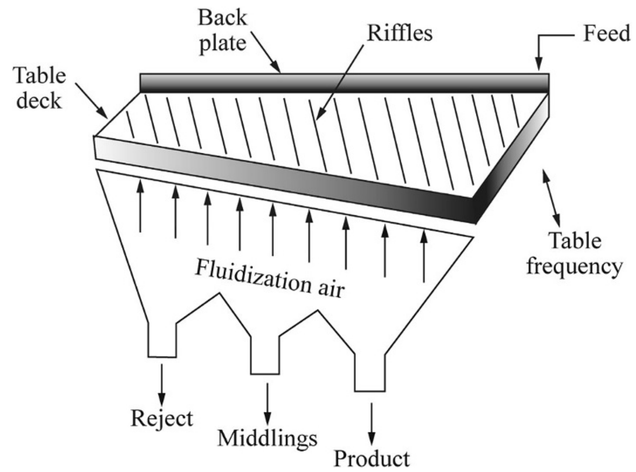

Fig. 12 Schematic diagram of the FGX dry separator and its processing system (Honaker et al. 2008)

bed and finally are discharged as gangue. Particles with intermediate density are discharged as middling. The FGX dry separator finally generates three products: clean coal product, middling, and gangue. Two dust collection systems are employed to clean the recycled air and to remove the dust from air before being emitted into the atmosphere.

Zhang et al. (2011) used a FGX dry separator with a capacity of 10 t/h to clean raw coals extracted from Illinois mines in America. The separation performance of the FGX dry separator was evaluated by separating the $-63.5 + 4.75$ mm coal and the results show that the specific gravity of separation and the probable error E values are 1.98 g/cm3 and 0.17, respectively. A modified log-logistic partition model was established using experimental data reported in literature and in this study to predict the FGX dry separator coal-cleaning performance, given in the following:

$$PN = 100 * \frac{1}{1 + \exp^{a * \ln \frac{x}{b}}}$$

$$X = D_m / D_{50}$$

where a and b are fitting constants; D_{m} is the mean density and D_{50} is the separation density.

Honaker et al. (2008) deployed a 5 t/h pilot-scale FGX dry separator to produce clean coal having qualities that meet contract specifications and maximize the amount of high-density rock rejected prior to transportation and processing. The separation results clearly indicate that the FGX dry separator is able to reject more than 70 % of the high-density rock in a run-of-mine coal at high separation density values of around 1.8–2.2 g/cm^3 with an E valued 0.25.

4.2 Air table

The air table has a flat deck with the uniformly distributed apertures and riffles. Ambient air after filtering enters the

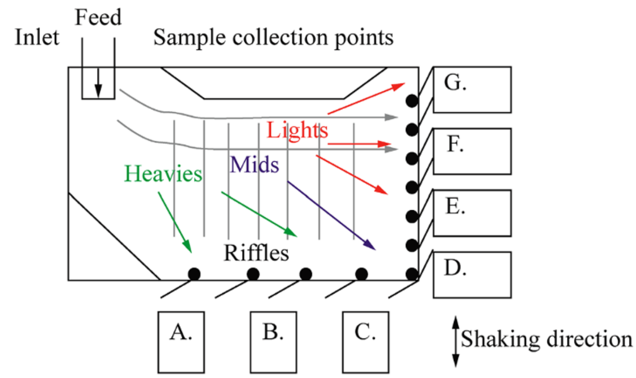

Fig. 13 Detailed separation results of air jig studied by Sampaio et al. (2008)

deck and fluidizes the feed coal. The feed coal stratifies depending on the difference in the terminal velocity of the particles. Particles with smaller density move to the top of the particulate layer and then travel down the slope towards the discharge open. Particles with larger density settle to the bottom of the particulate layer travel in the direction of the deck's vibration along the riffles. The schematic diagram of this separation process is shown in Fig. 13.

Patil and Parekh (2011) used a dry air table for processing of $-6.3 + 1.4$ mm coal from a mine located in Western Kentucky. The separation results show that the ash content is reduced from 27 % to 10 % with a clean coal yield of 75 %–80 % and the combustible recovery is 95 % with the ash rejection of 77 %–80 %. In addition, the pyritic sulfur is reduced by about 33 % and the heat content increases from 23,997 to 29,595 kJ/kg, indicating excellent separation efficiency.

