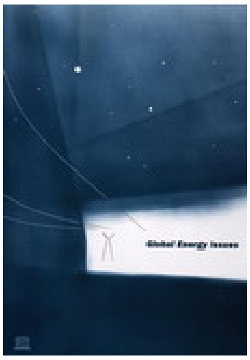

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Intelligent control of heavy media separation

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Abstract: The shortcomings of the density control system for heavy media suspension in the current coal preparation plant were introduced. The intelligent control system of heavy media separation suitable for different coal quality characteristics in LinHuan Coal Preparation Plant was proposed. The system was mainly composed of the following parts: relationship between ash and mineral content, automatic identification of raw coal production source information, automatic adjustment of online ash analyser parameters, closed loop control system based on clean coal ash content. After intelligent control of heavy media separation was applied. The processed raw coal production source information and ratio could be automatically identified by the system, and the parameters of the online ash meter could be automatically adjusted. The clean coal ash content after heavy media separating was relatively stable, and the product qualification rate was improved.

Keywords: raw coal; clean coal; separation; heavy media; ash content.

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1 Introduction

Heavy medium cyclones are widely used in the mineral processing industry due to high separation efficiency and high throughput (Das and Sarkar, 2018; Kawatra, 2020; Chen et al., 2012; Zhang et al., 2017). In the process control of heavy medium cyclone, the density of the heavy media suspension needs to be controlled in real-time according to the parameters such as hourly processing capacity of raw coal, raw coal ash content, clean coal ash content and suspension tank level (O'Brien et al., 2014; Zhang et al., 2014a). At present, most coal preparation plants rely on manual control (Zhang and Xia, 2014), before the start of each team, the operator shall give the initial heavy density of media suspension based on the previous density of the heavy media suspension, the previous raw coal and clean coal ash content value. In the early stage of production, it is necessary to frequently check and adjust the density of the heavy media suspension according to the production conditions. In the production process, the density of the suspension needs to be adjusted according to the clean coal ash (Wang et al., 2015). Since there are many factors affecting the separation effect of heavy medium cyclone (Firth, 2009), it is difficult to carry out comprehensive control by manual. Because the density of the heavy media suspension is fixed, when the properties of the raw coal are changed, the separation effect will be deteriorated (Meyer and Craig, 2014; Huang et al., 2019). The density of the suspension needs to be adjusted according to the required clean coal ash content value. However, it takes a long period of time to manually assay the clean coal ash (Wang et al., 2015; Zhang et al., 2017), which is difficult to guide production effectively.

In order to ensure that the clean coal ash content meets the user's requirement, the ash content of cleaned coal produced is generally lower than that required by customers (Gupta and Mohanty, 2006), which will lead to a decrease in the yield of clean coal and the economic benefits of the coal preparation plant. On the other hand, human factors also affect the quality of the product. With the development of detection technology, real-time monitoring of clean coal ash content value had been realised. Cierpisz and Heyduk (2002) studied that on-line nuclear meters was utilised for coal quality monitoring and dynamic models of ash-monitors was presented and discussed. The analysis shows that the best results were produced by the monitors in which the time of measurement was variable and adapted to changes of the input signal. Zhang and Xia (2015) proposed that the feed coal quality is taken as the feed forward information and the sampled and delayed measurement from the DMC output is utilised as feedback for the controller to improve the quality of coal product and ensure the robustness of the controller. However, without the feedback of clean coal ash as control, product quality cannot be guaranteed.

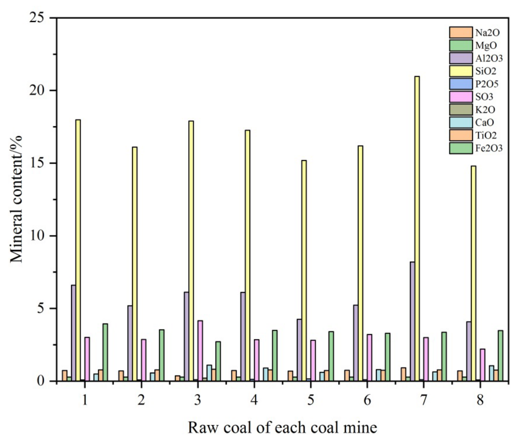
In order to improve the stability of the production system and product quality and maximise the removal of mineral impurities (Luttrell et al., 2000), and in LinHuan Coal Preparation Plant, the raw coal that needs to be separated and processed comes from different coal mines, so there is need of a well-designed control system to control production system (Zhang and Xia, 2014). Wang et al. (2015) also proposed raw coal from different mines make the quality of the feed undulated, so that the control of the density of the circulatory media becomes difficult and the quality of the product is unstable. So intelligent control system of heavy media separation suitable for different coal quality characteristics was proposed in this paper. It provides an efficient method for dense media separation system for raw coal with different quality characteristics to stabilise the quality of cleaned coal products, and also provides constructive suggestions for the development of intelligent coal preparation plant.

