The effect of feed-coal particle size on the separating characteristics of a gas-solid fluidized bed

by Y.M. Zhao*, Z.F. Luo*, Z.Q. Chen*, L.G. Tang*, H.F. Wang*, and H.B. Xing*

Synopsis

The separating performance of a pilot dry beneficiation system using a gas-solid fluidized bed was investigated with coal from South Africa. The coal used for the study has a low inherent moisture content, a moderate ash content, a moderate volatile content, a low sulphur content and a high calorific value. Its washability is moderate. Experimental results show that the separating quality of the fluidized bed drops gradually as the feed-coal particle size decreases. The probable error, *E*, values for 50–25 mm, 25–13 mm and 13–6 mm coals were 0.04 g/cm^3, 0.06 g/cm^3 and 0.09 g/cm^3, respectively. The cause of the differences in separating characteristics was analysed by particle dynamics and numerical modelling. Furthermore, the pilot fluidized bed was employed to separate 50-6mm coal. In this experiment the coal ash content was reduced from 23.74% to 11.79%, with a probable error, *E*, value of 0.07 g/cm^3 and a recovery efficiency of 98.26%. This indicates that the fluidized bed is applicable to the separation of coal from South Africa and has good separating performance and wide applicability.

Keywords: feed-coal particle size; gas-solid fluidized bed; dry coal beneficiation; numerical simulation.

Introduction

Water based wet separation processes are universally utilized in the field of coal beneficiation today[1,2]. These techniques are, however, unsuitable for coals located in regions where water resources are in short supply or where the weather is cold, or for coals that tend to slime under wet separation processes. In addition, during the wet separation of coal, a great deal of water is consumed, of which there is a shortage all around the world today. Many countries have been, therefore, exploring highly-efficient dry beneficiation of coal. China ranked third in proved recoverable coal reserves in 2006 in the world: 114.5 billion tons. Over two-thirds of the coal in China is in northwestern and northern China where water resources are scarce.

The proved recoverable coal reserves of South Africa were 48.75 billion tons and ranked sixth. This country is also, however, short of water resources. Over the past several years the per year mean rainfall was approximately 464 mm and available fresh water volume per capita per year was approximately 1 200 m^3. To strengthen the management and supply of water resources, the Department of Water Affairs and Forestry (DWAF) of South Africa has enacted a series of policies and laws on water since 1994. Water utilization during mineral processing is greatly restricted and is approved only with difficultly in accordance with the relevant laws and regulations.

Favourable mass and heat transfer properties make gas-solid fluidized beds popular in many processing industries[3]. Such beds were used for coal beneficiation as early as the 1920s[4,5]. Thereafter a number of scientists and engineers in many counties contributed to the development of dry coal cleaning using fluidized beds[6–12]. A series of dry coal beneficiation techniques based on gas-solid two-phase flow was developed by scientific and technical workers at China University of Mining and Technology (CUMT)[13–26]. These techniques use dense fluidized beds formed from a fluidizing gas and a ground solid powder of a certain size range (e.g. magnetite powder) as the separating medium[27,28]. One of these beds, a typical bubbling gas-solid fluidized bed, has been successfully applied to the industrial beneficiation of 50–6 mm coal in China. Coal Dry Wash CC. (CDW) of South Africa cooperated with CUMT during the development of this technique. Some 50–6 mm coals provided by CDW were studied in a pilot separator using the gas-solid fluidized bed by the CUMT workers. Based on those coals, this

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© *The Southern African Institute of Mining and Metallurgy, 2010. SA ISSN 0038–223X/3.00 + 0.00. Paper received Jul. 2009; revised paper received Dec. 2009.*

paper emphasizes differences in separating characteristics for different size ranges of coals. Moreover, the reasons for the differences were investigated employing particle dynamics and numerical simulations.

Experimental

Experiments were carried out in a 5–10 t/h pilot separation system using a gas-solid fluidized bed. The system consists of raw coal pre treatment (screening and crushing), coal separation, solid media recovery, an air supply and dust capture and removal. The separator, as illustrated in Figure 1, is composed of an air distributor, a separating room and a counterflow scraper conveyor. Pressure transducers are arrayed vertically along the sidewall. Both solid medium and feedstock (50–6 mm coal) were fed into the separator from inlets at the top. Compressed air flowed into the bed through an air buffer and then through a gas distributor located at the bottom. Under suitable technical and operating conditions the solid medium is fluidized by the gas to form a fluidized bed having some certain density and height. The coal then stratified according to the bed density with lighter coal particles floating and denser particles sinking. The separated products are transported away by the scraper conveyor.

