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INVESTIGATION OF PRESSURE VARIATION IN LONG DISTANCE SLURRY PIPELINE THROUGH TRANSPORT CYCLE

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The pressure variation along the slurry transportation pipeline is simulated and analysed during the different transport process. The whole process of slurry transportation is divided into 4 process with full water during cleaning pipeline period, full slurry during normal operation period and water pushed by slurry and slurry pushed by water during the transportation cycle. Several different formulas can be employed to calculate the pressure change so that the transport characteristics and safety assessment can be carried out. Take the Shenwei Coal transport pipeline as an example, which is the longest slurry transport pipeline in China at present and has biggest height difference in the last transportation pipeline section, the pressure variations inside the pipe under such 4 situations are calculated, and some special phenomena have been analysed, such as accelerating flow, cavitation, etc., at the same time, some preventive measures are suggested for the potential hazards.

KEY WORDS: slurry; pipeline transportation; pressure variation; friction loss

1. INTRODUCTION

Pipeline transportation of bulk solid materials has become one of the largest transportation methods after highway, railway, air and ship transportation (Fei, 1994). During the transportation of slurry by pipeline, topography changes and transport medium changes may lead to great changes in the pressure inside the pipeline, and even accelerate flow and cavitation (Qin, 2014; Chen, 2015; Xiao, 2015). These phenomena do great harm to the safety of the system, which may cause vertical and horizontal movement of the pipeline, loosening or displacement of the auxiliary facilities and foundations of the pipeline. When the destructiveness is further enlarged, it is easy to cause pipe distortion, fracture or rupture, etc. (Dong, 2012)

To ensure the safe operation of pipelines and prevent the occurrence of accelerated flow, cavitation and other phenomena, it is necessary to analyze the pressure changes along the pipeline and take protective measures.

2. CALCULATION METHOD OF PRESSURE SLURRY PIPELINE

In long-distance pipeline transportation, there are many factors affecting friction resistance. It is necessary to appropriate formulas from many empirical formulas, calculating friction loss, according to engineering practice

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In slurry pipeline, any two points a and b follow the law of conservation of energy. Thus the formula of pressure changes at the two points is as follows:

$$\frac{P_a}{\gamma_0} + \left[C_V\left(\frac{\rho_s}{\rho_0} - 1\right) + 1\right] Z_a = \frac{P_b}{\gamma_0} + iL_{ab}\cos\theta + \left[C_V\left(\frac{\rho_s}{\rho_0} - 1\right) + 1\right] Z_b \qquad (1)$$

where P_a and P_b are pressure energy of points a and b; γ_0 is unit weight of water, $\gamma_0 = \rho_0 g$, ρ_0 is density of water, g is gravity acceleration; Z_a and Z_b are pipeline elevation of points a and b; L_{ab} is pipeline distance between points a and b; θ is pipeline inclination; C_V is volume concentration of fluid; ρ_s is solid density; i is friction loss.

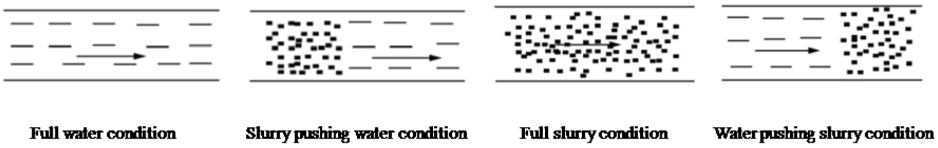
If $\frac{P_a}{\gamma_0} = H_a$, $\frac{P_b}{\gamma_0} = H_b$, $C_V\left(\frac{\rho_s}{\rho_0} - 1\right) = \gamma_m$, then formula (1) can be simplified as:

$$H_a = H_b + iL_{ab}\cos\theta + \gamma_m(Z_b - Z_a) \qquad (2)$$

Here the units of H_a and H_b are mH_2O.

3. VARIATION OF PRESSURE IN PIPELINE DURING SLURRY TRANSPORTATION

There are four working conditions in the whole operation cycle of pipeline slurry transportation: full water condition, Slurry pushing water condition, full slurry condition, water pushing slurry condition. As shown in Figure 1.



Full water condition **Slurry pushing water condition** **Full slurry condition** **Water pushing slurry condition**

Figure 1. Conditions of pipeline slurry transportation

Under the full water condition, the friction loss of water is smaller. However, In the case of large elevation difference of pipeline, it is easy to form negative pressure, Cavitation erosion will destroy valves and pipelines, and directly threaten safety in production (Wang, 2007; Liao, 2012).Under the full slurry condition, the resistance loss is much greater, if pump pressure is too low, resulting in the deposition and accumulation of solid particles in slurry (Mehment, 2001; Durand, 1952). The working conditions of slurry pushing water and water pushing slurry are complex. The pressure required for the pipeline with water as the conveying medium is smaller than that with slurry. In addition, different pressures lead to greater changes in fluid velocity, which is prone to water hammer phenomenon (Yang, 2007; Ghidaoui, 2005; Chen, 2004).