2 Relationship between ash and mineral content

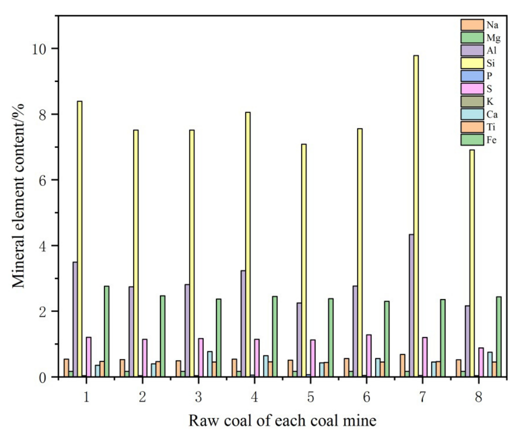
In this article, the ash content of the cleaned coal after heavy media processing was detected by the online ash meter in real time. In order to explore the relationship between ash content and mineral content, the ash and XRF tests were performed on the clean coal of all coal after washing and processing in the heavy media production system.

According to the XRF test results, as shown in Figure 1, the oxide minerals in clean coal mainly include Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, SO_3, K_2O, CaO, TiO_2, Fe_2O_3, SiO_2 and Al_2O_3. The relationship between the content of various oxidised minerals in the clean coal and the clean coal ash content was studied. As shown in Figure 2(a), Figure 2(b) is the corresponding element content converted from the mineral oxide form.

Figure 1 Relationship between ash and mineral content, mineral element content (1: fat coal produced by Linhuan Coal Mine, 2: coking coal produced by Linhuan Coal Mine, 3: raw coal produced by QingDong Coal Mine, 4: raw coal produced by SunTuan Coal Mine, 5: raw coal produced by TongTing Coal Mine, 6: raw coal produced by XunTuan Coal Mine, 7: raw coal produced by YangLiu Coal Mine, 8: raw coal produced by YuanYi Coal Mine

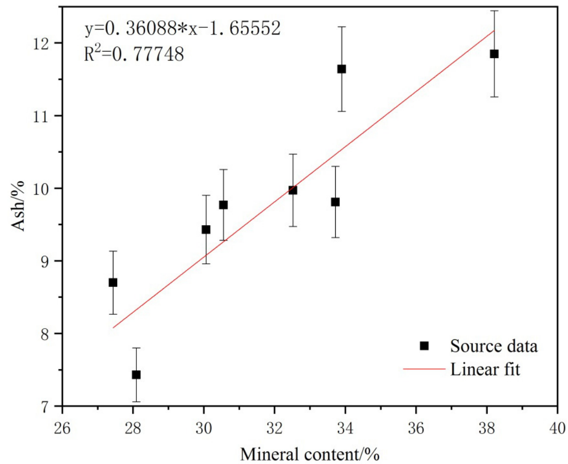


(a)

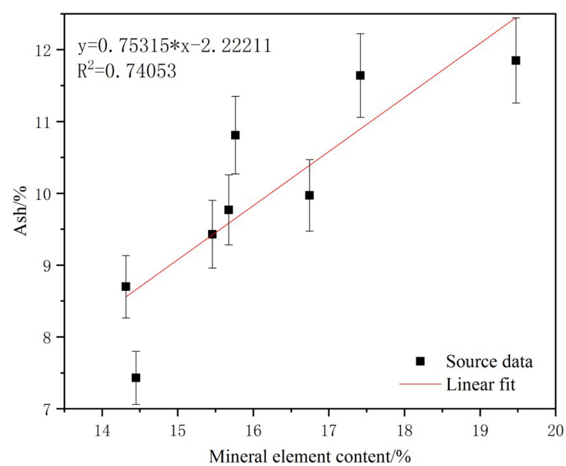


(b)

Figure 2 Relationship between ash and mineral content, mineral element content: (a) relationship between ash and mineral content, (b) relationship between ash and mineral element content



(a)



(b)

As shown in Figure 2, COD (Goodness of Fit) in Figure 2(a) was 0.77, and COD in Figure 2(b) was 0.74. The COD coefficients were small, indicating that there were positive correlations between the coal ash content and the mineral content, mineral element content. So the parameters of the online ash meter need to be adjusted, when the online ash meter detects different coal.

3 Automatic identification of coal type information

At present, coal blending is a common practice in coal preparation plants (Cierpisz and Heyduk, 2002). a total of 8 different types of raw coal were separated and processed in

LinHuan Coal Preparation Plant. As shown in Table 1 and Table 2, There are 12 raw coal warehouse, The raw coal warehouse numbers are 11#,12#,13#,14#,15#,16#,21#, 22#,23#,24#,25# and 26#. The raw coal warehouse number 11# was stored electric coal, which was specially used by nearby thermal power plants and did not participate in separating and processing. The coal stored in the remaining 11 raw coal warehouse are shown in Table 1 and Table 2. Because the raw coal properties of TongTing Coal Mine and LinHuan Coal Mine's fat coal were similar, they were all stored in the 16# raw coal warehouse. The same reason, QingDong Coal Mine and LinHuan Coal Mine's coking coal were all stored in the 22# raw coal warehouse.

