[Article ID] 1003- 6326(2001)03- 0438- 06

Attenuating water hammer pressure by means of gas storage tank ①

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[Abstract] The basic equations for computing the volume of gas storage tank were derived from the principles of attenuating water hammer pressure. Verifications using experiments indicate that the proposed equation can provide a fare precision in the predictions. By using the model of solid-liquid two-phase flow, the gas storage tank, pressure-relief valves and slow-closure reverse-control valves were compared with practical engineering problems, and the functions of gas storage tank in attenuating water hammer pressure were further investigated.

[Key words] water hammer pressure; protective equipment; gas storage tank; water hammer model
[CLC number] TV 134 **[Document code]** A

1 INTRODUCTION

In the design and operation of pipelines of long-distance hydraulic solid particles transportation, not only the steady flows with uniform discharge and pressure, but also the unsteady ones with non-uniform discharge and pressure should be considered. The variation of discharge and velocity results in the fluctuation of pressure, and the instant change of pressure in pipelines is defined as the water hammer. The water hammer pressure may generate oscillation and noise. Under severe conditions it may even cause pipelines to crack, resulting in slurry and water leaking, and eventually to stop working. Therefore, in the design of pipelines, the additional pressure caused by water hammer must be analyzed and computed. The corresponding protective measures should be taken to avoid accidents. Due to high density and viscosity of solid-liquid flow and great resistance in pipelines, the additional pressure of water hammer is higher than that in the clear water. It means that, for pipelines of solid particle transportation, more protective measures should be employed to ensure safe operation of pipelines. Based on the factors affecting the additional pressure of water hammer[1], the following measures can be taken:

1) Changing the closure velocity of valves, converting direct water hammer into indirect one to reduce the pressure of water hammer[2].

2) Installing pressure-relief valve, turning on the valve to release part of fluid if the pressure of water hammer exceeds a certain quantity. Due to the low compressibility of the fluid, the pressure decreases rapidly with the release of the fluid[3].

3) Aerifying to decrease the wave velocity of water and to alleviate the pressure of water hammer. Due to the very small elastic modulus of gas, it can make remarkable effect on decreasing the wave velocity. However oxygen concentration in fluid increases after aerifying, accelerating the corrosion of pipelines[4].

4) Installing gas storage tank on pipelines[5]. The gas storage tank is a closed orbicular or cylindric tank, its lower part is connected with the pipeline by a short conduit. There is gas in the upper layer of the tank and liquid in the underlayer. When the pressure in the pipeline is higher than that in the tank, the gas in the tank will be compressed and the fluid in the pipe will flow into the gas storage tank. On the contrary, the gas in the tank will expand and supply the pipeline with liquid from the underlayer. Gas storage tanks can not only attenuate the additional pressure of water hammer, absorb noise, and prevent oscillation, but also decrease the sine fluctuations of the pressure and the discharge of slurry supply pumps. This paper mainly describes the principles of gas storage tanks in attenuating the pressure of water hammer, deduces the computation equation for the volume of gas storage tanks, and calibrates the equation with experimental results.

2 VOLUME EQUATION

When water hammer occurs, the pressure wave propagates to the gas storage tank. The pressure in

① **[Foundation item]** Project(59879007) supported by the National Natural Sciences Foundation of China
[Received date] 2000- 06- 14; **[Accepted date]** 2000- 11- 20

the pipeline is higher than that in the tank, a portion of solid-liquid flow may flow into the tank and do work by compressing gas that absorbs energy in this process. Therefore, the crest of pressure wave will greatly decrease. Contrarily, when the negative pressure wave propagates to the gas storage tank, the pressure in the tank is higher than that in the pipeline, the underlayer liquid in the tank will flow into the pipeline. The gas in the tank expands and releases energy. Then it alleviates the decrease of the pressure in the pipeline and prevents the pipe from making solid-liquid flow to break and generating vacuum corrosion and close water hammer due to the decrease of pressure[6].