Results and discussion

Washability of the coal from South Africa

The properties of the coal from South Africa were first analyzed. The coal had a low inherent moisture content of 2.49%, a moderate ash content of 23.74%, a moderate volatiles content of 28.01%, a low sulphur content of 0.9% and a high calorific value of 26.8 MJ/kg. The coal used for the study, accordingly, belonged to the weakly caking coals.

Then an investigation of coal washability was performed. The results are illustrated in Figure 2. When the clean coal ash content was 13%, 12% or 11% the theoretical yield of clean coals was 90%, 88% or 86%, respectively. Likewise, the theoretical separation densities were 2 g/cm^3, 1.84 g/cm^3 and 1.59 g/cm^3 and the near-density yields were 4.5%, 2% and 17%, respectively, which indicates that the washability of the coal was good in the two former cases but moderate in the last case. To sum up, as clean coal quality increases, the yield decreases and the washability drops.

Separating characteristics of the fluidized bed for different size ranges of coals

50–25 mm, 25–13 mm and 13–6 mm coals were each separated in the pilot separation system. The separation results are shown in Figure 3. As shown there, the separating density increases gradually and the partition curves become less abrupt as the coal particle size decreases. The separating densities were 1.70 g/cm^3, 1.79 g/cm^3 and 1.99 g/cm^3, and the E values were 0.04 g/cm^3, 0.06 g/cm^3 and 0.09 g/cm^3, respectively. This indicates that denser particles were more inefficiently separated with respect to the bed density. Those particles were misplaced into the floats layer thus enhancing the misplacing effect. The separating performance of the bed, therefore, decreased gradually. The recovery efficiencies were 99.05%, 97.63% and 90.25%, respectively.

The cause of the differences in separating characteristics

The forces acting on the coal particles were analysed to help understand the reason for the observed separation results. The forces acting on the coal particles include gravity, G, the solid-medium resistance, F_r[29], the bed buoyancy, F_f, and the