Table 1 Coal stored in 11#–16# raw coal warehouse

Warehouse number	*11*	*12*	*13*	*14*	*15*	*16*	*26*
Coal types	electric Coal	SunTuan Coal	YuanYi Coal	QingDong Coal	XunTuan Coal	TongTing Coal or LinHuan Coal Mine's fat coal	TongTing Coal

Table 2 Coal type stored in 21#–26# raw coal warehouse

Warehouse number	*21*	*22*	*23*	*24*	*25*	*26*
Coal types	TongTing Coal	QingDong Coal or LinHuan Coal Mine's coking coal	YuanYi Coal	YangLiu Coal	YangLiu Coal	TongTing Coal

There were three sets of same production systems in LinHuan Coal Preparation Plant, and the process flow of each production system was heavy medium cyclone, and the new raw coal heavy medium cyclone produced by Beijing Guohua Technology Group Co., Ltd. was used. The raw coal processing capacity per production system was 850t/h, coal separated and processed were shown in Table 1 and Table 2. In order to be able to produce to meet the needs of customers and the diversification of clean coal products, the raw coal in Table 1 and Table 2 was blended and then separated and processed. There were 11 kinds of blended raw coal modes, as shown in Table 3.

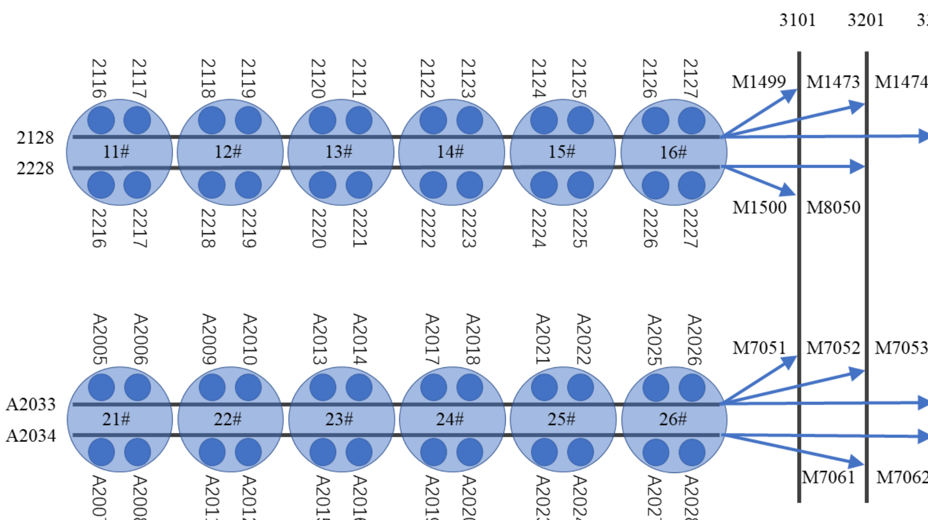
Table 3 Blended raw coal modes

Blended raw coal	*Blended ratio*
QingDong Coal:TongTing Coal	2:1
YuanYi Coal:QingDong Coal	2:1
YuanYi Coal: QingDong Coal	1:1
XunTuan Coal	–
LinHuan Coal Mine's fat coal	–
TongTing Coal	–
XunTuan Coal:YangLiu Coal	1:1
XunTuan Coal:YangLiu Coal	2:1
YangLiu Coal	–
SunTuan Coal	–
YuanYi Coal	–

Note: – indicates that a single coal type is washed and has no ratio.

The selection of coal and production systems was shown in Figure 3. Four raw coal feeders with uniform symmetrical arrangement were installed under each raw coal warehouse, and the distribution of each raw coal feeder was shown in Figure 3. 2118# and 2119#, 2120# and 2121#, 2122# and 2123#, 2124# and 2125#, 2126# and 2127# raw coal feeders were located under 12#,13#,14#,15#,16# raw coal warehouses, and raw coal from 2118# and 2119#, 2120# and 2121#, 2122# and 2123#, 2124# and 2125#, 2126# and 2127# raw coal feeders were delivered to the 2128# belt conveyor. Similarly, 2218# and 2219#, 2220# and 2221#, 2222# and 2223#, 2224# and 2225#, 2226# and 2227# raw coal feeders were delivered to the 2228# belt conveyor. raw coal from A2005# and A2006#, A2009# and A2010#, A2013# and A2014#, A2017# and A2018#, A2021# and A2022#, A2025# and A2026# raw coal feeders were delivered to A3033# belt conveyor. raw coal from A2007# and A2008#, A2011# and A2012#, A2015# and A2016#, A2019# and A2020#, A2023# and A2024#, A2027# and A2028# raw coal feeders were delivered to A3034# belt conveyor. Then, the raw coal of the 3101# belt conveyor was all transported to the 1# system for separating and processing, the raw coal of the 3201# belt conveyor was all transported to the 2# system for separating and processing, the raw coal of the 3301# belt conveyor was all transported to the 3# system for separating and processing.