4. ENGINEERING CASE APPLICATION

4.1 GENERAL SITUATION OF PIPELINE AND PARAMETERS

The total length of a coal transportation pipeline is about 130 km. The topography of the whole pipeline fluctuates greatly. The difference between the lowest elevation and the highest elevation is about 1 000 m. The designed flow rate of the pipeline is 1 775 m^3/h, the diameter of the pipeline is 590.0 mm, the conveying velocity is 1.80 m/s, the solid density is 1 320 kg/m^3, and the mass concentration range of the slurry is 45%, 50% and 55%. Clean water density used in pipeline transportation system is ρ_0=1 000 kg/m^3, viscosity is η_0=0.001 Pa•s. When velocity is v=1.80 m/s, Reynolds number is Re=1.062× 10^6, resistance coefficient is λ=0.0131.

4.2 SELECTION OF FORMULA FOR FRICTION LOSS CALCULATION

4.2.1 FORMULA FOR CALCULATING FRICTION LOSS OF CLEAR WATER

The friction loss of clean water can be calculated by the following formula:

$$i_0 = \lambda \frac{v^2}{2gD} \tag{3}$$

where i_0 is friction loss of water, λ is friction coefficient, v is transportation velocity, D is pipeline diameter. In turbulence, the friction coefficient λ is related to Reynolds number Re and absolute roughness of pipe wall Δ. Altschul equations can be used to calculate λ (Lei, 2017):

$$\lambda = 0.11 \left(\frac{\Delta}{D} + \frac{68}{Re}\right)^{0.25} \tag{4}$$

4.2.2 FORMULA FOR CALCULATING FRICTION LOSS OF SLURRY

The main influencing factors of slurry friction loss are pipe diameter, transportation velocity, slurry concentration, particle size and so on. Many scholars at home and abroad have done a lot of experiments and put forward different calculation formulas based on their experimental data and theoretical analysis. The more famous formulas are shown in Table 1. (Durand, 1952; Newitt, 1955; Worster, 1955; Babcock, 1968; Fei, 1994; Chen, 1994; Xu, 1999; Liu, 1982)

Table 1

Empirical formula of friction loss of slurry flow

No.	Author	Formula	Parametric Significance
1	Durand	$\frac{i_m - i_0}{C_V i_0} = 82\left[\frac{v^2\sqrt{C_D}}{gD(s-1)}\right]^{-1.5}$	C_D is drag coefficient, f is

2	Newitt	$\frac{i_m - i_0}{C_V i_0} = 1100(s-1)\frac{w}{v}\frac{gD}{v^2}$	Fanning friction coefficient, $\bar{d}$ is average particle size, C_{Vm} is limit volume concentration, ζ is shape correction coefficient, v_w,v_s,v_m are average velocity of water, granule and slurry, $\varphi(1)$,k_3,k_4 are coefficients, $\bar{q}$ is average volume concentration, d_e is sphere equivalent diameter, F_h is interference force, C_{Dr} is drag coefficient based on $v_m - v_s$, ρ_m is density of slurry, L_a is acceleration distance, ξ is friction increase coefficient.
3	Worster	$i_m = i_0 + 0.25C_V(s-1)$	
4	Babcock	$\frac{i_m - i_0}{C_V i_0} = 70\left[\frac{v^2}{gD}\cdot\frac{\sqrt{C_D}}{(s-1)}\right]^{-1}$	
5	Fei Xiangjun	$i_m = \alpha i_0 + 11\mu_s C_V(s-1)\frac{w}{v}$ $\alpha = \eta\left[1 + \left(1 - 11\frac{w}{v}\right)C_V(s-1)\right]$	
6	Chen Guangwen Gu Desheng	$i_m = \frac{2fv^2}{gD} + \zeta C_V(s-1)\frac{\omega}{v} + \frac{\bar{d}v}{D^2}\frac{C_V}{\left(1 - \frac{C_V}{C_{Vm}}\right)^{\frac{5C_V}{2}}}$	
7	Xu Zhenliang	$i_m = \frac{\lambda}{2gD}\left\{\frac{v_w + [1 - 0.56\varphi(1)]\frac{s\bar{q}}{(1-s)v_w}\cdot}{\left[v_s - \sqrt{\frac{8(F_h + k_4F_f)}{\pi d_e{}^2 C_{Dr}\rho_0}}\right]^2 \cdot \left[1 + 33k_4\lambda\frac{k_3\sqrt{L_a g}}{v_m}\left(1 - \frac{1}{s}\right)\right]^2}\right\}^2$	
8	Anshan Mine Design Institute	$i_m = \xi\lambda\frac{v^2}{2gD}\frac{\rho_m}{\rho_0}$	

