Brazilian Journal
of Chemical
Engineering

ISSN 0104-6632
Printed in Brazil
www.abeq.org.br/bjche

Vol. 36, No. 02, pp. 845 - 853, April - June, 2019
dx.doi.org/10.1590/0104-6632.20190362s20180209

PREDICTION OF COAL SLURRY PIPELINE TRANSPORTATION GRADING REDUCTION AND ITS INFLUENCE ON PIPE TRANSPORTATION PARAMETERS

Li-an Zhao[1*], Tieli Wang[2] and Ronghuan Cai[3]

[1] Liaoning Technical University, Liaoning Province, Fuxin, China. E-mail: anlizhao1@163.com - ORCID: 0000-0001-6946-1823
[2] Wuhan Design and Research Institute of China, Coal Technology Engineering Group, Wu Han, China.
[3] Northeastern University, Shenyang, China.

(Submitted: May 17, 2018 ; Revised: November 28, 2018 ; Accepted: December 18, 2018)

Abstract - Coal slurry pipe, being a new type of energy transportation mode, changes of the particle composition and the effect on other parameters are worth studying. Comparison of ring tube test measured data and batch grinding model simulation data shows that batch grinding model can predict the coal particle gradation to a certain extent. The effect of collision and wear of overcurrent components in the centrifugal pump, friction and collision between particles and piping and piping accessories, and initial particle size distribution during hydraulic conveying were also investigated by laboratory studies. Meanwhile, the effect of particle composition change on slurry viscosity, hydraulic resistance and minimum resistance critical velocity was studied based on the experimental data. The experimental and theoretical analysis indicates that the change of slurry particle composition can lead to the change of viscosity, resistance and minimum resistance critical velocity of the slurry. Moreover, based on the previous studies, the calculation model of minimum resistance critical velocity of coal slurry is proposed.
Keywords: Coal slurry; Minimum resistance critical velocity; Hydraulic conveying parameters; Slurry hydraulic resistances; Particle composition.

INTRODUCTION

In the 1950s, pipeline hydraulic coal transportation served as a mature technology widely applied in underground coal mines of China. Long distance pipeline coal transportation, which has been under construction since 2012, indicated that the application entered into a new stage (Liu, 2012). Coal, being an important mineral resource, is soft and brittle in pipeline transportation. Therefore, the collision between particles, between particles and liquid pipelines and ancillary parts, wetting effect caused by liquid striking against coal particles, the fragmentation effect of impeller of slurry pump, as well as the loading/unloading process during the particle access/discharge to/from the pipe system, can lead to the alteration of particle composition, and then influence the hydraulic conveying parameters. Previous studies indicated that the change of coal slurry particle composition could influence the viscosity of the slurry (Boylu et al., 2004; Mani et al., 2015; Pulido et al.,1995). However, almost no previous work focused on the effect of slurry average velocity, initial particles size distribution and pumping time on particle composition. Additionally, the effect of particle composition change on slurry viscosity, hydraulic resistance and minimum resistance critical velocity (MRCV) of the slurry at which the least energy is required in slurry flow) was explored in this study.

* Corresponding author: Li-an Zhao - E-mail: anlizhao1@163.com

PUMPING TEST OF COAL PIPELINE

The pipeline coal conveying measurement was conducted to study the influential factors of particle grade degradation of pipeline coal transportation and its impact on pipeline transportation parameters. Figure 1 shows the layout of the pipeline, where the inner diameter and length of the pipeline are 150mm and 25m, respectively. The rubber lined pump (Linatex) was used as slurry pump, with outlet diameter ranging from 45 to 360 mm. The flow rate and the head of the pump are 4.6-2420 m^3/h and 6.5-136 m, respectively. Additionally, the motor power of the slurry pump is 412kw.

The slurry density and viscosity were measured by a DMA35 portable densimeter and a SNB-1 digital rotary viscometer by collecting samples from the sampling valve (Fig.1). The collected samples were dried in an oven, and then the Particle Size Distribution (PSD) curve was determined by the sampling sieve analysis method. The average flow velocity of the slurry V_m , the pressure drop and Slurry Hydraulic Resistance (SHR) per unit length can be obtained from the utrasonic flowmeter (flow meter 4 in Fig.1) and mercury manometer (meter 7 in Fig.1), respectively. The solids flow behaviour was observed in the acrylic transparent tube 8 (Fig.1).

MRCV, the average velocity corresponding to the minimum SHR per unit length, can be obtained through drawing a relationship curve between SHR per unit length and mean flow velocity of the slurry. Also, particle movement state can be observed.

Meanwhile, a heat exchanger 5 (Fig.1) was utilized to maintain 25°C in order to control the influence of temperature fluctuation during the experimental process. Two kinds of clean coal from a coal mine in the north part of Shaanxi Province were used in this study. The selected samples are all coking coal. Specific gravity of clean coal 1 and 2 are 1.34 and 1.36, respectively; ash contents are 2.2% and 2.4%, respectively. The initial grading curves of the two kinds of clean coal particles are presented in Fig. 2. The maximum particle diameter of clean coal 1 and 2

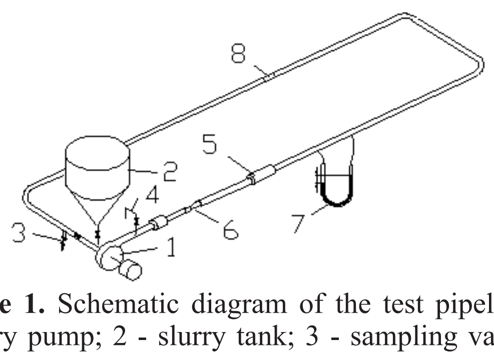

Figure 1. Schematic diagram of the test pipeline: 1 - slurry pump; 2 - slurry tank; 3 - sampling valve; 4 - flowmeter; 5 - heat exchanger; 6 - necking valve; 7 - mercury manometer; 8 - Acrylic transparent tube.