From the above analysis, the gas in the gas storage tank plays a role of adjusting energy in the pipeline. When the pressure rises, it attenuates greatly the peak value of pressure fluctuation. If the gas volume is too small, the expected result can not be obtained. While the gas volume is too large, the volume of the gas storage tank becomes larger and it may be not economical. It is very important to choose the correct initial gas volume in the design of gas storage tanks. The initial gas volume of steady flows in gas storage tanks can be obtained based on the power equilibrium principle, i. e. the work done by water hammer pressure in compressing gas is equal to the kinetic energy mutation of fluid in the pipeline. The structure of a gas storage tank is shown in Fig. 1. When the pressure wave of water hammer propagates to the gas storage tank, the liquid flows in and the liquid surface rises in the tank, and the gas is compressed and the work is done. Assuming that the work done by the liquid in the rising segment dx is dW, then

$$dW = pA\,dx = p\,dV \tag{1}$$

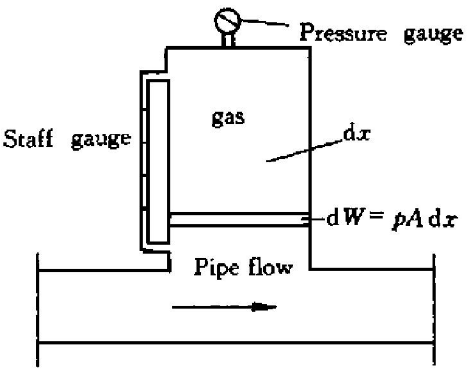

Fig. 1 Structure of gas storage tank

where p is the additional pressure of water hammer; A is the cross-section area of the tank; and dV is the gas compression deformation volume in the tank or the volume of liquid flowing into the tank. From the gas-state equation, the relationship of the gas volume and pressure is

$$p_0 V_0^n = p V^n = K \tag{2}$$

where K is the gas coefficient constant and n is the gas compression index that depends on the thermodynamics property in the process of compression. If it belongs to the process of isothermal compression, then n is equal to 1. 0; and n is equal to 1. 4[7], when it belongs to the process of adiabatic compression.

Substituting Eqn. (2) into Eqn. (1) and integrating to compute the work done by compressing gas, we have

$$W = -\int_{V_0}^{V} p\,dV = -\int_{V_0}^{V} \frac{K}{V^n}\,dV = \frac{pV - p_0V_0}{n-1} \tag{3}$$

where p_0 is the initial pressure of the steady flow, V_0 is the initial gas volume of the steady flow, and V is the final gas volume after compression under the additional pressure of water hammer.

The kinetic energy variation in the pipeline induced by the velocity of solid-liquid flow is

$$E = \frac{m(u_0^2 - u^2)}{2} = \frac{LA'\rho_m(u_0^2 - u^2)}{2} \tag{4}$$

where L is the length of the pipeline; A' is the pipe cross-section area; ρ_m is the density of solid-liquid flow; and u_0 and u are the initial and final flow velocities in the pipeline.

Assuming that all the increment of solid-liquid flow momentum due to the decrease of flow velocity does work on the gas in the tank, Eqn. (4) should be equal to Eqn. (3), i. e

$$\frac{pV - p_0V_0}{n-1} = \frac{LA'\rho_m(u_0^2 - u^2)}{2} \tag{5}$$

Substituting Eqn. (1) into Eqn. (5) and simplifying yield the computation equation for the initial gas volume in the tank

$$V_0 = \frac{LA'\rho_m(u_0^2 - u^2)(n-1)}{2[p(p_0/p)^{\frac{1}{n}} - p_0]} \tag{6}$$

where p_0 is the pressure in the tank under the normal operation of the pipeline with steady flows; and p is the possible maximum water hammer pressure in the pipeline. If the maximum design pressure in the pipeline is p_s, then p is equal to $0.85p_s \sim 0.95p_s$, where p_s is the maximum design supporting pressure for the pipeline. According to the gas-state equation, both p_0 and p should be absolute pressure. The number on the pressure meter should be converted into absolute pressure by adding atmospheric pressure. In Eqn. (6), n is gas compression index. The compression process may be regarded as an isothermal process when it is very long; and it is may be approximated as an adiabatic process if the process is extremely short. Generally n is between these two states, and can be specified as average value 1. 2[8].

