Influence of coal slurry particle composition on pipeline hydraulic transportation behavior

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Abstract. Acting as a new type of energy transportation mode, the coal pipeline hydraulic transmission can reduce the energy transportation cost and the fly ash pollution of the conventional coal transportation. In this study, the effect of average velocity, particle size and pumping time on particle composition of coal particles during hydraulic conveying was investigated by ring tube test. Meanwhile, the effects of particle composition change on slurry viscosity, transmission resistance and critical sedimentation velocity were studied based on the experimental data. The experimental and theoretical analysis indicate that the alter of slurry particle composition can lead to the change of viscosity, resistance and critical velocity of slurry. Moreover, based on the previous studies, the critical velocity calculation model of coal slurry is proposed.

1. Introduction
In 1950s, the pipeline hydraulic coal transportation acted as a mature technology for widely application in underground coal mine of China. Long distance pipeline coal transportation, which is under constructing since 2012, indicated the application step into a new stage \cite{1}. Coal, acts as an important mineral resource, is characterized by soft and brittle in the pipeline transportation. Therefore, the collision between particles and particles with liquid pipelines and ancillary parts, wetting effect caused by liquid struck to coal particles, the fragmentation effect of impeller of slurry pump, as well as the loading/unloading process during the particles access/discharge the pipe system, could lead to the alteration of particle composition, and then influence the hydraulic conveying parameters. Previous studies indicates that the change of coal slurry particle group will affect the viscosity of slurry \cite{2}\cite{3}\cite{4}. However, no work focus on the influence of coal particle group on the transportation parameters. In this study, the relationship of coal particle group and transportation parameters was investigated, and the results was then discussed.

2. Pumping test of coal pipeline
The pipeline coal conveying measurement was conducted to study the influence factors of particle gradation degradation of pipeline coal transportation and its impact on pipeline transportation parameters. Figure 1 shows the layout of the pipeline. The inner diameter and length of the pipeline are 150mm and 25m, respectively. The rubber lined pump (Linatex) was used as slurry pump, with caliber of 45-360 mm. The flow rate and the head of the pump are 4.6-2420 m\textsuperscript{3}/h and 6.5-136 m, respectively. Additionally, the motor power of slurry pump is 412kw.
The slurry density and viscosity can be measured by a DMA35 portable densimeter and a SNB-1 digital rotary viscometer by collecting sample from sampling valve(fig.1). The collected samples were dried by an oven, and then the particle size distribution curve can be determined by sampling sieve analysis method. The value of critical sedimentation velocity can be determined by calculating from flow velocity (flow meter 4 in Fig.1), mercury pressure difference (meter 7 in Fig.1) and observing the flow behaviour by the acrylic transparent tube 8. Meanwhile, a heat exchanger 5 (Fig.1) was utilized to maintain 25°C in order to prevent the influence of temperature fluctuation during experiment process.

Two kinds of clean coals from a coal mine in 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 figure 2. The maximum particle diameter of clean coal 1 and 2 are 25.4mm and 58mm, and weighted mean particle size are 3.75mm and 14.13mm, respectively. The coal slurry concentration of clean coal 1 and 2 are 10.2% and 11.5%, respectively.

Fig. 1 Schematic diagram of test pipeline line
1-slurry pipe; 2-slurry tank; 3-sampling valve; 4-flowmeter; 5-heat exchanger; 6-necking valve; 7-Mercury manometer; 8-Acrylic transparent tube

The average velocity of clean sample 2 was set at 5.5 m/s in the initial stage, the particle size grading of coal slurry with different flow distance, including 1500m and 4500m, were measured (Fig. 3). Additionally, the particle gradation alterations of two samples with different transportation time were determined(fig.4). Finally, the resistance of clean coal 1 and 2 slurry was tested after different transportation time. Meanwhile, the critical sedimentation velocity of coal slurry under different transportation conditions was determined through the observation of transparent acrylic pipe section. It indicates that gradation degradation can be observed in two kinds of clean coal slurry have after a period of transportation.

3. Analysis of factors influencing gradation degradation of slurry

3.1. slurry flow velocity
The influence of slurry flow rate on gradation degradation of coal slurry is presented in figure 3. The results indicate that obvious degradation trend of clean coal slurry 2 can be discovered after transporting with the same long distance, and the degradation trend of the particle with section larger than 1mm is obviously larger than that of the particle with size <1mm. Meanwhile, the degradation trend can be more obvious with increasingly slurry transport velocity. The amount of coarse particles decrease with the increase of pipeline transportation time(Fig.3).