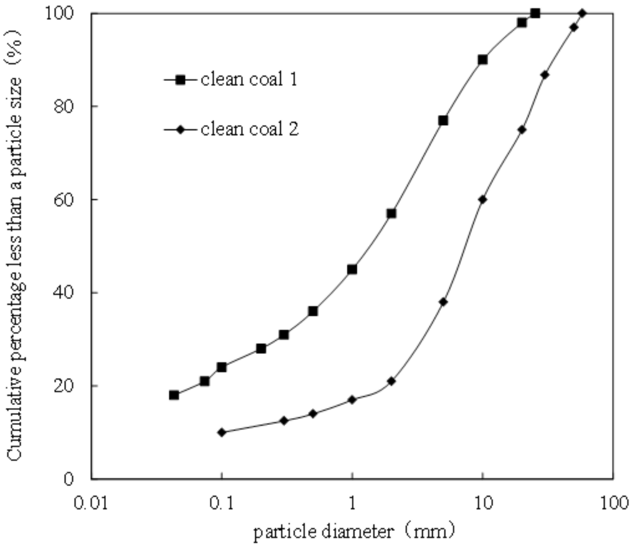

Figure 2. Initial grading curves.

is 25.4mm and 58.0mm, and weighted mean particle size is 3.75mm and 14.13mm, respectively. The coal slurry concentration of clean coal 1 and 2 is 10.2% and 11.5%, respectively.

The average velocity of clean sample 2 slurry was set at 4.5 ms^{-1} and 5.5 ms^{-1} in the initial stage. The particle size grading of coal slurry with different flow distance, including 1500m and 4500m, was measured (Fig.3). Additionally, the particle grade alterations of two samples with different transportation time for V_m*=3.0m/s* were determined (Fig.4). Finally, the hydraulic resistance of clean coal 1 and 2 slurry was tested after different transportation time. Meanwhile, MRCV of coal slurry under different transportation conditions was determined by analysing the relationship curve between SHR per unit length and average flow velocity of the slurry**.** It indicates that grade degradation can be observed in two kinds of clean coal slurry after a period of transportation.

The errors of pipe diameter and sensor installation have obvious influence on the measurement accuracy of the ultrasonic flowmeter. In this experiment, the measured pipe diameter and strict installation are input for controlling purpose. The mercury manometer should be kept in a strict vertical position in order to keep the measured value of SHR in an acceptable range. The line of sight should be levelled with the liquid level in reading. In the test, in order to overcome human errors, multiple readings and checks are used.

The precision grade of the flowmeter is 0.5, working environment temperature range is 30ºC~60ºC, and the working humidity range is 2%-5%.The precision grade of the mercury manometer is 1.0 for 2.5kPa. The larger the measuring range, the higher the measured pressure, and the higher the measurement accuracy.

In the experiment, the operation of the slurry pump inevitably causes pipeline vibration to a certain extent. Some studies have shown that slurry pipe vibration can reduce resistance (Sun et al., 2001, Sun and Wu ., 2002, Wu., 2017), and other studies have observed that slurry pipe vibration can not only increase resistance, but also reduce resistance (Lin et al., 2006), so in this experiment, the possible existence of pipeline vibration is an uncertainty in the change of resistance.

PREDICTION OF COAL SLURRY PIPELINE CONVEYING GRADE

Previous studies mainly focus on grinding theory for iron concentrate (Huang et al., 2016, He et al., 2016, Yang et al., 2017), and research work has been done by using grinding theory for degradation of solid while coal slurry is conveyed in a pipeline (Henderson.,1983.,Shook et al., 1978). However, the solution of the grinding model and the selection of relevant parameters needs further study.

It is obvious that the working process of a ball mill or a rod mill is different from the pipeline transportation. In this study, the slurry pipeline transportation process is regarded as a special ball mill or rod mill grinding process.

According to grinding theory, the overall equilibrium model for batch grinding can be expressed as follows (Huang et al., 2016):

$$\frac{df_i(t)}{dt} = \sum_{j=1}^{i-1} b_{ij} S_j f_i(t) - S_i f_i(t) \tag{1}$$

Among these, $f_i(t)$ is the weight fraction of the grain grade i^{th} at time t; b_{ij} is a breakage function, that refers to the fraction of the material from grain grade i^{th} which falls into grain grade j^{th} after breakage. S_i is a breakage rate function, also known as the selection function, that refers to the probability of rupture in unit time.

In the above equation, if b_{ij} and S_i are known, according to the given initial PSD, the PSD at t time of grinding can be obtained.