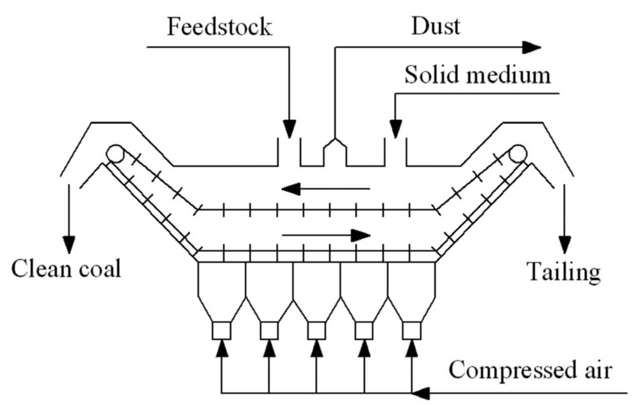

Figure 1—Schematic of the pilot gas-solid fluidized bed separator

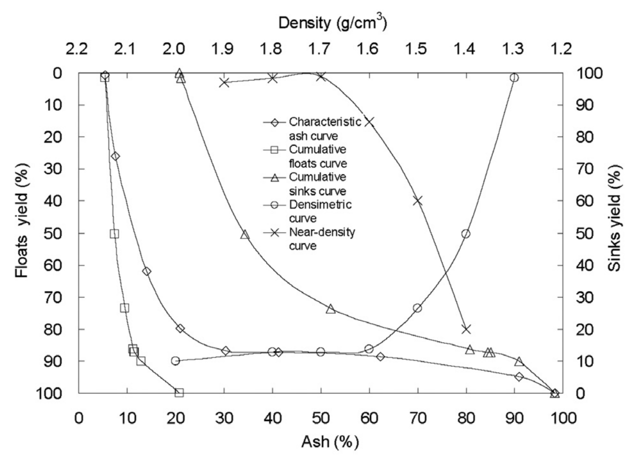

Figure 2—Washability curves of the raw coal

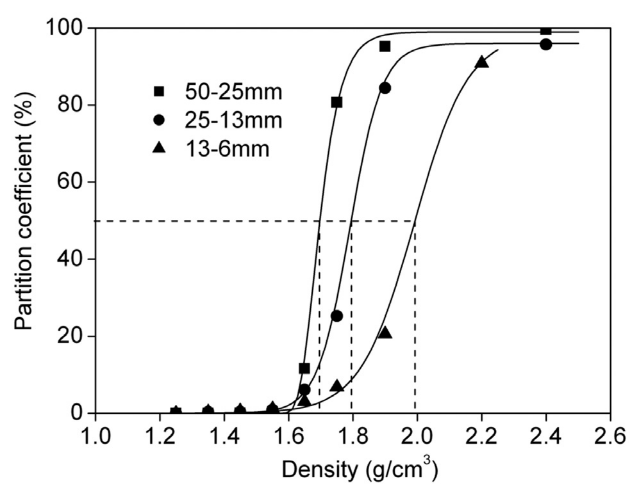

Figure 3—Partition curves of different coal size ranges

fluidizing gas drag, F_d. Because of the low gas velocity of the bed F_d is far smaller than G. The resultant force, hence, can be expressed as:

$$F = G - F_f - F_r \quad [1]$$

Then

$$\frac{1}{2}\pi d_p^3 \rho_p \frac{dv_p}{dt} = \frac{1}{6}\pi d_p^3 \rho_p g - \frac{1}{6}\pi d_p^3 \rho_b g - \left(3\pi\mu d v_r + \pi d_p^2 \sigma\right) \quad [2]$$

where d_p is the diameter of a coal particle, ρ_p is the particle density of coal, v_p is the velocity of a coal particle, ρ_b is the bed density, g is the gravitational acceleration,   is the plastic viscosity of the bed, v_r is the velocity of a coal particle when the velocity of the medium particle $v = 0$, and σ is the yield stress.

Equation [2] allows the instantaneous acceleration of a particle to be expressed as:

$$\frac{dv_p}{dt} = \frac{\rho_p - \rho_b}{\rho_p} g - \left(\frac{18\mu v_r}{d_p^2 \rho_p} + \frac{6\tau}{d\rho_p}\right) \quad [3]$$

The settling velocity of a coal particle in the bed is[30]:

$$v_t = \left(\mathrm{Re}_m\, d_p \left|\rho_p - \rho_b\right| g \Big/ \left(18\left(\frac{1+0.15}{\mathrm{Re}_m^{0.687}}\right)\rho_b\right)\right)^{1/2} + v \quad [4]$$

with $Re_m = d_p v_r \rho_b / (\mu + \tau d_p / 3 v_r)$

where Re_m is the modified Reynolds number.

From Equation [3] it can be seen that the effective gravity of the coal particle is proportional to d^3. As the size decreases the effective gravity drops sharply. The smaller the coal particles, the greater the mixing effect of bubbles on those particles becomes, which enhances the misplacing effect on those particles. The separating efficiency of the bed is, as a result, decreased. In addition, Equation [4] can predict that as the size decreases, the settling velocity of the particle decreases gradually. Movement of the solid-medium then makes the velocity of a smaller particle fluctuate more. This, hence, results in denser coal particles of small size being misplaced and transported away before crossing the floats layer. The separating performance of the bed, accordingly, drops.

Fluent 6.2 computational fluid dynamics software was employed to analyse the different behaviour of various sized particles. The dynamic behavior of a 2D fluidized bed was investigated.

The mass conservation equations of the gas and solid-medium phases in the fluidized bed are:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g\right) + \nabla \cdot \left(\alpha_g \rho_g \boldsymbol{u}\right) = 0 \quad [5]$$

$$\frac{\partial}{\partial t}\left(\alpha_s \rho_s\right) + \nabla \cdot \left(\alpha_s \rho_s \boldsymbol{v}\right) = 0 \quad [6]$$

where g and s are the phase indexes (g for the gas phase and s for the solid-medium phase), α is the volume fraction, ρ is the actual density, $\boldsymbol{u}$ is the velocity of the gas and $\boldsymbol{v}$ is the velocity of the solid-medium.