Figure 3 Coal type process selection chart in production system



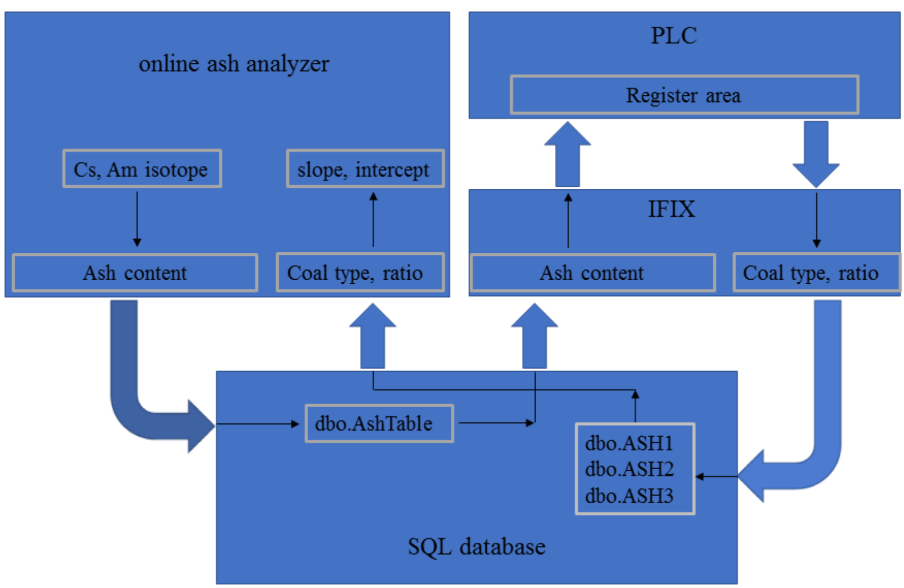
The coal stored in each raw coal warehouse was fixed, when the raw coal feeder under the raw coal warehouse was run, so the coal can be determined by the feedback run signal of the raw coal feeder. The direction of material conveying of the belt conveyor under the raw coal warehouse was selected, and then, the coal types that need to be separated and processed were determined in the production system. The blending ratio of the currently raw coal that needs to be separated and processed was calculated by calculating the running frequency of the raw coal feeder. Therefore, coal type information was automatically identified in the production control system.

4 Automatic adjustments of online ash analyser parameters

The online ash meter had been utilised for coal quality monitoring in the coal preparation plant for many years (Sowerby and Watt, 1990; Cierpisz and Heyduk, 2002). The selected online ash meter was produced by China Institute of Atomic Energy in this paper. In the daily calibration, the slope and intercept of the online ash analyser were mainly calibrated. When different raw coals were separated and processed, the physical properties of the raw coal were quite different, and the corresponding slope and intercept parameters was needed to be adjusted to accurately measure the ash content of the clean coal.

In LinHuan Coal Preparation Plant, 3117A, 3217A, and 3317A belong to the clean coal product belt conveyor of the 1#, 2#, and 3# production systems, respectively. 3117A, 3217A, 3317A clean coal products belt conveyor respectively installed an online ash meter. An online ash meter server was shared by three online ash meter, and the data of all the online ash meter was collected in real-time. Since the control system of heavy media separation and the online ash meter server were respectively two independent systems, and data did not exchange directly in both. When different raw coal was separated and processed, in order to enable the ash content of the clean coal was accurately detected, the slope and intercept parameters of the online ash meter should be automatically adjusted according to the different coals and ratios.

Figure 4 Automatic adjustment of online ash analyser parameters



As shown in Figure 4, the ash meter operating software and SQL2008 database were installed on online ash analyser server, the ash meter operation software was mainly used for processing and displaying the collected ash content data. And then, the processed data was stored in the SQL2008 database. Data from the heavy media separation control system and the online ash meter server can be exchanged in an indirect way. After communicating with the engineers of the online ash meter, firstly, the IFIX software was installed on the online ash meter server as the human computer interaction software of the control system. Then, the SQL2008 database was used as a public database by the control system and the online ash meter. And the data of the two systems was interactively operated through the SQL database to realise data sharing between the two systems.

The raw coal information and ratios of the current 1#, 2#, 3# system separating and processing were calculated by PLC (Programmable Logic Controller) according to the selection of the coal, raw coal feeder, belt conveyor under the raw coal warehouse and the transfer belt conveyor. The raw coal information and ratio information of 1#, 2#, 3# production system separating and processing were read by IFIX from PLC and stored in ASH1, ASH2 and ASH3 tables in SQL2008 database. And then, the corresponding raw coal information and ratio information in the ASH1, ASH2, and ASH3 tables were read by the ash meter operating software. So the slope and intercept parameters were automatically adjusted by the ash meter operating software according to the current raw coal and ratio information of the 1#, 2#, and 3# production systems, parameter settings were shown in Table 4.