If the coarsest grain level is j, then (Huang et al., 2016):

$$B_{ij} = \frac{\ln \dfrac{1-F_i(t)}{1-F_i(0)}}{\ln \dfrac{1-F_{j+1}(t)}{1-F_{j+1}(0)}} \tag{2}$$

where B_{ij} is cumulative broken distribution function,

$$B_{ij} = \sum_{k=n}^{i} b_{kj}$$

$F_i(0)$ is cumulative percentage of particles less than the grain grade i^{th} at the initial time, and $F_i(t)$ is cumulative percentage of particles less than the grain grade i^{th} at t.

The following formula is used to standardize the matrix, which can be expressed as follows:

$$b_{ij} = B_{ij} - B_{i+1,j} \tag{3}$$

Therefore, from Eqs (1), (2) and (3), the value of the breakage function b_{ij} can be obtained.

According to the results of related studies, the value of S_j can be known from the following formula (Yin and Li, 1993):

$$S_j = \frac{\ln \dfrac{1-F_i(0)}{1-F_i(t)}}{B_{ij} t} \tag{4}$$

Equation (1) can be written in a matrix form as follows:

$$\frac{df(t)}{dt} = \langle\left(B - I\right) S f(t) \tag{5}$$

where S is a diagonal matrix with diagonal elements S_i, B is a strict lower triangular matrix with elements $b_{ij,}$ I is a n order unit matrix.

The initial grade of the coal particles can be obtained and the simulations of t=2400 s and t=4200 s are carried out by using MATLAB software. Comparison of measured data and simulation data of PSD of clean coal 1 slurry and clean coal 2 slurry is shown in Table 1 and Table 2, respectively. It shows that the relative error between measured data and simulation data is minor, and maximum relative deviation is 6.01% after pipe transport of 2400 s in Table 1. Maximum relative deviation increased to 6.99% at a transport time of 4200 s. Table 2 shows the comparison of measured data and simulation data of clean coal 2 slurry, and maximum relative deviation is 7.0% after 2400 s. Maximum relative deviation increased to 8.0% at 4200 s. Additionally, the proportion of coarser particles decreased with transportation, whereas the particle proportion of -0.074 and -0.043 increased during transportation. In the experiment, the sieving method was used to determine the particle grade. The sieving method is to pass through the sieve hole with the smallest size of the particle, and the measuring method is the smallest size. Therefore, to some extent, the measured value is smaller than the simulation data and this can be seen in Tables 1 and 2.

From the results of the comparison, the batch grinding model can predict the influence of pipeline transportation time on the change of coal particle grade to a certain extent.

Table 1. Comparison of measured data and simulation data of clean coal 1.

Particle grade	Cumulative percentage less than a particle size(%)					Relative deviation (%)	
	t=0	t=2400s (Mea)	t=2400s (Sim)	t=4200s (Mea)	t=4200s (Sim)	t=2400s	t=4200s
25.4	100	100	100.02	100	102	0	2.00
15	94.2	96.20	98.16	97.60	93.75	2.03	3.95
10	90.23	92.40	95.24	95.12	90.36	3.07	-5.00
5	77.32	78.85	81.22	80.43	84.45	3.01	5.00
2	57.32	58.71	60.88	61.06	65.33	3.7	6.99
1	45.33	46.80	45.40	48.6	46.66	-2.99	-3.99
0.5	36.65	38.20	36.4	39.69	42.07	4.23	6.00
0.3	31.12	32.14	30.65	33.85	31.50	-4.64	-6.94
0.2	28.20	29.12	27.66	30.28	30.88	-5.01	1.98
0.1	24.10	24.96	26.46	25.71	26.74	6.04	4.00
0.074	21.23	23.20	22.74	24.34	23.58	-1.98	-3.45
0.043	18.20	20.21	20.91	22.42	23.09	3.46	2.99

Note: Sim means Simulation data; Mea means Measured data.

Table 2. Comparison of measured data and simulation data of clean coal 2.

Particle grade	Cumulative percentage less than a particle size(%)					Relative deviation (%)	
	t=0	t=2400s (Mea)	t=2400s (Sim)	t=4200s (Mea)	t=4200s (Sim)	t=2400s	t=4200s
58	100	-	-	-	-	-	-
44	91.87	100	100.06	-	-	0.06	-
30	86.81	94.8	96.50	100	100.03	1.79	0.03
20	75.00	83.63	79.45	90.63	85.25	-5.00	-5.94
10	60.32	67.32	64.63	73.01	67.17	-4.00	-8.0
5	38.43	44.84	47.94	48.89	51.82	6.91	5.99
2	21.32	24.54	25.77	28.01	29.97	5.01	7.00
1	17.37	19.55	20.92	21.90	21.02	7.00	-4.02
0.5	14.76	16.52	16.19	18.21	18.77	2.00	3.08
0.3	12.53	14.5	13.92	16.00	15.2	-4.00	-5.0
0.1	10	11.15	11.73	12.12	12.6	5.20	3.96
0.074	0	9	8.46	11.00	10.67	-6.00	-3.00
0.043	0	0	0	8.80	8.97	-6.00	1.93

Note: Sim means Simulation data; Mea means Measured data.