Çicek (2008) developed a modified air table to beneficiate Turkish coal by a dry cleaning method and the separation results show that the coal samples having three size fraction of 8–5, 5–3 and 3–1 mm can be efficiently beneficiated by this modified air table with E values of 0.21, 0.14 and 0.09, respectively, indicating a satisfactory separation performance.

5 Triboelectrostatic separation

The triboelectrostatic beneficiation is an advanced dry fine coal cleaning technology and can effectively process fine coal of less than 300 μm (Dwari and Hanumantha Rao 2008; Zhang et al. 2009). During the process of triboelectrostatic separation, coal particles are charged by contact or friction with other particles or with a third material including the walls of a container or pipe and then conduct free-fall process through an electric field that deflects the particles according to the magnitude and sign of their charge. The mechanism of triboelectrostatic separation

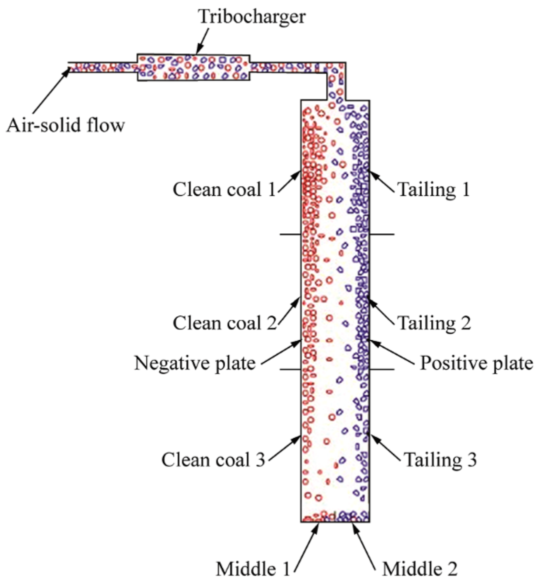

Fig. 14 Principle of triboelectrostatic separator and sampling rule (Zhang et al. 2009)

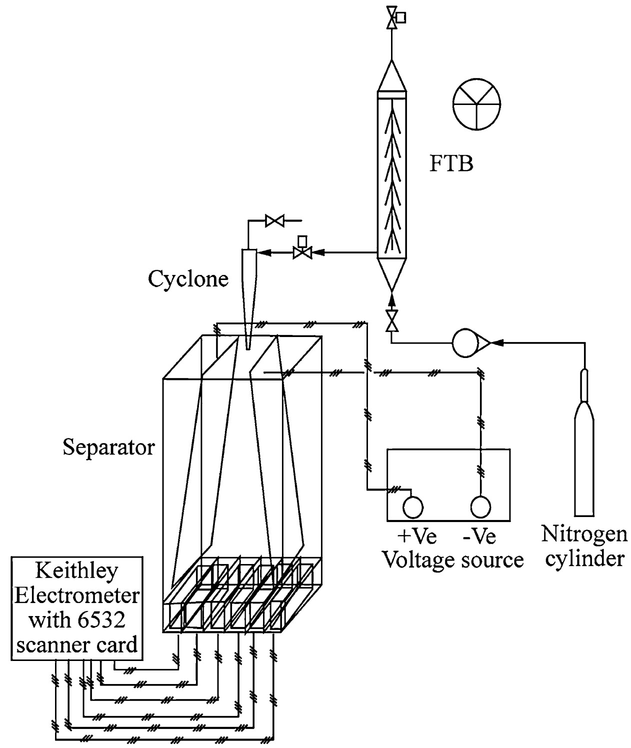

Fig. 15 Schematic diagram of experimental setup for electrostatic separation (Dwari and Hanumantha Rao 2009)

determines that the feed coal must achieve a certain degree of dissociation and the coal particles and the gangue particles mainly exist in the form of monomer. Therefore, this technology has a comparative small handling capacity and is usually used for producing high value-added clean coal product.

Zhang et al. (2009) deployed the triboelectrostatic separation of mineral matters from clean coal with density of < 1.35 g/cm^3 and the samples of feed coal with a size smaller than 75 μm was separated and analyzed with XRF, sulphur and ash analyzer. Figure 14 depicted the principle of triboelectrostatic separator and the sampling rule. The separation results showed that a quantity of quartz of 69.31 %–71.27 %, kaolin of 75.66 %–81.93 % and pyrite of 86.74 %–90.52 % could be removed and also indicated that coal would be charged positively and quartz, kaolin, pyrite and calcite would be charged negatively, leading to efficient separation of coal and these mineral matters.