3.2. Initial particles size distribution
The particle size of clean coal 2 is larger than that of sample 1. However, the sample with the small particle size is characterized by significantly degraded (Fig.4). Therefore, the degradation rate is increased with the increasingly feed size. For the same grading, the degradation range of the large particle section is larger than that of the small particle section. Therefore, no essential difference in grain size composition (gradation) between fine particles and different conveying speeds. However, a significant difference between the different particle size can be observed in the coarse particle region.

3.3. slurry pumping time (length)
The figures 3 and 4 show that the particle degradation rate in the slurry increases with the increase of the slurry pump time. Meanwhile, the decline rate of particle degradation rate shows a narrowing trend as the increase of pumping time.

4. Effects of coal slurry gradation reduction on some conveying parameters

4.1. 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 increased, it can enhance the viscosity of the slurry. Therefore, the gradation 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 Newton body to non-Newton 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 [5]. Relationship between coal slurry concentration limit $C_{vm}$ and critical concentration $C_{v0}$ from Newtonian fluid into Bingham body can be described as the following equation (1):

$$C_{v0} = 1.87 \cdot C_{vm}^{1.2}$$

The results of calculation show that the slurry flow pattern of clean coal 1 slurry and clean coal 2 slurry in the test are all Newton body.

Relative viscosity of coal slurry is measured by SNB-1 digital rotary viscometer. The results show that the relative viscosity of the two coal samples increases with the prolongation of the experiment time (Fig.5)

4.2. slurry resistance
The influence of slurry gradation degradation on the resistance can be reflected in following aspects. The addition of fine particles can increase the viscosity of coal slurry, leading to the sliding movement of coarse particles in bottom of pipe moving in the form of suspended movement. Consequently, thus can lead to slurry transportation becomes more easily. Meanwhile, with the addition of fine particles, the settling velocity of particles in coal slurry is reduced, leading a uniform vertical velocity distribution,

Fig.3 Change of particle size distribution with convey distance and velocity

Fig.4 Change of particle size distribution with convey time
which is beneficial to reduce the flow resistance. However, fine particles may increase the viscosity and increase the viscous resistance of the flow, which is a serious obstructs to the transportation of coal slurry.

The conveying resistance of coal slurry 1 and 2 were measured in this study and the results were presented in figure 6 and figure 7. The results show that the resistance values of two kind of coal slurry are reduced after conveying for 70min.

4.3. Critical sedimentation velocity

Previous studies indicate that the increasing proportion of fine particles in the slurry can reduce the settling velocity of particles[6]. Consequently, the distribution of vertical concentration becomes more uniform, thus lead to a diminution of the critical sedimentation flow rate. Moreover, the gradation degradation leads to the reduction of the overall particle size with total conveying concentration of the slurry remains constant. The critical velocity of the slurry suspended in the slurry decreases with decrease of the particle size. The critical velocity in this paper refers to the critical sedimentation velocity, it represents the maximum average velocity of the slurry at which stationary particles are firstly observed.

Critical sedimentation velocities of clean coal slurry 1 and 2 reduced over time(fig.8). The reduction rate of critical sedimentation for coarse coal slurry 2 is larger than that of fine coal slurry. Additionally, the critical sedimentation velocity of coarse particle slurry is larger than of in fine particle slurry in general.
5. Main parameter theoretical prediction model during change of gradation

Two slurry resistance prediction calculation formula are widely accepted, including Wasp resistance model and Fei Xiangjun formula. In this study, Fei Xiangjun resistance model is used for discussion, owing to the fact that the wasp resistance formula requires complex iterative computation. However, deviation between theoretical and measured values for Fei Xiangjun resistance model is small [7], the Fei Xiangjun formula can be expressed as follows:

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

Among them, \( f_0 \) is resistance coefficient; \( V_m \) is the flow velocity of the slurry, m/s; \( g \) is the acceleration of gravity, m/s^2; \( D \) is the diameter, m; \( \mu_s \) is friction coefficient; \( C_v \) is the slurry volume concentration; \( \gamma_s \), \( \gamma_m \) and \( \gamma \) are the bulk density of solid particles, slurry and water, N/m³; \( \omega \) is the average precipitation of particles in the slurry, m/s; \( \alpha \) is the correction factor for the existence of the suspended matter to the turbulence, which can be expressed as follows [7]:

\[
\alpha = 1 - 0.4 \log \mu_r + 0.2 \left( \log \mu_r \right)^2 \quad (3)
\]

Where \( \mu_r \) is relative viscosity.

In formula (2), \( \omega \) is calculated through weighted average method. According to the particle size distribution, 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 precipitation \( \omega \) by weighted average method can be achieved on further consideration of the proportion of each particle level.