ANALYSIS OF FACTORS INFLUENCING GRADE DEGRADATION OF SLURRY

Collision and wear of overcurrent components in the centrifugal pump

A rubber lining was used in the slurry centrifugal pump. However, the degrading effect on the coal particles during operation is still obvious. The overcurrent components of the centrifugal pump are the main wear parts, including the impeller, guards and pump casings (Jian, 2004). Previous studies show that small-diameter particles are relatively evenly distributed in the flow channel with small probability of collision in overcurrent components. However, the angle and rate at which the particle diameter impacts the flow-through component are smaller in great diameter particles and multiple impact processes exist in collisions (Wang, et al., 2014, Wu, et al., 2012, Hui, 2009). Based on this, the finer coal slurry 1 particles are relatively less abraded by the pump's overcurrent components in the centrifugal pump in same conditions, while the coarser coal slurry 2 particles are abraded by the flow components and secondary crushing can occur with more significant grading reduction. It can be concluded from figure 4 that the particle grade of the coarser coal slurry 2 is more obvious than that of the coal slurry 1 at the same time and at the same pump rotation speed (V_m=3.0m/s). Meanwhile, the slurry grade reduction of the coal slurry 2 becomes more obvious with increasing rotation speed (average slurry speed) of the pump, and the degradation trend of the particle with section larger than 1mm is obviously larger than that of the particle with size less than 1mm, as shown in Figure 3.

Friction and collision between particles and pipe and pipe accessories

The steel pipes, which act as the main transport pipe, are used in the experiment. The accessories of pipe include pipe fittings for connecting pipes, valves for controlling pipe operation and measuring instruments (Figure 1). The grade reduction caused by the collision between particles is small and can be neglected due to the fact that the slurry concentration is not more than 11.5%. In the experiment, the motion state of the slurry particles is basically controlled in the partial suspension and partial slip motion. As a result, the particles on the bottom of the pipe moving

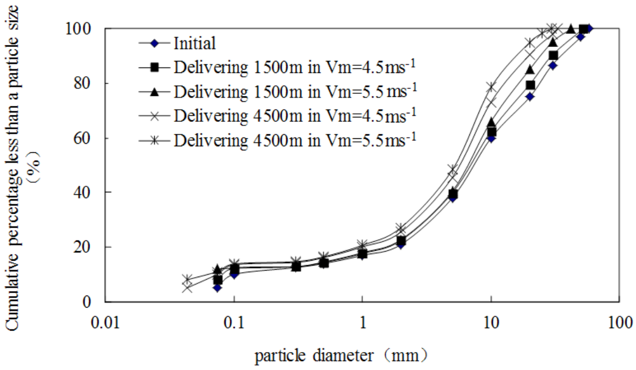

Figure 3. Change of PSD of clean coal 2 with convey distance and average slurry velocity.

in the sliding bed will have friction and collision with the pipe and the pipe attachment, which will result in the degradation of the particle grade. Figure 3 shows that the cumulative friction and collision effect of the particles and the pipeline and the pipe attachment become more significant and the grading degradation become more obvious with the increasing transport distance for the slurry in the pipeline.

Initial particle size distribution

The particle size of coal slurry 2 is larger than that of coal slurry 1, and the group 1 with the coarse particle size is characterized by significant degrading (Fig.4). Therefore, the degradation rate increases with increasing feed size. For the same grading (solid), the degradation range of the large particle section is larger than that of the small particle section. Therefore, there is no essential difference in slurry size (gradation) caused by different conveying speeds for fine particle areas. However, a significant difference between the different particle sizes can be observed in the coarse particle region.

EFFECT OF COAL SLURRY GRADE REDUCTION ON SOME CONVEYING PARAMETERS

Slurry viscosity

The upper limit of clean coal particles is reduced as pipeline transportation continues (Figs. 3 and 4), and the proportion of -200 mesh particles increases, and it can enhance the viscosity of the slurry. Therefore, the grade degradation of coal slurry produces many fine particles, which can alter the suspension particle size composition, and slurry rheological properties. Moreover, it can transform the coal slurry from a Newtonian body to non-Newtonian body.

In this experiment, clean coal 1 and 2 contain a certain amount of ash, which can be ignored in studying the influence on rheological parameters (Zhao, 2016). Relationship between coal slurry concentration limit C_{Vm} and critical concentration C_{V0} from a Newtonian

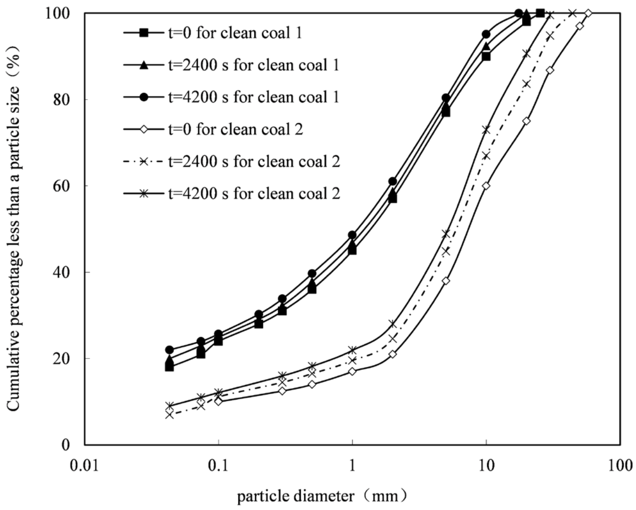

Figure 4. Change of PSD with convey time.

fluid into a Bingham body can be described by the following equation (Fei, 1994):

$$C_{V0} = 1.87 \cdot C_{Vm}^{\ 3.2} \tag{6}$$

where C_{V0} is the critical concentration from a Newtonian fluid into a Bingham, and C_{Vm} is the slurry concentration limit.