Momentum conservation in the bed gas or solid-medium phases are:

$$\frac{\partial}{\partial t}\left(\alpha_g \rho_g \boldsymbol{u}\right) + \nabla \cdot \left(\alpha_g \rho_g \boldsymbol{uu}\right) = -\alpha_g \nabla p_g + \nabla \cdot \tau_g + \alpha_g \rho_g \boldsymbol{g} - K_{gs}\left(\boldsymbol{u} - \boldsymbol{v}\right) \quad [7]$$

$$\frac{\partial}{\partial t}\left(\alpha_s \rho_s \boldsymbol{v}\right) + \nabla \cdot \left(\alpha_s \rho_s \boldsymbol{vv}\right) = -\alpha_s \nabla p_s + \nabla \cdot \tau_s + \alpha_s \rho_s \boldsymbol{g} - K_{gs}\left(\boldsymbol{u} - \boldsymbol{v}\right) \quad [8]$$

where p is the pressure, τ is the stress tensor and K_{gs} is the interphase momentum transfer coefficient.

The variation in the bed pressure drop is shown in Figure 4. Note that the bed pressure-drop drops sharply when fluidization begins. The pressure drop then fluctuates only slightly around a steady value after 1.5 s, which shows a good fluidization state.

Simulated data from the above analysis were taken after 1.5 s and the movement and distribution of bubbles across the bed were investigated. As shown in Figure 5 the formation of bubbles is visible. The bubbles were generated from the air distributor apertures and had a small size initially. They then pass through the bed, coalesce and grow. When the bubbles rise to the top surface of the bed they explode. The bubble distribution was non-uniform. Large sized bubbles were, however, very few. The bed surface, therefore, maintains a certain level despite some fluctuation caused by the moving bubbles, which indicates a steady fluidization characteristic for the bed.

Figure 6 represents the instantaneous fluctuation in local bed void space. The simulated data were extracted at a 1000 Hz rate. The bed hydrodynamics are understood better from the void curve. The large peaks indicate the passing of bubbles. The uniform peaks after 1.5 s show an overall regularity with respect to the number and frequency of the bubbles being formed. Due to the solid-medium remixing, and to uneven interphase action, the void fraction in the dense phase fluctuates to some degree but only slightly while remaining near 0.42, which, hence, indicates steady fluidization of the bed.