3 VERIFICATION OF VOLUME EQUATION

To test the pressure-relief effect of gas storage tanks and verify Eqn. (6) for computing initial gas volume, a gas storage tank is installed on the circular pipeline in the laboratory to compare pressure fluctuations under the conditions of different gas volumes. The tank in the laboratory is cylindrical with an inner diameter of 205 mm (see Fig. 1). The volume of the gas is measured by the transparent organic glass vessel, which is connected nearby. The experiment is done on a d152.4 mm pipeline system. A quick flat slab valve driven by springs is located at the end of the pipeline, a water hammer happens as it is closed rapidly. The gas storage tank is fixed on the pipeline 11.2m upstream from the quick valve. The No. 1 pressure sensor is located at 10m downstream from the tank, No. 2 is located at 5 m upstream from the tank. A pressure meter is fixed on the tank to determine the initial pressure in the tank. No. 1 and No. 2 pressure sensors are used to determine the water hammer fluctuation pressure at different cross-sections of the pipeline.

In the experiment, the average velocity of pipeline with steady flow is 1.71 m/s and the measured pressure of the tank is 3.2×10^4 Pa. The measured pressure waveforms are shown in Fig. 2 for different gas volumes aerified into the gas storage tank and with the valve closing rapidly. It can be seen from the waveform that the gas storage tank transfers short-time pressure waves (high peak values) into long-time pressure waves (low values). Though total energy does not change, high fluctuation pressure is attenuated. The experiments show that gases with different volumes have different pressure attenuation effects. Table 1 lists the pressure attenuation effects by measuring gases with different volumes. In the above experiments, the measured initial pressure is p_0, the pressure measured by meter is 3.210 Pa. The measured gas volume and corresponding maximum pressure p are shown in Table 1, in which, the set No. 9 experiment is the fluctuation pressure with measured gas volume being zero. Table 1 indicates that, compared with no gas in the gas storage tank, the effects of gas attenuating pressure are remarkable,

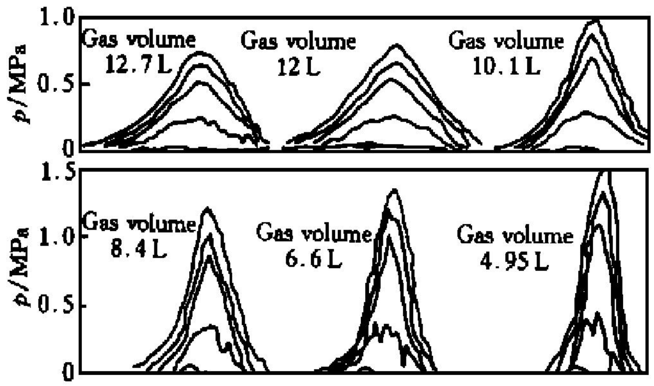

Fig. 2 Oscillogram of measured water hammer pressure with air vessels of different volumes

Table 1 Effects of attenuating pressure with different gas volumes

No.	Height of gas column / cm	Gas volume / L	Water hammer pressure / 10^5 Pa	Reduction of pressure / 10^5 Pa	Relative reduction of pressure/ %
1	38.5	12.7	6.7	11.5	63.2
2	36.5	12.0	7.2	11.0	60.4
3	30.5	10.1	9.2	9.0	49.5
4	25.5	8.4	11.3	6.9	37.9
5	20.0	6.6	12.7	5.5	30.2
6	15	4.95	14.5	3.7	20.3
7	9.7	3.2	16.5	1.7	9.3
8	5.0	1.65	16.9	1.3	7.1
9	0	0	18.2	0	0

and the pressure can be reduced above 60% when the gas volume is larger.

To verify the reliability of Eqn. (6), the experimental parameters such as initial flow velocity in the pipeline of 1.71 m/s, final flow velocity of 0.26 m/s (The quick valve was leakage.), pipe diameter of 148mm, water hammer pressure and so on are substituted into Eqn. (6). The measured results and calculated values are compared in Table 2. It can be seen from the table that both are in close agreement as the gas volumes are large. Therefore, Eqn. (6) can be used to design the volume of gas storage tank. For the measured data obtained from the small volume tanks, the computed results from Eqn. (6) may have certain errors because the pipeline deformation and absorbed energy are neglected.