The results of calculation show that the slurry flow patterns of clean coal 1 slurry and clean coal 2 slurry in the test are all Newtonian.

Relative viscosity of the coal slurry is measured by a SNB-1 digital rotary viscometer. The results show that the relative viscosities of the coal slurry 1 are 1.31, 1.35 and 1.39, respectively for t=0, 2400s and 4200s, whereas the relative viscosities of the coal slurry 2 are 1.25, 1.28, and 1.32, respectively. It is obvious that the viscosities of two coal samples increase with the prolongation of the experiment time.

It is difficult to measure the viscosity of low concentration slurry containing coarse particles by a rotating viscometer. The slurry viscosity is measured after removing the coarse particles whose diameter is larger than 0.5mm (Fei,1994). The viscosity values vary with the size of the rejected coarse particles.

Hydraulic resistance of slurry

The influence of slurry grade degradation on the Slurry Hydraulic Resistance (SHR) can be reflected in the following aspects. The addition of fine particles can increase the viscosity of coal slurry, leading to the sliding movement of coarse particles on the bottom of the pipe moving in the form of suspended movement. Consequently, slurry transportation becomes more easy. Meanwhile, with the addition of fine particles, the settling velocity of particles in the coal slurry is reduced, leading to a uniform vertical velocity distribution, which is beneficial to reduce the SHR.

However, fine particles may increase the viscosity and the viscous resistance of the flow, which is a serious obstacle to the transportation of coal slurry.

SHR of coal slurry 1 and 2 was measured in this study and the results were presented in Figs. 5 and 6 for some particles moving in a sliding bed and others by suspending. The results show that the resistance values of the two kinds of coal slurry are all reduced after conveying for 70 min. It can be seen from Figs. 5 and 6 that coal slurry 1 and 2 all have a minimum point in the i_m-V_m curve for t=0 and t=4200s, The average slurry velocity at which the least SHR is obtained in a slurry is often referred to MRCV.

The results elucidate that the SHR of coal slurry 1 and coal slurry 2 decreases by 2.10%~4.82% and 5.96%~10.11% respectively while coal slurry flows for 4200s. So the influence of grade degradation on the SHR is relatively small for the coal slurry 1 with finer particles compared with the coal slurry 2.

In the experiment, the operation of the slurry pump inevitably causes pipeline vibration to a certain extent. Some studies have shown that slurry pipe vibration can reduce resistance (Sun et al., 2001; Sun and Wu, 2002; Wu, 2017), and other studies have noticed that

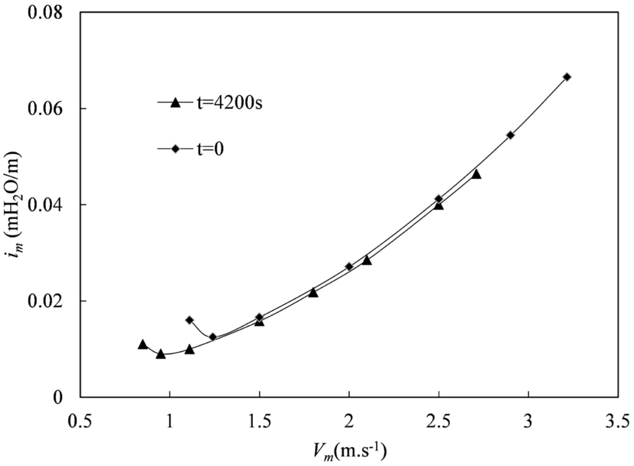

Figure 5. Effects of *t* on i_m of clean coal 1 slurry.

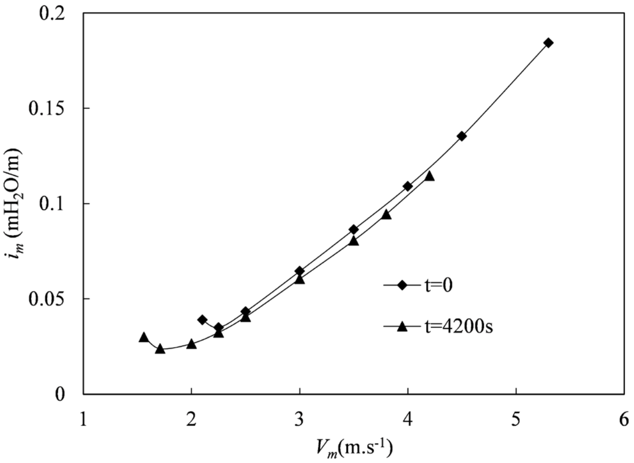

Figure 6. Effects of *t* on i_m of clean coal 2 slurry.

slurry pipe vibration can not only increase resistance, but also reduce resistance (Lin et al., 2006), so in this experiment, the possible existence of pipeline vibration is an uncertainty in the change of resistance.

Minimum resistance critical velocity

The minimum resistance critical velocity (MRCV) in this paper refers to the slurry average velocity V_m at which the slurry is in the most energy efficient running state, and this is the optimum conveying speed of slurry at a given density. However, in a slurry transportation system, the MRCV is not a feasible operating velocity, but it is closely related to the critical sedimentation velocity(CSV) . CSV represents the maximum slurry average velocity V_m at which stationary particles are first observed and a slurry average velocity V_m below this threshold velocity might be inefficient and potentially dangerous.