Table 4 The slope and intercept parameters of the ash analyser

Blended raw coal	*Blended ratio*	*Slope*	*Intercept*
QingDong Coal:TongTing Coal	2:1	36	–70.35
YuanYi Coal:QingDong Coal	2:1	36	–70.19
YuanYi Coal: QingDong Coal	1:1	36	–69.54
XunTuan Coal	–	36	–68.27
LinHuan Coal Mine's fat coal	–	36	–68.64
TongTing Coal	–	36	–68.79
XunTuan Coal:YangLiu Coal	1:1	36	–68.19
XunTuan Coal:YangLiu Coal	2:1	36	–69.54
YangLiu Coal	–	36	–71.25
SunTuan Coal	–	36	–64.25
YuanYi Coal	–	36	–67.21

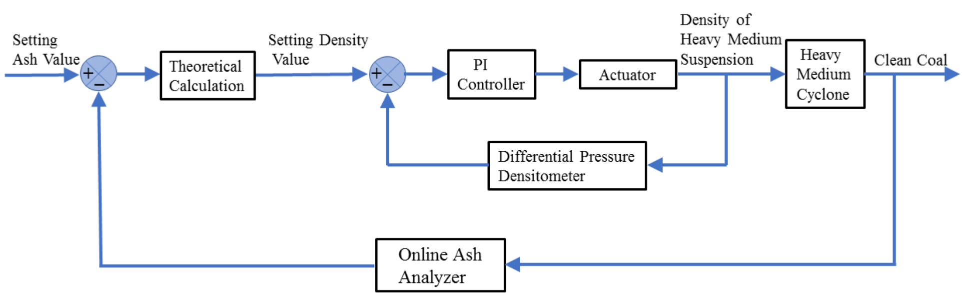
5 Closed-loop control of clean coal ash content value

5.1 System structure

As shown in Figure 4, the ash content of the three online ash meter on the 3117A, 3217A, and 3317A belt conveyors were stored in the AshTable table of the SQL2008 database by the ash meter operating software. Three corresponding ash content in the SQL2008 database AshTable table were read by IFIX. And then, the ash content of the three ash meter were transferred to the PLC registers. Therefore, closed-loop control of clean coal ash content value could be completed in PLC. However, the raw coal property and raw coal feed rate were an important influence factor (Meyer and Craig, 2015; Wang et al., 2015). The coal preparation plant did not have a raw coal online ash detection device, and the running frequency of raw coal feeder was fixed, so the system had no feedforward control (Zhang and Xia, 2014; Zhang et al., 2015).

The novel separation control system was mainly composed of three parts: (a)density control inner loop (Meng et al., 2005; Xiang, 2009; Guo et al., 2018), (b)heavy media ash content outer loop, (c) calculation of relationship between clean coal ash content and separation density. As shown in Figure 5, the detection unit used in the density control inner loop was a differential pressure densimeter, which was installed on the vertical pipe at the front end of inlet of dense medium cyclone. And the detection unit used in the outer loop control of clean coal ash content was an online ash meter. The online ash meter was installed behind the centrifugal dehydrator due to it is sensitive to the media (Sripriya et al., 2006). The PI algorithm was used for implementing the density control inner loop and the theoretical calculation was used for the ash control outer loop (Zhang et al., 2014b). The core hardware of the control system was PLC. The water supplement was achieved by an electric actuator (Meyer and Craig, 2010). the position feedback signal and control signal of the electric actuator were 4-20mA DC (Cierpisz et al., 2016).

Figure 5 Diagram of a new separation control system based on clean coal ash closed loop



As presented in Figure 5, the online ash meter was added to the control system to form a closed-loop control system. The working process of the system was as follows. Firstly, setting the ash content value (the target ash content) according to the user's requirement and then the density of the suspension was automatically calculated by the ash-density relationship module according to the setting ash content value. Then, a density deviation between the calculated density and the feedback real-time density was formed which was used as the input of the PI controller in the PLC. Then a corresponding digital quantity was calculated by the PI controller and converted into a 4-20 mA DC electric signal by the PLC analog quantity output module. The electric signal was used to control the opening degree of the electric actuator.

The ash content of the clean coal would change along with the changes of the density (Napier-Munn, 1991; Chu et al., 2009; Mohanty et al., 2014). After a certain period, the changes of the ash content were detected by an online ash meter. Then, the ash content deviation between the setting ash content value and detected ash content value was formed which was used as the input of the ash-density relationship module. The setting density was adjusted according to the output of the ash-density relationship module. Through the joint action of density control inner loop and heavy media ash outer loop, the precise adjustment of the product ash was finally realised.

5.2 Theoretical calculation

Theoretical calculation, the current separation density value was obtained according to the float-sink data of the coals selected in the current production system (Callen et al., 2008). The current theoretical separation density was calculated based on setting ash content value (Habetinejad et al., 2012; Deniz and Umucu, 2013). If coal blending comes from different coal mines, a new float–sink analysis data was synthesised according to some ratio (Cierpisz and Heyduk, 2002; Guanghui et al., 2012; Wang et al., 2015), the theoretical yield and ash calculation of the coal blending were as shown in Formula 1 and Formula 2.

$$Y = \frac{Y1 \times R1 + Y2 \times R2}{R1 + R2} \tag{1}$$

Y – The yield of a mixture of two different ratio of coal at a certain density level, %.

$Y1$ – The yield of coal type 1 at a certain density level, %.