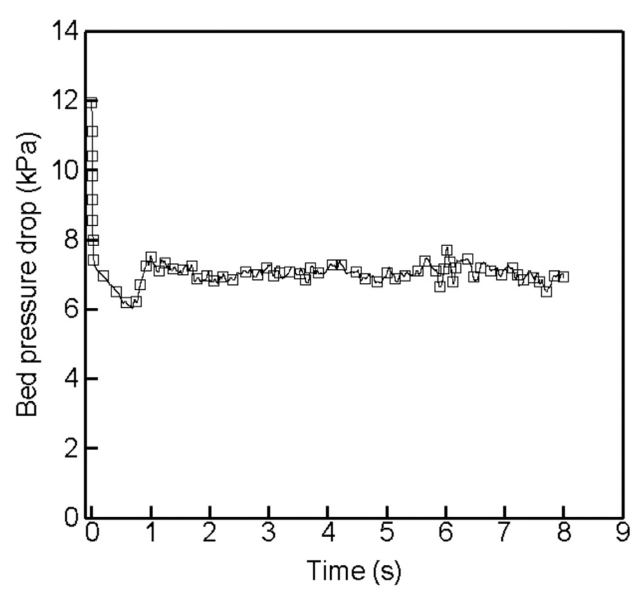

Figure 4—The fluctuation in the bed pressure drop

The effect of feed-coal particle size

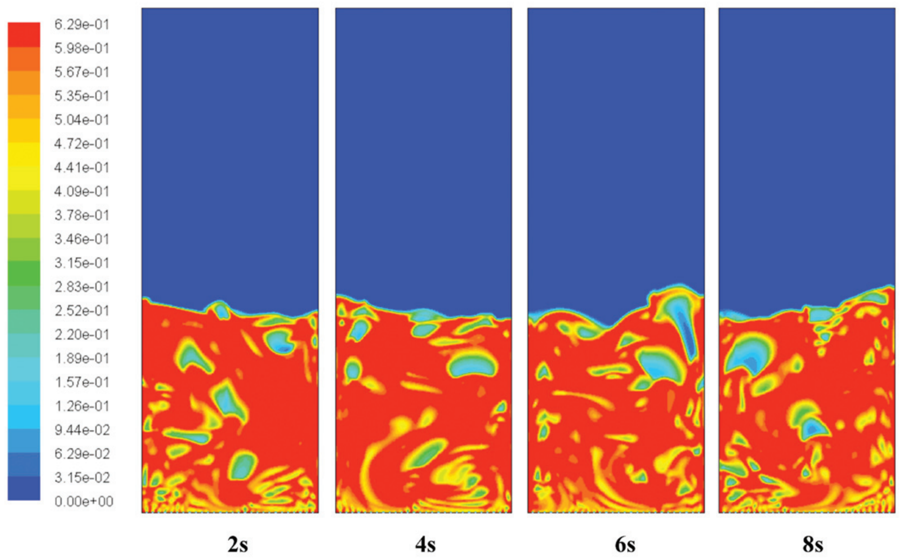

Figure 5—The solid-medium volume fraction profile

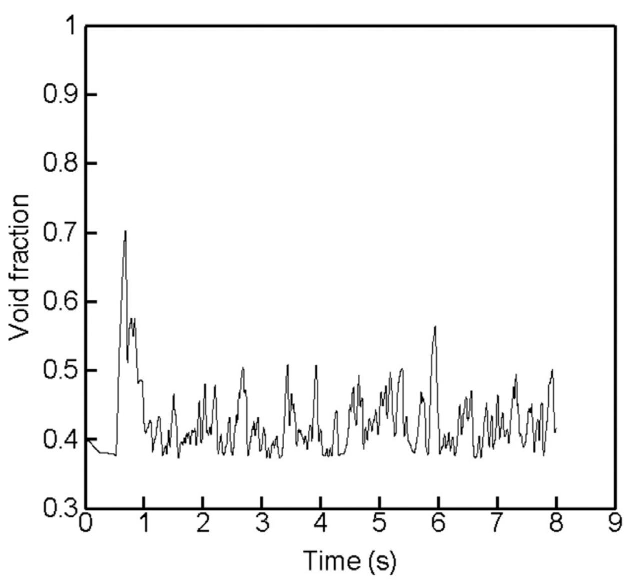

Figure 6—Simulated instantaneous voidage plot: H=0.2 m

The solid-medium particles are moved from the bottom to the top of the bed entrained by bubbles. This results in the remixing of the particles. Figure 7 shows the local velocity variation of particles versus the transverse position. As shown there the particles have a high velocity under the effects of the bubbles and the fluidizing gas. The overall velocity rises as the distance from the bed bottom, *H*, increases at 7.5 s: the maximum velocity is 0.8 m/s. A certain degree of remixing can increase the bed activity and enhance the uniformity of the solid-medium distribution across the bed. The fluidization quality and separating performance are, accordingly, improved. However, smaller sized coal particles sinking to the bed bottom (based on their density relative to the bed density) are recycled into the floats layer during this remixing process. As a result, these coal particles become misplaced and the separating quality decreases. Therefore, the smaller the feed-coal particle size is, the greater the remixing and misplacing effects will be, which consequently decreases the separating quality of the bed.

The separating characteristics of the fluidized bed using 50–6 mm coal

Given the aforementioned analysis we know that the larger the coal particle size is, the better the fluidized bed will separate the coal. The application of a fluidized bed is not limited only to coarser coal. The technical and operating parameters can be adjusted during the separation process. The actions among gas, solid-medium and coal particles can be optimized to expand the range of applications. For this reason the experimental bed was used to separate 50–6 mm