It can be concluded from the experiment that an approximate speed ranging from 0.1 m/s to 0.15 m/s exists while the slurry particles change from a stable sliding bed motion state to a distinct fixed bed state. It means that the accurate determination of CSV is difficult and a large error exists in the process of determination. Previous studies indicate that the difference between MRCV and CSV is unobvious if the concentration of the slurry is small (Zhao et al., 2016). Therefore, the MRCV can be used instead of CSV to prevent slurry pipeline blockage at low concentration, considering a certain amount of affluence.

The i_m-V_m curve can be obtained from the experimental data and the results are shown in Figures 5 and 6. The MRCV can be achieved from the average velocity corresponding to the minimum point of the i_m map. The MRCVs of coal slurry 1 and coal slurry 2 were obtained while the particles were partially suspended and partially slid bed moved from analysis of the i_m-V_m curve. The analysis results show that the MRCVs of the coal slurry 1 are 1.36, 1.25 and 0.86m/s respectively for t=0, 2400s and 4200s and 2.23, 1.95 and 1.49 m/s respectively for coal slurry 2. Hence, The MRCVs of coal slurry 1 and coal slurry 2 decrease with time and the range of decrease for those two groups are almost same.

Previous studies indicate that the increasing proportion of fine particles in the slurry can reduce the settling velocity of particles (Fei, 1994). Consequently, the distribution of vertical concentration becomes more uniform with running of the slurry pipe, thus leading to a diminution of the CSV. Moreover, the grade degradation leads to the reduction of the overall particle size with total conveying concentration of the slurry remaining constant. The CSV in the slurry decreases with decrease of the particle size. So the MRCVs and CSVs of coal slurry 1 and coal slurry 2 decrease with running of the slurry pipe.

THEORETICAL PREDICTION MODEL FOR THE MAIN PARAMETERS DURING CHANGE OF GRADE

SHR prediction

Two SHR prediction calculation formulas are widely accepted, including the Wasp model and the Fei Xiangjun equation. In this study, the Fei Xiangjun resistance equation is used for discussion owing to the fact that the wasp resistance model requires complex iterative computation. However, deviation between theoretical and measured values for the Fei Xiangjun resistance model is small (Qiu, 1999). The Fei Xiangjun equation can be expressed as follows (Fei, 1994):

$$i_m = \alpha \frac{f_0 \cdot V_m{}^2}{2g \cdot D} \frac{\gamma_m}{\gamma} + 11\mu_s \cdot C_v \left(\frac{\gamma_s - \gamma_m}{\gamma} \right) \frac{\omega}{V_m} \quad (7)$$

where i_m is the SHR per unit length, f_0 is resistance coefficient of clear water, V_m is the average flow velocity of the slurry, g is the acceleration of gravity, D is the diameter, μ_s is friction coefficient, μ_s=33 f_0, C_v is the slurry volume concentration, γ_s,γ_m and$\gamma$are the bulk density of solid particles, slurry and water, ω is the average settling velocity of particles in the slurry and α is the correction factor to the turbulence for the existence of suspended matter, which can be expressed as follows (Qiu, 1999):

$$\alpha = 1 - 0.4 \log \mu_r + 0.2 (\log \mu_r)^2 \quad (8)$$

where μ_r is relative viscosity.

In equation (7), ω is calculated through the weighted average method. According to the PSD, it can be divided into several particle groups. By calculating the average particle size of each particle group, the settling velocity of particles in each group can be obtained, and then the average settling velocity ω by weighted average method can be achieved on further consideration of the proportion of each particle level. The friction coefficient u_s is included in equation (7), so it can only be used in the case of solids with partial sliding and partial suspension.

Equation (7) can be utilized to calculate the SHR per unit length of the clean coal 1 slurry and clean coal 2 slurry for 70 min, and the comparison between the calculated value and the measured value is presented in Fig. 7. It shows that maximum deviation between measured and calculated SHR per unit length for clean coal 1 slurry clean coal 2 slurry are no more than 6.70% and 10.00%, respectively. The calculated values of i_m are mostly less than the measured values due to the fact that the value of u_s (μ_s=33f_0) in Eq. (7) is undervalued by using the water resistance coefficient f_0 instead of slurry resistance coefficient f_m which is very close to f_0 (Figure 7). Therefore, the Fei Xiangjun resistance Eq. (7) can accurately predict the SHR on unit length of coal slurry pipe convey in the course of hydraulic transportation.

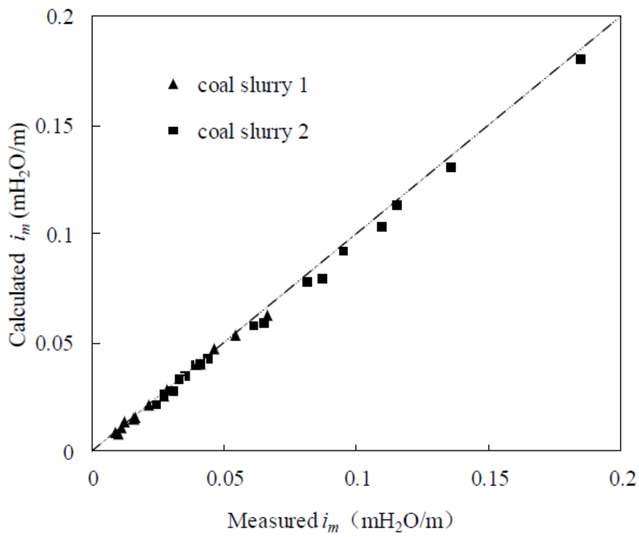

Figure 7. Comparison of i_m between measured and the calculated value.