$Y2$ – The yield of coal type 2 at a certain density level, %.

$R1$ – The ratio of coal type 1 after blended two different coal types.

$R2$ – The ratio of coal type 2 after blended two different coal types.

$$A = \frac{\frac{Y1 \times R1}{R1 + R2} \times \mathrm{A1} + \frac{Y2 \times R2}{R1 + R2} \times \mathrm{A2}}{\frac{Y1 \times R1}{R1 + R2} + \frac{Y2 \times R2}{R1 + R2}} \tag{2}$$

A – The ash content of a mixture of two different ratio of coal at a certain density level, %.

$A1$ – The ash content of coal type 1 at a certain density level, %.

$A2$ – The ash content of coal type 2 at a certain density level, %.

The new raw coal yield and new raw coal ash content at different density levels of blended raw coal under different ratios were calculated by formula 1 and 2. The cumulative yield of the floating matter, the cumulative ash of the floating matter, the cumulative yield of the sediment, yield of separation density ±0.1, and the cumulative ash of the sediment could be calculated from sink-float data of new raw coal.

Table 5 shows sink-float data of raw coal in QingDong mine, and Table 6 shows sink-float data of raw coal in TongTing mine. The mixing ratio of raw coal in mine QingDong and mine TongTing was 2: 1, which was one of the processing methods of raw coal blending and processing in coal preparation plant. The new comprehensive table of sink-float data calculated according to formulas 1 and 2 was shown in Table 7. Then, based on the set clean coal ash and the data in Table 7, a new separating density value was calculated.

Table 5 Comprehensive table of raw coal sink-float data of QingDong mine

Density class	Raw coal (+0.5 mm)		The cumulative of the floating matter		The cumulative of the sediment		Separation density ±0.1	
	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Density	Yield (%)
–1.3	3.95	4.61	3.95	4.61	100	19.96	1.3	49.81
1.3–1.4	45.86	8.4	49.81	8.1	96.05	20.6	1.4	69.26
1.4–1.5	23.41	16.28	73.22	10.72	50.19	31.73	1.5	32.9
1.5–1.6	9.49	25.6	82.71	12.42	26.78	45.24	1.6	15.81
1.6–1.8	6.32	36.13	89.02	14.11	17.29	56.02	1.7	6.32
+1.8	10.98	67.47	100	19.96	10.98	67.47		
Total	100	19.96						

Table 6 Comprehensive table of raw coal sink-float data of TongTing mine

Density class	Raw coal (+0.5 mm)		The cumulative of the floating matter		The cumulative of the sediment		Separation density ±0.1	
	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Density	Yield (%)
–1.3	3.64	3.7	3.64	3.7	100	58.37	1.3	17.53
1.3–1.4	13.89	8.81	17.53	7.75	96.36	60.44	1.4	23.11
1.4–1.5	9.22	15.36	26.75	10.37	82.47	69.13	1.5	13.66
1.5–1.6	4.44	19.73	31.19	11.7	73.25	75.9	1.6	8.7
1.6–1.8	4.26	28.25	35.45	13.69	68.81	79.53	1.7	4.26
+1.8	64.55	82.92	100	58.37	64.55	82.92		
Total	100	58.37						

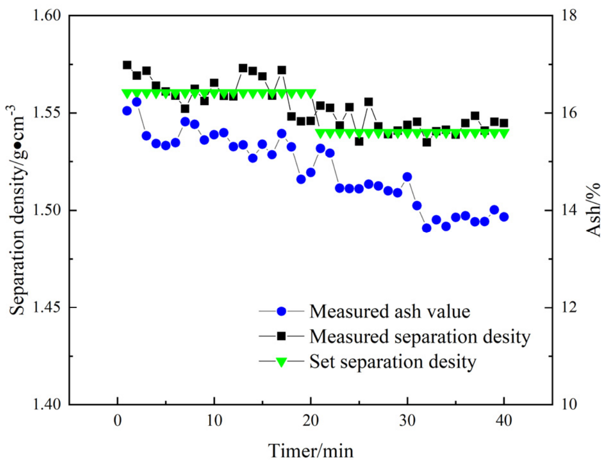
Table 7 Comprehensive table of sink-float data of raw coal after mixing

Density class	Raw coal (+0.5 mm)		The cumulative of the floating matter		The cumulative of the sediment		Separation density ±0.1	
	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Yield (%)	Ash (%)	Density	Yield (%)
–1.3	3.85	4.32	3.85	4.32	100.00	32.76	1.30	39.05
1.3–1.4	35.20	8.45	39.05	8.05	96.15	33.90	1.40	53.88
1.4–1.5	18.68	16.13	57.73	10.66	60.95	48.60	1.50	26.49
1.5–1.6	7.81	24.49	65.54	12.31	42.27	62.95	1.60	13.44
1.6–1.8	5.63	34.14	71.17	14.04	34.46	71.66	1.70	5.63
+1.8	28.84	79.00	100.01	32.77	28.83	78.99		
Total	100.00	32.76						