Dwari and Hanumantha Rao (2008, 2009) used a new laboratory fluidized bed triboelectrostatic separator to beneficiate −300 μm Indian thermal non-coking coal from Ramagundam coal mines, shown as in Fig. 15. The tribocharger consisted of the internal baffles made up of copper metal and the coal and mineral particles charged with positive and negative polarities respectively. It was pointed out that the magnitude of particles charge is relevant with the efficiency of contact electrification in fluidized bed tribocharger. The separation results showed that the ash content can be reduced to 18 % and 33 % from 43 % in feed coal with an yield of about 30 % and 67 %, respectively.

6 Dry magnetic separation

Dry magnetic separation technology beneficiates coal powder depending on the different magnetic susceptibilities of coal and mineral materials under high gradient magnetic field. In similarity to triboelectrostatic separation technology, dry magnetic separation technology also requires that the feed coal has high degree of dissociation in order to facilitate the separating process of coal and gangue depending on magnetic susceptibilities difference. Meanwhile, dry magnetic separation technology also has comparative small handing capacity.

Jiao et al. (2009) used dry magnetic separation to improve desulphurization and deash efficiency of fine coal and investigated the relation between magnetic susceptibility and density, size as well as magnetic field intensity. The results showed that there is a linear correlation between magnetic susceptibility and density, as shown in Fig. 16. It was also pointed out that the magnetism of high density coal and low density coal was opposite at the cut density of 1.6 g/cm^3. Furthermore, the diamagnetism property of low density coal weakened and the paramagnetism of high density coal enhanced along with the size reduction of fine coal. The separation results showed that the desulphurization and deash rates achieved 55.52 % and 64.41 %, respectively.

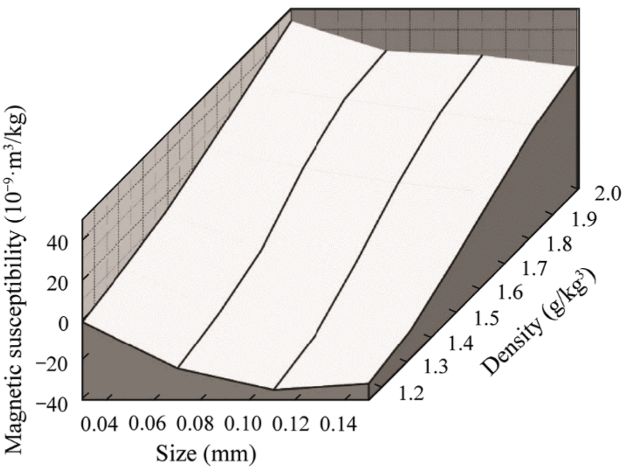

Fig. 16 The correlation between magnetic susceptibility and densiy and size (Jiao et al. 2009)

7 Prospects and challenges

Dry coal beneficiation has an inherent advantage since it uses no process water and reduces the costs that are associated with process water, fines dewatering and slurry confinement. In particular, dry coal beneficiation is more suitable for coal cleaning in dry regions that lack available processing water. Meanwhile, the low-rank coal easily conducts the process of argillation when using wet coal beneficiation, yielding the difficulties in slurry treatment and product dewatering. Therefore, dry coal beneficiation is comparatively more suitable for low-rank coal cleaning and upgrading. Countries that heavily relay on coal for energy supply all progressively exploit and utilize low-rank coal to meet the increasing required energy consumption and protect the hard coal resource. Thus, it is imperative to develop high-efficiency dry coal beneficiation to support the utilization of low-rank coal.

However, there are a lot of works need to be done in order to form a reliable and stable solution that consists of several dry coal beneficiation technologies. Especially the separation stability and the separation efficiency of dry coal beneficiation technologies should be further improved in future. Furthermore, some demonstrational industrial dry coal beneficiation systems should be established for engineering verification and academic studies, providing an advanced research platform to carry out sufficient industry-university joint investigations. The significance of developing dry coal beneficiation should be paid sufficient attentions and the policy support and adequate financial support are required to facilitate the considerable progress in coal dry cleaning.