Formulas (2) ~ (4) in the table are applicable to coarse particles, the particle size is small (average particle size is 0.35 mm) in this case. The applicable concentration of formula (5) in the table is lower, while the concentration of slurry transported in the case is 45%-55%. In the formula (6) in the table, it is difficult to determine the particle interference force and the limit concentration. Formula (7) is applicable to settling slurry. So, the formula (1) or formula (8) in Table 1 can be selected for this project case. Formula (1) contains an unknown parameter C_D. The formula for C_D calculation is as follows (Xia, 2000):

$$C_D = \begin{cases} \frac{24}{Res}\left(1 + 0.15Res^{0.678}\right) & (1 \le Res \le 700) \\ \left[\sqrt{\frac{24}{Res}} + 0.34\left(Res^{0.06} + \frac{1}{1.72 + 0.018Res}\right)\right]^2 & (700 \le Res \le 1.5 \times 10^5) \\ 0.49 & (Res \ge 1.5 \times 10^5) \end{cases} \tag{5}$$

where $Res = \frac{dw\rho_0}{\eta_0}$ is Reynolds number of particles, w is particle settling velocity, d is particle diameter. Based on the engineering case data, the formulas (1) and (8) in Table 1 are used to calculate the results. The results are shown in Table 2.

Table 2

Comparisons of calculation results

v/(m•s^{-1})	D/mm	C_w/%	ρ_m/(kg•m^{-3})	η_m/(Pa•s)	i_m/(mH$_2$O•m^{-1})	
					Formula (1)	Formula (8)
1.80	590	45	1 122	0.016	0.00393	0.00670
		50	1 138	0.020	0.00388	0.00710
		55	1 154	0.036	0.00378	0.00830
2.34	518	45	1 122	0.016	0.00727	0.01260
		50	1 138	0.020	0.00723	0.01340
		55	1 154	0.036	0.00716	0.01540

The results show that, the friction loss of all slurries is much smaller than those calculated by formula (8). The smaller the friction loss is, the smaller the pump pressure required. However, the pump pressure is large, as is the energy dissipation carried out at the end of the pipeline. Therefore, formula (8) is chosen to calculate the friction loss of slurry.

$$i_m = \xi\lambda \frac{v^2}{2gD}\frac{\rho_m}{\rho_0} \tag{6}$$

where ξ=1.08, $\lambda = 0.11\left(\frac{\Delta}{D}+\frac{68}{Re}\right)^{0.25}$, Re $=\frac{vD\rho_m}{\eta_m}$.

4.2.3 CALCULATION RESULTS AND ANALYSIS

The whole pipeline is generalized to 40 sections. The pressure at the end of the pipe is set to a certain value to ensure that there is no negative pressure in the pipe. According to the above parameters, the calculation and analysis of working conditions are carried out. The results are shown in Figure 2.

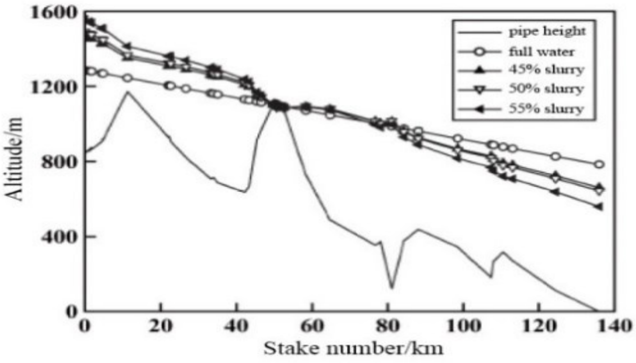


Figure 2. Pressure change diagram of full water and full slurry pipeline transportation

From Figure 2, the pressure increases with the increase of concentration under full slurry condition. Under full water and full slurry conditions, all pressure lines can cross the first and second peaks, to ensure that there is no negative pressure. After crossing the two peaks, the sum of increased lift and gravity action obviously exceeds the friction loss of fluid, which may form accelerated flow. Because of the small resistance and the large residual pressure head at the end, energy dissipation is needed. Similar to full-water and full-slurry, all pressure lines along slurry pushing and water pushing need to move upward, so that the medium can cross two peaks, and there is no negative pressure.

5. MEASURES TO PREVENT ACCELERATED FLOW

The difference of topography and medium density will lead to accelerated flow phenomenon and negative pressure. Preventing accelerated flow is essentially eliminating the excess energy. The solutions are as follows: 1) Shrinking pipe diameter. The smaller the pipe diameter and larger the flow velocity cause impact and abrasion on pipelines and the stronger the turbulence. So, only reducing the diameter of the pipe can not adapt to the change of working conditions. 2) Install orifice plate and adopt end orifice plate to dissipate energy. However, orifice plate energy dissipation requires higher automation (Han, 1994) and the stronger turbulence (Ai, 2009) brings the risk of cavitation. 3) Combination of two measures. After taking the above joint measures, it can not only save costs and reduce energy waste, but also ensure the safety and prevent acceleration phenomenon.

6. CONCLUSIONS

Slurry pipeline transportation is an effective way for long-distance transportation of solid materials. But the operation of slurry pipeline transportation is complex, especially in the case of large topographic fluctuations. In pipeline design, the pressure along the pipeline must be calculated, and protective measures must be taken. Combined with specific engineering cases, the pressure in the pipeline was analysed in different process and the specific countermeasures to prevent accelerated flow were discussed according to the analysis results after analysing the whole process of slurry transportation in pipeline.

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