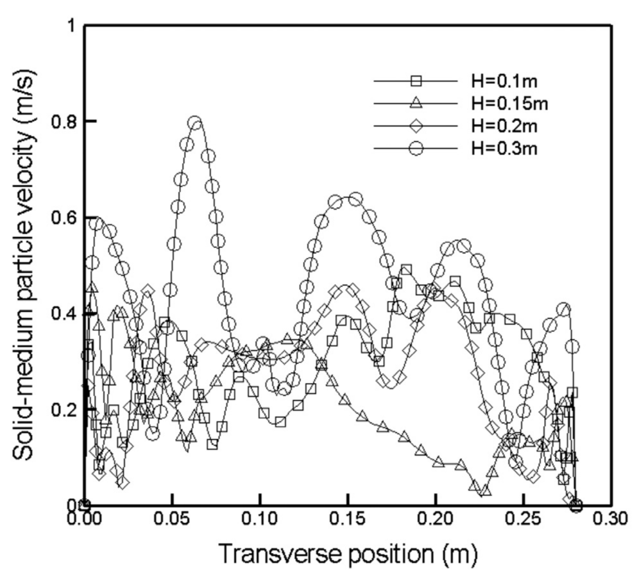

Figure 7—Simulated local solid-medium particle velocity at 7.5 s

coal. The separation results are shown in Table I and in Figure 8. It can be seen that at a separating density of 1.76 g/cm³ the coal ash content was reduced from 23.74% to 11.79%. The probable error, *E*, value and the recovery efficiency were 0.07 g/cm³ and 98.26%, respectively, showing good separating performance.

Conclusions

- ➤ The coal from South Africa used for this study has a low inherent moisture content, a moderate ash content, a moderate volatile content, a low sulphur content and a high calorific value. The washability of the coal is moderate.
- ➤ As the feed-coal particle size decreases, the separating performance of the pilot gas-solid fluidized bed drops progressively. When using the bed to separate 50–25 mm, 25–13 mm and 13–6 mm coals the probable error, *E*, values were 0.04 g/cm³, 0.06 g/cm³ and 0.09 g/cm³, respectively. This is because the settling velocity of a coal particle decreases, and the remixing effect caused by bubbles increases, as the particle size decreases. Both factors enhance the misplacing effect on the coal particles, which makes the separating quality of the bed poor.
- ➤ The pilot gas-solid fluidized bed separator is suitable for 50–6 mm coal. The ash content of the processed coal was reduced from 23.74% to 11.79%. The *E* value was 0.07 g/cm³ and the recovery efficiency was 98.26%. The separation results are satisfactory.
- ➤ Dry beneficiation using a gas-solid fluidized bed is applicable to South African coal. The method has a high separating quality and wide applications.

Acknowledgements

This work is financially supported by the Hi-tech Research and Development Program of China (No. 2007AA05Z318), the National Natural Science Foundation of China (Nos. 50921002, 90510002 and 50774084), and the Key Project for Science and Technology Research of the Ministry of Education of China (No. 306008).

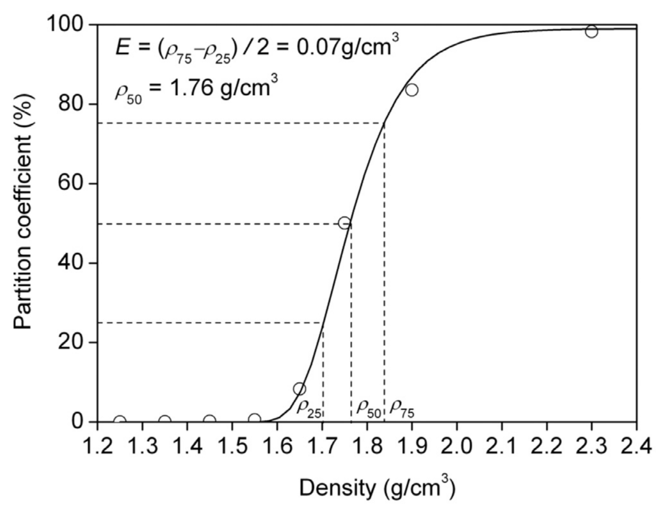

Figure 8—Partition curve using 50–6 mm coal

Table I

The float–sink results from 50–6 mm coal separation

Density range/ (g/cm⁻³)	Clean coal (%) O	Clean coal (%) O/F	Clean coal (%) Ash	Tailing (%) O	Tailing (%) O/F	Tailing (%) Ash	Calculated feedstock F (%)	Partition coefficient (%)
-1.3	1.07	0.93	5.48	0.00	0.00	0.00	0.93	0
1.3–1.4	61.40	53.65	8.05	0.43	0.05	7.24	53.70	0.10
1.4–1.5	22.28	19.47	14.66	0.33	0.04	12.09	19.51	0.21
1.5–1.6	13.62	11.90	21.12	0.50	0.06	21.07	11.96	0.53
1.6–1.7	1.12	0.97	29.21	0.70	0.09	35.22	1.06	8.28
1.7–1.8	0.17	0.15	41.54	1.18	0.15	43.06	0.30	50.10
1.8–2.0	0.11	0.09	49.63	3.78	0.48	58.23	0.57	83.55
+2.0	0.24	0.21	84.73	93.09	11.76	91.58	11.96	98.27
Total	100.00	87.37	11.79	100.00	12.63	88.38	100.00	