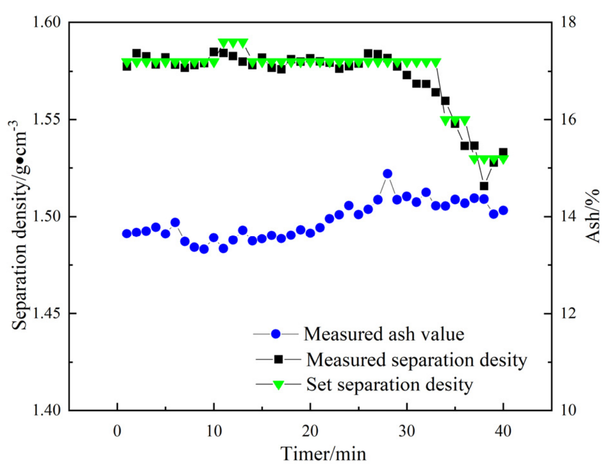
5.3 Application effect

The production situation before and after the system application was compared. The mixed raw coal with a mixing ratio of 2: 1 of mine QingDong and mine TongTing was separated and processed. After using the system, the set ash content of the clean coal was 15.5%, and then the newly set clean coal ash content was 14.0%. As shown Figure 6(a), the system could better make the clean coal product ash content close to the set ash content value. And the qualification rate was significantly increased. The system was not used, when the system was disturbed, the changing trend of ash could not be controlled, as shown Figure 6(b).

Figure 6 Comparison of application effects before and after using the system: (a) after using the system, (b) before using the system



(a)



(b)

The annual raw coal processing capacity of the plant is very large and can reach 1600Mt/a in LinHuan Coal Preparation Plant (Zhang et al., 2019). The qualified rate of clean coal products had increased from approximately 45% to 49%. The average yield of the clean coal was 50.17% in the presence of the new control system compared with that of 50.12% in the absence of the system, and the clean coal yield had increased by approximately 0.05%.

6 Conclusions

In this paper, a heavy media separation intelligent control system suitable for different coal quality characteristics was successfully developed to control and stabilise product quality. The working process of the system was described in detail in the paper. After using the system, the interference of human factors is eliminated, and the stability of production is improved. It reduces the labor intensity of workers and greatly improves the economic benefits of coal preparation plants. The system has a high promotion value in the coal preparation industry.

1 The washed coal type and ratio could be automatically identified by the system, and the parameters of the online ash meter could be automatically adjusted.

2 The new sink-float data was obtained by using the weighted average method.

3 After using the system, the ash content of the clean coal products after heavy media separating was relatively stable, and the product qualification rate was improved.

In the future, an electronic belt scale will be installed on the belt conveyor of the cleaned coal. Based on the characteristics of the washed raw coal, the real-time yield of the cleaned coal of the current heavy media separation system will be calculated, and the factors affecting the cleaned coal yield will be analysed to maximise the cleaned coal yield under the maximum qualified ash content, so as to maximise the economic benefits of the coal preparation plant.

References

Callen, A.M., Patel, B., Zhou, J. and Galvin, K.P. (2008) 'Development of water-based methods for determining coal washability data', *International Journal of Coal Preparation and Utilization*, Vol. 28, No. 1, pp.33–50.

Chen, J., Chu, K.W., Zou, R.P., Yu, A.B. and Vince, A. (2012) 'Prediction of the performance of dense medium cyclones in coal preparation', *Minerals Engineering*, Vol. 31, pp.59–70.

Chu, K.W., Wang, B., Yu, A.B., Vince, A., Barnett, G.D. and Barnett, P.J. (2009) 'CFD–DEM study of the effect of particle density distribution on the multiphase flow and performance of dense medium cyclone', *Minerals Engineering*, Vol. 22, No. 11, pp.893–909.

Cierpisz, S. and Heyduk, A. (2002) 'A simulation study of coal blending control using a fuzzy logic ash monitor', *Control Engineering Practice*, Vol. 10, No. 4, pp.449–456.

Cierpisz, S., Kryca, M. and Sobierajski, W. (2016) 'Control of coal separation in a jig using a radiometric meter', *Minerals Engineering*, Vol. 95, pp.59–65.

Das, A. and Sarkar, B. (2018) 'Advanced gravity concentration of fine particles: a review', *Mineral Processing and Extractive Metallurgy Review*, Vol. 39, No. 6, pp.359–394.

Deniz, V. and Umucu, Y. (2013) 'Interpretation using sink-float data by simple recovery equations for two different pumices', *Mineral Processing and Extractive Metallurgy*, Vol. 114, No. 2, pp.109–114.

Firth, B.A. (2009) 'Dense medium cyclone control – a reconsideration', *International Journal of Coal Preparation and Utilization*, Vol. 29, No. 3, pp.112–129.

Guanghui, W., Yali, K., Zhangguo, W., Ying, W. and Li, J. (2012) 'A real-time prediction model for production index in process of dense-medium separation', *International Journal of Coal Preparation and Utilization*, Vol. 32, No. 6, pp.298–309.

Guo, X., Shao, H., Yang, C. and Zhang, Z. (2018) 'Research on PFC-PID control algorithm of density and liquid level in heavy medium suspension', *Industry and Mine Automation*, Vol. 44, No. 1, pp.89–95.