The formula (2) can be utilized to calculate the resistance of the clean coal 1 slurry and clean coal 2 slurry for 70min, and the comparison between the calculated value and the measured value is presented in Figure 9. It shows that maximum deviation between measured and calculated for clean coal 1 slurry and clean coal 2 slurry are not more than 4.8% and 7.4%, respectively. Therefore, the Fei Xiangjun resistance model (2) can be accurately predicted the hydraulic gradient of coal slurry pipe convey in the course of hydraulic transportation.

The previous study shows that the difference between the minimum critical velocity and the critical deposition rate is unobvious at a low concentration [8]. Therefore, by deriving on both sides of the formula (2), and following formula can be obtained by using \( \text{d} \text{m}/ \text{d} V_m = 0$.

\[
 V_{cr} = \left( \frac{11 \cdot \frac{g \cdot D \cdot \mu_s \cdot C_v \cdot \omega}{\alpha \cdot f} \cdot \left( \frac{\gamma_s - \gamma_m}{\gamma_m} \right)^{\frac{1}{3}}}{\gamma_m} \right) \quad (4)
\]
The upper formula can be simplified as:

$$V_{csv} = 2.224 \left( \frac{g \cdot D \cdot u \cdot C_v \cdot \omega \cdot (\gamma_s - \gamma_m)}{\alpha \cdot f \cdot (\gamma_m)} \right)^{\frac{1}{2}}$$

(5)

Based on the above formula, the average sedimentation velocity of the particles $\omega$ and the correction factor $\alpha$ (essentially relative viscosity $\mu_r$) is the key factor affecting the critical deposition rate. The comparison between the critical deposition velocity calculated by the use of (5) and the experimental measured values are shown in figure 10. It indicates that the deviation between the calculated value and measured value of the critical deposition velocity for clean coal 1 and 2 slurry is small (the maximum deviation is not more than 11.3%). The deviation between the calculated value and measured value of the critical deposition velocity for clean coal 2 slurry is slightly larger (the maximum deviation is not more than 13.2%). Although the deviation exists in the comparison of experiment and calculation, the formula (5) can provide some guidance to accurately predict the critical deposition velocity of coal slurry.

6. Conclusions:

(1) Clean coal slurry has gradation degradation after a period of transportation, the particle demotion became more obvious with the increasing of the convey velocity or initial particle size or the pumping time.

(2) Slurry gradation reduction can influence on several conveying parameters, including slurry viscosity, slurry resistance and critical sedimentation velocity. With the duration of convey time increases, coal slurry relative viscosity shows a trend of rise, while hydraulic gradient and critical sedimentation velocity show a trend of reducing. Additionally, influence of gradation degradation on the resistance and critical sedimentation velocities is obvious for coarse coal slurry.

(3) The comparison between the calculated value and the measured value shows that the Xiangjun resistance model can be accurately predicted the hydraulic gradient of coal slurry pipe convey. Formula of critical sedimentation velocity can be obtained by derivation of the Fei Xiangjun resistance formula. Consequently, maximum deviation between formula calculated value and measured value is not more than 13.2%.

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References:

[1] Liu Wei. Study on cost management measures of Shen Wei pipeline coal transportation project in Shaanxi coal chemical industry group [D], 2012, Northwest University, Xi’an.

[2] Mani Kanwar Singh, Dwarikanath Ratha, Satish Kumar & Deepak Kumar. Influence of Particle-Size Distribution and Temperature on Rheological Behavior of Coal Slurry[J], International Journal of Coal Preparation and Utilization, 2016,36(01): 150527094541002.

[3] F Boylu, H Dinçer, G Atéseok. Effect of coal particle size distribution, volume fraction and rank on the rheology of coal–water slurries[J], Fuel Processing Technology, 2004,85(04): 241-250.

[4] I.E.Pulido, C.P.Rojasa, G.Acro,etal. Rheology of colombian coal-water slurry fuels: Effect of particle-size distribution[J], Coal Science and Technology,1995(24): 1585-1588.

[5] ZHAO Li an. Test analysis of particle size distribution degradation for coal slurry conveying by pipelines[J], Hydro-Science and Engineering,2016(06):107-115.

[6] Fei Xiangjun. Slurry and granular material conveying hydraulics [M], Tsinghua University press, Beijing, 1994: 41-44;328-331.
[7] QIU Yue-qin. Analysis of Two Calculating Methods on the Drug Loss of Slurry Pipeline Transportation[J]. Journal of gunzhou University of Technology (natural science edition),1999,28(05):31-35.

[8] ZHAO Li-an, XU Zhen-liang, WANG Tie-li. Experimental studies on critical velocities of sand-water heterogeneous flow in horizontal pipelines, Hydro-Science and Engineering,2016(04):63-69.