References

1. Dwari, R.K. and Rao, K.H. Dry beneficiation of coal—a review. *Mineral Processing and Extractive Metallurgy Review*, vol. 28, no. 3, 2007. pp. 177-234.

2. Van Houwelingen, J.A. and De Jong, T.P.R. Dry Cleaning of Coal: Review, Fundamentals and Opportunities. *Proceedings of the 5th European Coal Conference*. Geologica Belgica, 2004. vol. 7, pp. 335–343.

3. Kunii, D. and Levenspiel, O. *Fluidization Engineering*. Boston, Butterworth —Heinemann, 1991.

4. Fraser, T. and Yancey, H.F. The air-sand process of cleaning coal. US Pat 153, 4846: Acc. 21 April 1925.

5. Chapman, W.R. and Mott, R.A. *The Cleaning of Coal*. London, Chapman & Hall Ltd., 1928.

6. Beeckmans, J.M. Separation of Mixed Granular Solids Using the Fluidized Counter Current Cascade Principle. *The Canada Journal of Chemical Engineering*, vol. 75, no. 10, 1997. p. 55.

7. Chan, E.W. and Beeckmans, J.M. Pneumatic beneficiation of coal fines using the counter-current fluidized cascade. *International Journal of Mineral Processing*, vol. 9, no. 2, 1982. pp. 157–165.

8. Dong, X. and Beeckmans, J.M. Separation of Particulate Solids in a Pneumatically Driven Counter-current Fluidized Cascade, *Powder Technology*, vol. 62, no. 3, 1990. pp. 261–267.

9. Oshitani, J., Tani, K., Takase, K., and Tanaka, Z. Dry Coal Cleaning by Utilizing Fluidized Bed Medium Separation (FBMS). *Proceedings of the SCEJ Symposium on Fluidization. J*apan, 2003. vol. 9, pp. 425–430.

10. Tanaka, Z., Oshitani, J., Kubo, Y., and Zushi, T. Dry Coal Cleaning in Drewboy Bath Type by Dry Heavy Medium. *Proceedings of First International Symposium on Dry Coal Cleaning, Clean Coal Technology*. Chen, Q. R. and Tanaka, Z. (eds.). Xuzhou. China University of Mining and Technology Press, 2002. pp. 73–78.

11. Kubo, Y. and Zushi, T. Designing Points of the Fluidized Bed Type Dry Coal Cleaning System. *Proceedings of First International Symposium on Dry Coal Cleaning, Clean Coal Technology*. Chen, Q. R. and Tanaka, Z. (eds.). Xuzhou. China University of Mining and Technology Press, 2002. pp. 79–89.

12. Tanaka, Z., Sato, H., Kawai, M., Okada, K., and Takahashi, T. Dry Coal Cleaning Process for High-quality Coal. *Journal of chemical engineering of Japan*, vol. 29, no. 2, 1996. pp. 257–263.

13. Luo, Z.F., Zhu, J.F., Li, Z., and Liu, K.L. Surface Modification of Hydrophobic Magnetite Powder. *Journal of China University of Mining & Technology*, vol. 38, no. 1, 2009. pp. 75–79. (in Chinese)

14. Luo, Z.F., Zhu, J.F., Fan, M.M., Zhao, Y.M., and Tao, X.X. Low Density Dry Coal Beneficiation Using an Air Dense Medium Fluidized Bed. *Journal of China University of Mining and Technology*, vol. 17, no. 3, 2007. pp. 0306–0309.

15. Luo, Z., Zhao, Y., Fan, M., Tao, X., and Chen, Q. Density Calculation of a Compound Medium Solids Fluidized Bed for Coal Separation. *The Journal of The Southern African Institute of Mining and Metallurgy*, vol. 106, no. 11, 2006. pp. 749–752.