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References

Azimi E, Karimipour S, Rahman M, Szymanski J, Gupta R (2013a) Evaluation of the performance of air dense medium fluidized bed (ADMFB) for low-ash coal beneficiation. Part 1: effect of operating conditions. Energy Fuels 27(10):5595–5606

Azimi E, Karimipour S, Rahman M, Szymanski J, Gupta R (2013b) Evaluation of the performance of air dense medium fluidized bed (ADMFB) for low-ash coal beneficiation. Part 2: characteristics of the beneficiated coal. Energy Fuels 27(10):5607–5616

Charan GT, Chattopadhyay US, Singh KMP, Kabiraj SK, Haldar DD (2011) Beneficiaron of high-ash, Indian non-coking coal by dry jigging. Miner Metall Process 28(1):21–23

Chen QR, Yang YF (2003) Development of dry beneficiation of coal in China. Coal Prep 23(1–2):3–12

Çicek T (2008) Dry Cleaning of Turkish Coal. Energy Sources Part A 30(7):593–605

Dwari RK, Hanumantha Rao K (2008) Non-coking coal preparation by novel tribo-electrostatic method. Fuel 87(17–18):3562–3571

Dwari RK, Hanumantha Rao K (2009) Fine coal preparation using novel tribo-electrostatic separator. Miner Eng 22(2):119–127

Fan MM, Chen QR, Zhao YM, Luo ZF (2001) Fine coal (6-1 mm) separation in magnetically stabilized fluidized beds. Int J Miner Process 63(4):225–232

Fan MM, Chen QR, Zhao YM, Guan YP, Li B (2002) Magnetically stabilized fluidized beds for fine coal separation. Powder Technol 123(2–3):208–211

Fan MM, Chen QR, Zhao YM, Luo ZF, Guan YP (2003) Fundamentals of a magnetically stabilized fluidized bed for coal separation. Int J Coal Prep Utili 23(1):47–55

Honaker RQ, Saracoglu M, Thompson E, Bratton R, Luttrell GH, Richardson V (2008) Upgrading coal using a pneumatic density-based separator. Int J Coal Prep Utili 28(1):51–67

Jiao HG, Cui JY, Liu P, Chen QR, Tie ZX (2009) Experimental study of magnetic property and dry magnetic separation of fine coal. J China Univ Min Technol 38(1): 131–134, 148

Luo ZF, Chen QR (2001) Dry beneficiation technology of coal with an air dense-medium fluidized bed. Int J Miner Process 63(3):167–175

Luo ZF, Chen QR, Zhao YM (2002a) Dry beneficiation of coarse coal using an air dense medium fluidized bed (ADMFB). Coal Prep 22(1):57–64

Luo ZF, Zhao YM, Chen QR, Fan MM, Tao XX (2002b) Separation characteristics for fine coal of the magnetically fluidized bed. Fuel Process Technol 79(1):63–69

Luo ZF, Zhao YM, Tao XX, Fan MM, Chen QR, Wei LB (2003) Progress in dry coal cleaning using air-dense medium fluidized beds. Coal Prep 23(1–2):13–20

Luo ZF, Zhu JF, Fan MM, Zhao YM, Tao XX (2007) Low density dry coal beneficiation using an air dense medium fluidized bed. J China Univ Min Technol 17(3):306–309

Luo ZF, Fan MM, Zhao YM, Tao XX, Chen QR, Chen Z (2008) Density-dependent separation of dry fine coal in a vibrated fluidized bed. Powder Technol 187(2):119–123

Luo ZF, Tang LG, Dai NN, Zhao YM (2013) The effect of a secondary gas-distribution layer on the fluidization