MRCV prediction

Since MRCV is the optimal slurry conveying velocity at a given density and it is closely related to CSV, it is important to study its calculation formula. The preceding discussion shows that equation (7) can accurately predict the SHR per unit length of coal slurry pipe. Therefore, by taking the derivative of Eq. (7), the following formula can be obtained by setting di_m/dV_m=0.

$$V_{MRCV} = \left[11 \frac{g \cdot D \cdot u_s C_V \cdot \omega}{\alpha \cdot f_0} \left(\frac{\gamma_s - \gamma_m}{\gamma_m} \right) \right]^{\frac{1}{3}} \quad (9)$$

where V_{MRCV} is the MRCV.

The formula above can be simplified as:

$$V_{MRCV} = 2.224 \left[\frac{g \cdot D \cdot u_s C_V \cdot \omega}{\alpha \cdot f_0} \left(\frac{\gamma_s - \gamma_m}{\gamma_m} \right) \right]^{\frac{1}{3}} \quad (10)$$

Based on the above formula, the average settling velocity ω and the correction factor α (essentially relative viscosity μ_r) are the key factors affecting the MRCV. The comparison between the MRCV calculated by the use of Eq. (10) and the experimental measured values is shown in Fig.8. It indicates that the deviation between the calculated value and measured value of the MRCV for clean coal 1 and 2 slurry is small (the maximum deviation is no more than 9.47%). The calculated values of MRCV are mostly less than the measured values due

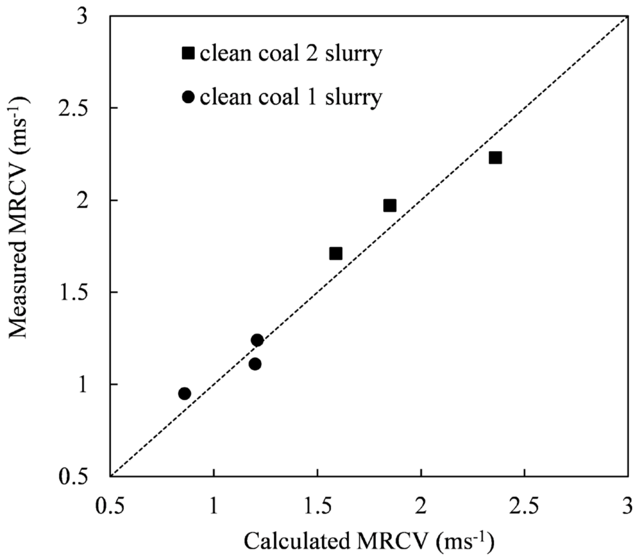

Figure 8. Comparison of MRCV between measured and the calculated values.

to the fact that the value of u_s (μ_s=33f_0) in Eq. (10) is undervalued by using the water resistance coefficient f_0 instead of the slurry resistance coefficient f_m which is very close to f_0. Although the deviation exists in the comparison of experiment and calculation, Eq. (10) can provide a guidance to accurately predict the MRCV and even the CSV of coal slurry.

CONCLUSIONS

The batch grinding model can predict the influence of pipeline transportation on the change of coal particle grade to a certain extent. The results indicate that the maximum relative deviation is less than 8.0%.

Clean coal slurry has grade degradation after a period of transportation, and collision and wear of overcurrent components in the centrifugal pump, friction and collision between particles and piping and piping accessories, and initial particle size distribution all have important influence on grade degradation.

- Slurry grade reduction can influence several conveying parameters, including slurry viscosity, SHR and MRCV. With the increase of convey time, coal slurry relative viscosity shows a trend of rise, while SHR and MRCV show a trend of reducing. Additionally, the influence of grade degradation on the SHR and MRCV is obvious for coarse coal slurry.
- The comparison between the calculated value and the measured value shows that the Fei Xiangjun resistance equation can accurately predict the SHR of coal slurry pipe convey. A formula for the MRCV can be obtained by derivation of the Fei Xiangjun resistance equation. Consequently, the maximum deviation between the MRCV equation calculated value and measured value for clean coal 1 and 2 slurry is no more than 9.47%.

ACKNOWLEDGEMENTS

This work was partly supported by the Special fund project for technology innovation of China Coal Technology Engineering Group(Project name: Research on Key Technologies of Long Distance Coarse particle Coal Slurry Pipeline Transportation. Project number: 2019-ZD003). Here, the authors thank Wuhan Design and Research Institute of China Coal Technology Engineering Group for its experimental conditions and great assistance.