Gupta, V. and Mohanty, M.K. (2006) 'Coal preparation plant optimization: a critical review of the existing methods', *International Journal of Mineral Processing*, Vol. 79, No. 1, pp.9–17.

Habetinejad, H., Jorjani, E. and Sam, A. (2012) 'Evaluation of Mayer curve validity on feed blending at the Zarand coal washery plant', *International Journal of Mining Science and Technology*, Vol. 22, No. 1, pp.19–22.

Huang, B., Xu, H., Chen, J. and Zhu, Z. (2019) 'Discrete analysis and numerical simulation for separation for separation process of dense medium cyclone', *Journal of China Coal Society*, Vol. 44, No. 4, pp.1216–1223.

Kawatra, S.K. (2020) *Advanced Coal Preparation and Beyond, CO_2 Capture and Utilization*, CRC Press, pp.73–100.

Luttrell, G.H., Kohmuench, J.N. and Yoon, R.-H. (2000) 'An evaluation of coal preparation technologies for controlling trace element emissions', *Fuel Processing Technology*, Vols. 65/66, pp.407–422.

Meng, F., Wang, Y., Jiang, J. and Wang, J. (2005) 'Study of multivariable fuzzy control for density and level of suspension in heavy media coal processing', *Journal of China University of Mining and Technology*, Vol. 34, No. 2, pp.253–255.

Meyer, E.J. and Craig, I.K. (2010) 'The development of dynamic models for a dense medium separation circuit in coal beneficiation', *Minerals Engineering*, Vol. 23, No. 10, pp.791–805.

Meyer, E.J. and Craig, I.K. (2014) 'Coal dense medium separation dynamic and steady-state modelling for process control', *Minerals Engineering*, Vol. 65, pp.98–108.

Meyer, E.J. and Craig, I.K. (2015) 'Dynamic model for a dense medium drum separator in coal beneficiation', *Minerals Engineering*, Vol. 77, pp.78–85.

Mohanty, M., Zhang, B., Wang, H., Mahajan, A., Akbari, H., Bashir, Z., Ramamoorthy, S. and Hirschi, J. (2014) 'Development and demonstration of an automation and control system for coal spirals', *International Journal of Coal Preparation and Utilization*, Vol. 34, Nos. 3/4, pp.157–171.

Napier-Munn, T.J. (1991) 'Modelling and simulating dense medium separation processes – a progress report', *Minerals Engineering*, Vol. 4, Nos. 3/4, pp.329–346.

O'Brien, M., Firth, B. and McNally, C. (2014) 'Effect of medium composition on dense medium cyclone operation', *International Journal of Coal Preparation and Utilization*, Vol. 34, Nos. 3/4, pp.121–132.

Sowerby, B.D. and Watt, J.S. (1990) 'Development of nuclear techniques for on-line analysis in the coal industry', *Nuclear Instruments & Methods in Physics Research*, Vol. 299, Nos. 1–3, pp.642–647.

Sripriya, R., Dutta, A., Dhall, P.K., Narasimha, M., Kumar, V. and Tiwari, B.S. (2006) 'An analysis of medium losses in coal washing plants', *International Journal of Mineral Processing*, Vol. 80, Nos. 2–4, pp.177–188.

Wang, Z., Kuang, Y., Deng, J., Wang, G. and Ji, L. (2015) 'Research on the intelligent control of the dense medium separation process in coal preparation plant', *International Journal of Mineral Processing*, Vol. 142, pp.46–50.

Xiang, Y. (2009) *Research on Fuzzy Control Methods for Suspension Density and Liquid Levels in Dense-Medium Separation*.

Zhang, G., Wu, C. and Cheng, X. (2019) 'Application practice of a new type of raw coal heavy medium cyclone in Linhuan Coal Preparation Plant', *Coal Processing and Comprehensive Utilization*, No. 3, pp.1–6.

Zhang, L. and Xia, X. (2014) 'A model predictive control for coal beneficiation dense medium cyclones', *IFAC Proceedings Volumes*, Vol. 47, No. 3, pp.9810–9815.

Zhang, L., Xia, X. and Zhang, J. (2014a) 'Improving energy efficiency of cyclone circuits in coal beneficiation plants by pump-storage systems', *Applied Energy*, Vol. 119, pp.306–313.

Zhang, L., Xia, X. and Zhang, J. (2015) 'Medium density control for coal washing dense medium cyclone circuits', *IEEE T Contr Syst T*, Vol. 23, No. 3, pp.1117–1122.

Zhang, L.J., Xia, X.H. and Zhu, B. (2017) 'A dual-loop control system for dense medium coal washing processes with sampled and delayed measurements', *IEEE T Contr Syst T*, Vol. 25, No. 6, pp.2211–2218.

Zhang, R., Wu, S. and Gao, F. (2014b) 'Improved PI controller based on predictive functional control for liquid level regulation in a coke fractionation tower', *Journal of Process Control*, Vol. 24, No. 3, pp.125–132.