characteristics of a fluidized bed used for dry coal beneficiation. Int J Miner Process 118:28–33
Macpherson SA, Galvin KP (2010) The effect of vibration on dry coal beneficiation in the reflux classifier. Int J Coal Prep Utili 30(6):283–294
Macpherson SA, Iveson SM, Galvin KP (2010) Density based separations in the reflux classifier with an air–sand dense–medium and vibration. Miner Eng 23(2):74–82
Macpherson SA, Iveson SM, Galvin KP (2011) Density-based separation in a vibrated Reflux Classifier with an air-sand dense-medium: tracer studies with simultaneous underflow and overflow removal. Miner Eng 24(10):1046–1052
Mohanta S, Chakraborty S, Meikap BC (2011) Influence of coal feed size on the performance of air dense medium fluidized bed separator used for coal beneficiation. Ind Eng Chem Res 50(18):10865–10871
Mohanta S, Daram AB, Chakraborty S, Meikap BC (2012) Characteristics of minimum fluidization velocity for magnetite powder used in an air dense medium fluidized bed for coal beneficiation. Part Part Syst Charact 29(4):228–237
Mohanta S, Chakraborty S, Meikap BC (2013a) Optimization process of an air dense medium fluidized bed separator for treating high-ash non-coking indian coal. Miner Process Extr Metall Rev 34(4):240–248
Mohanta S, Rao CS, Daram AB, Chakraborty S, Meikap BC (2013b) Air dense medium fluidized bed for dry beneficiation of coal: technological challenges for future. Part Sci Technol 31(1):16–27
Patil DP, Parekh BK (2011) Beneficiation of fine coal using the air table. Int J Coal Prep Utili 31(3–4):203–222
Prashant D, Xu ZH, Szymanski J, Gupta R, Boddez J (2010) Dry cleaning of coal by a laboratory continuous air dense medium fluidized bed separator. In: Honaker RQ (ed) Processding of the international coal preparation congress 2010. SME, Lexington, pp 608–616
Sahu AK, Biswal SK, Parida A (2009) Development of air dense medium fluidized bed technology for dry beneficiation of coal_A review. Int J Coal Prep Utili 29(4):216–241
Sahu AK, Tripathy A, Biswal SK, Parida A (2011) Stability Study of an air dense medium fluidized bed separator for beneficiation of high-ash Indian coal. Int J Coal Prep Utili 31(3–4):127–148
Sahu AK, Tripathy A, Biswal SK (2013) Study on particle dynamics in different cross sectional shapes of air dense medium fluidized bed separator. Fuel 111:472–477
Sampaio CH, Aliaga W, Pacheco ET, Petter E, Wotruba H (2008) Coal beneficiation of Candiota mine by dry jigging. Fuel Process Technol 89(2):198–202
Song SL, Zhao YM, Luo ZF, Tang LG (2012a) Motion behavior of particles in air-solid magnetically stabilized fluidized beds for separation. Int J Min Sci Technol 22(5):725–729
Song SL, Zhao YM, Luo ZF, Tang LG, Yang XL (2012b) Fine coal particles separation by air-solid magnetic fluidization. Meitan Xuebao/J China Coal Soc 37(9):1586–1590
Yang XL, Zhao YM, Luo ZF, Chen ZQ, Song SL, Duan CL (2013a) Energy transfer mechanism of vibro-fludization and its separation for fine coal. Zhongguo Kuangye Daxue Xuebao/J China Univ Min Technol 42(2):266–270
Yang XL, Zhao YM, Luo ZF, Song SL, Duan CL, Dong L (2013b) Fine coal dry cleaning using a vibrated gas-fluidized bed. Fuel Process Technol 106:338–343
Zhang XX, Duan DY, Tian B, Wang JS, Deng F, Li HS, Ma RX (2009) Research on the triboelectrostatic separation of minerals from coal. Procedia Earth and Planet Sci 1(1):845–850
Zhang B, Akbari H, Yang F, Mohanty MK, Hirschi J (2011) Performance optimization of the fgx dry separator for cleaning high-sulfur coal. Int J Coal Prep Utili 31(3–4):161–186
Zhao YM, Luo ZF, Chen ZQ, Tang LG, Wang HF, Xing HB (2010a) The effect of feed-coal particle size on the separating characteristics of a gas-solid fluidized bed. J S Afr Inst Min Metall 110(5):219–224
Zhao YM, Tang LG, Luo ZF, Liang CC, Xing HB, Wu WC, Duan CL (2010b) Experimental and numerical simulation studies of the fluidization characteristics of a separating gas-solid fluidized bed. Fuel Process Technol 91(2):1819–1825
Zhao YM, Li GM, Luo ZF, Liang CC, Tang LG, Chen ZQ, Xing HB (2011a) Modularized dry coal beneficiation technique based on gas-solid fluidized bed. J Cent South Univ Technol 18(2):374–380
Zhao YM, Liu XJ, Liu KL, Luo ZF, Wu WC, Song SL, Tang LG (2011b) Fluidization characteristics of a gas-paigeite-powder bed to be utilized for dry coal beneficiation. Int J Coal Prep Utili 31(3–4):149–160