NOTATION

B	A strict lower triangular matrix with elements b_{ij} (-)
b_{ij}	Breakage function (-)
B_{ij}	Cumulative broken distribution function (-)
C_v	The slurry volume concentration (-)
C_{Vm}	Coal slurry concentration limit (-)
D	The diameter (m)
$f_i(t)$	Weight fraction of the grain grade ith at time t (-)
F_i(t)	Cumulative percentage of particles less than the grain grade ith at time t (-)
f_0	Resistance coefficient (-)
g	The acceleration of gravity (m.s^{-2})
i_m	SHR per unit length (mH_2O/m)
I	A n order unit matrix (-)
S	A diagonal matrix with diagonal elements S_i (-)
S_i	Breakage rate function(-)
t	Time (second)
V_{csv}	Critical deposition velocity (m.s^{-1})
V_m	The mean flow velocity of the slurry (m.s^{-1})
α	The correction factor to the turbulence for the existence of the suspended matter (-)
γ	Bulk density of coal water (N.m^{-3})
γ_m	Bulk density of coal slurry (N.m^{-3})
γ_s	Bulk density of solid particles (N.m^{-3})
μ_s	Friction coefficient for pipe (-)
μ_r	Relative viscosity (-)
ω	The average precipitation of particles in the slurry (m.s^{-1})

REFERENCES

Boylu, F., Dinçer, H., Ateşok, G., Effect of coal particle size distribution, volume fraction and rank on the rheology of coal-water slurries. Fuel Processing Technology, 85, 241-250 (2004). https://doi.org/10.1016/S0378-3820(03)00198-X

Fei, X. J. Slurry and granular material conveying hydraulics. Beijing: Tsinghua University press (1994).

He, K., Ku, J., Guo, Y. X. Grinding Kinetics of Vanadic Titanomagnetite from Pan zhi hua. Mining and Metallugical Engineeing, 36, 35-38(2016).

Henderson, C. B., Scheffee, R. S. The Optimum Particle-Size Distribution of Coal for Coal-Water Slurries, Prepr. Pap. - Am. Chem. Soc., Div. Fuel Chem, 28:2 (3), 36(1983)

Huang, L.L., Zhang, G.W., Song, X.L., Xiao, X., Zhao, X., Shi, L., Long, Y. Modelling and Simulation of Batch Grinding with Vertical Stirred Mill Based on MATLAB / Simulink. Mining and Metallurgical Engineering, 36, 26-30 (2016).

Hui, W. Numeration Simulation of the Solid/Liquid Two-phase Flow Field in a Slurry Pump, Xi'an University of Architecture and Technology, Xi'an, PRC (2009).

Jian, Y.H., Zhou, R., Ceng, Q.H., Lu, D.H. Selection of surface Layer Composites for the parts of Slurry Pump, Journal of Kunming University of Science and Technology (Science and Technology), 29, 29-32 (2004).

Lin, Y., Yang, Q.X., Lin, Q. Study and Experimental Analysis on Drag Reduction of Coal Log Pipeline[j], China Mining Magazine, 15, 84-87 (2006).

Liu, W. Study on cost management measures of Shen Wei pipeline coal transportation project in Shaanxi coal chemical industry group. Northwest University, Xi'an, PRC(2012).

Mani, K. S., Dwarikanath, R., Satish, K., Deepak, K. Influence of Particle-Size Distribution and Temperature on Rheological Behavior of Coal Slurry. Coal Preparation, 36, 44-54 (2015). https://doi.org/10.1080/19392699.2015.1049265

Pulido, I.E., Rojasa, C.P., Acero, G., Duran, M., Orozco, M. Rheology of colombian coal-water slurry fuels: Effect of particle-size distribution. Coal Science and Technology, 24, 1585-1588 (1995). https://doi.org/10.1016/S0167-9449(06)80112-6

Qiu, Y.Q. Analysis of Two Calculating Methods on the Drug Loss of Slurry Pipeline Transportation. Journal of Gunzhou University of Technology (natural science edition), 28, 31-35 (1999).

Shook, C.A., Haas, D.B., Husband, W.H.W., Small, M., Breakage Rates of Lignite Particles During Hydraulic Transport, The Canadian Journal of Chemical Engineering, 56, 448-454 (1978). https://doi.org/10.1002/cjce.5450560403

Sun, Y.Z., Wu, A.X., Li, J.H. Vibration Drag-reduction of Pipeline Transport of High Density Slurry, Mining and Metallurgical Engineering, 21, 4-6 (2001)

Sun, Y.Z., Wu, A.X. Study on Drag Reduction of Materials Transported by Pipeline, Journal of Vibration, Measurement & Diagnosis, 22, 29-33(2002).

Yang, J.L., Zhou, W.T., Jiang, L.L., Ma, S.J., Yang, X.J. Review of Grinding Kinetics Research. Multipurpose Utilization of Mineral Resources, 4, 4-10 (2017).

Yin, D., Li, S.R. Mathematical model of mineral separation. Changsha: Zhongnan Industrial University Press (1993).

Wu, W. Study on the influence of fluid pipeline vibration on wall resistance reduction.Wu han University of Science and Technology,Wuhan, PRC (2017).

Wang, J.Q., Ye, Q., Yan, K.W., Feng, Y.N., Yu, X.N. Effects of particle diameter on performance of slurry erosion wear, Journal of Drainage and Irrigation Machinery Engineering, 32, 840-844 (2014).

Wu, B., Hong, H. Y., Xu, H., Tan, Y. Numerical simulation about erosion characteristics of solid particle in slurry pump, Journal of Central South University (Science and Technology), 43, 124-129 (2012).

Zhao L.A. Test analysis of particle size distribution degradation for coal slurry conveying by pipelines. Hydro-Science and Engineering, 6, 107-115 (2016).

Zhao, L.A., Xu, Z.L., Wang, T.L. Experimental studies on critical velocities of sand-water heterogeneous flow in horizontal pipelines. Hydro-Science and Engineering, 4, 63-69 (2016).