16. Luo, Z.F., Zhao, Y.M., Chen, Q.R., Tao, X. X., and Fan, M.M. Effect of Gas Distributor on Performance of Dense Phase High Density Fluidized Bed for Separation. *International Journal of Mineral Processing*, vol. 74, nos. 1–4, 2004. pp. 337–341.

17. Luo, Z.F., Zhao, Y.M., Tao, X.X., Fan, M.M., Chen, Q.R., and Wei, L.B. Progress in Dry Coal Cleaning Using Air-dense Medium Fluidized Beds. *Coal Preparation*, vol. 23, nos. 1–2, 2003. pp. 13–20.

18. Luo, Z.F., Chen, Q.R., and Zhao, Y.M. Dry Beneficiation of Coarse Coal Using an Air Dense Medium Fluidized Bed (ADMFB). *Coal Preparation*, vol. 22, no. 1, 2002. pp. 57–64.

19. Luo, Z.F. and Chen, Q.R. Effect of Fine Coal Accumulation on Dense Phase Fluidized Bed Performance. *International Journal of Mineral Processing*, vol. 63, no. 4, 2001. pp. 217–224.

20. Luo, Z.F. and Chen, Q.R. Dry Beneficiation Technology of Coal with an Air Dense-medium Fluidized Bed. *International Journal of Mineral Processing*, vol. 63, no. 3, 2001. pp. 167–175.

21. Luo, Z.F., Fan, M.M., Zhao, Y.M., Tao, X.X., Chen, Q.R., and Chen, Z.Q. Density-dependent Separation of Dry Fine Coal in a Vibrated Fluidized Bed. *Powder Technology*, vol. 187, no. 2, 2008. pp. 119–123.

22. Luo, Z.F., Fan, M.M., Zhao, Y.M., Tao, X.X., and Chen, Z.Q. Separation of Material in a Vibration Fluidized Bed. *Journal of China University of Mining &Technology*, vol. 36, no. 1, 2007. pp. 27–32. (in Chinese)

23. Luo, Z.F., Fan, M.M., Chen, Q.R., Zhao, Y.M., Liang, C.C., Tao, X.X., and Chen, Z.Q. Effects of Vibrating Parameters on Separation Performance of Fluidized Beds. *Journal of China University of Mining & Technology*, vol. 35, no. 2, 2006. pp. 209–213. (in Chinese)

24. Luo, Z.F., Zhao, Y.M., Chen, Q.R., Tao, X.X., and Fan, M.M. Separation Lower Limit in a Magnetically Gas–solid Two-phase Fluidized Bed. *Fuel Processing Technology*, vol. 85, nos. 2-3, 2004. pp. 173–178.

25. Fan, M.M., Chen, Q.R., and Zhao, Y.M. Fundamentals of a Magnetically Stabilized Fluidized Bed for Coal Separation. *Coal Preparation*, vol. 23, nos. 1-2, 2003. pp. 47–55.

26. Luo, Z.F., Zhao, Y.M., Chen, Q.R., Fan, M.M., and Tao, X.X. Separation Characteristics for Fine Coal of the Magnetically Fluidized Bed. *Fuel Processing Technology*, vol. 79, no. 1, 2002. pp. 63–69.

27. Wang, J.H., Chen, Q.R., Kuang, Y.L., Lynch, A.J., and Zhuo, J.W. Grinding Process Within Vertical Roller Mills: Experiment and Simulation, *Mining Science and Technology*, vol. 19, no. 1, 2009. pp. 97–101.

28. Wang, Y.L., Zhao, Y.M., and Yang, J.G. Research on Super-low-ash Anthracite Preparation. *Journal of China University of Mining & Technology*, vol. 18, no. 4, 2008. pp. 0580–0583.

29. Cai, S.T. The mechanical property of the slurry and the resistance force of a sphere moving with uniform velocity in the slurry. *Applied Mathematics and Mechanics*, vol. 2, 1981. pp. 267–272. (in Chinese)

30. Wei, L.B., Bian, B.X., Chen, Q.R., and Zhao, Y.M. Study on terminal velocity of objects moving in fluidized beds. *Journal of China University of Mining & Technology*, vol. 30, no. 1, 2001. pp. 5–8. (in Chinese). ◆