Table 2 Calibration for equation of initial gas volume

u_0 /(m·s^{-1})	u /(m·s^{-1})	p_0 /10^5 Pa	p /10^5 Pa	V_C/L	V_M/L
1.71	0.26	0.32	6.7	12.1	12.7
1.71	0.26	0.32	7.2	11.8	12.0
1.71	0.26	0.32	9.2	10.1	10.1
1.71	0.26	0.32	11.3	9.1	8.4

4 GAS STORAGE TANKS AND OTHER WATER HAMMER PROTECTIVE EQUIPMENT

To further explain the effects of gas storage tanks on attenuating water hammer pressure, and to verify Eqn. (6), several water hammer protective measures in practical engineering were compared. A gangue pipeline of lead and zinc ore was designed initially as a first order pumping station. The reciprocating pump was used as the pressurizing pump. The pipeline was 2 500 m long. In the middle of the pipeline, it crossed a river with the width of more than 60 m. The end of pipeline was free outflow, which was 434 m higher than the pumping station. Fig. 3 shows the actual layout of the pipeline. The pipeline has a constant diameter and uniform wall for all segments, with the outer diameter D = 137. 0 mm, wall thickness δ= 6. 0 mm and wall absolute roughness of 0. 055 mm.

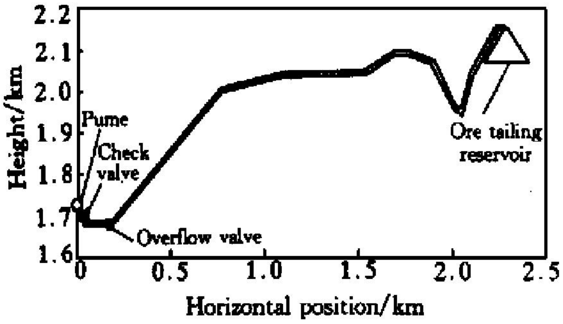

Fig. 3 Layout of gangue pipeline

The linear density of transporting gangue is 2.797×10^3 kg/ m, the mass fraction of transporting gangue is 50%, discharge is 0. 018 3 m^3/s, solid-liquid specific density is 1. 473. According to the design of pipelines, it has only inverse flow water hammers caused by power failure and mechanical failure. To reduce the danger caused by water hammer, gas storage tank, check value and surplus press-relief valve are chosen.

Because the pipeline is designed for transporting high density solid-liquid flow, computation equations for water hammer pressure in pseudo-homogeneous solid-liquid flow are deduced based on the basis of the density, elastic modulus, viscosity, resistant characteristics of solid-liquid flow[9].

1) Continuity equation

$$V\frac{\partial p}{\partial x}+\frac{\partial p}{\partial t}+a_m^2\rho_m\frac{\partial v}{\partial x}=0 \qquad (7)$$

where ρ_m is the density of two-phase flow; and a_m is the wave velocity of two-phase flow, which can be computed by

$$a_m=\sqrt{\frac{1/\rho_m}{\frac{1-C_V}{E_t}+\frac{C_V}{E_s}+\frac{D}{E_p e}}} \qquad (8)$$

2) Momentum equation

$$\frac{\partial h}{\partial x}+\frac{\partial Z}{\partial x}+\frac{v}{g}\frac{\partial v}{\partial x}+\frac{f_m v|v|}{2gD}+\Delta F=0 \qquad (9)$$

where f_m is the resistance coefficient of two-phase flow and ΔF is the additional resistance item[10] caused by heterogeneous suspended particles,

$$\Delta F=K\mu_e C_V\frac{\gamma_s-\gamma_m}{\gamma_m}\frac{\overline{\omega}}{v_0}\frac{v}{|v|} \qquad (10)$$

The above mathematical model can be discretized and the corresponding program can be carried out. Several water hammer protective measures are computed and compared with practical engineering problems.

The detailed procedure for computing water hammer[11] can be described as: 1) input initial data, such as length, elevation and wall thickness of pipe, mechanics parameters of wall material, related parameters for boundary conditions and related parameters for transported solid-liquid flow (such as specific density, grade, rheological parameters and so on); 2) divide computation cross-sections according to time step, determine related computation parameters, and compute elevation, piezometric pressure, working pressure and discharge of each cross-section in the initial steady flow; 3) compute discharge, piezometric pressure and working pressure at each cross-section in the pipeline at different times after the water hammer occurs. Count the maximum and minimum piezometric pressure and working pressure of each computation cross-section in the whole process of water hammer; and count the maximum and minimum working pressure and their positions in the entire pipeline as well as their occurring time during water hammer.

The figure of pressure outline is commonly used to assist the analysis of computational results of water hammer. To compare several water hammer protective measures, solid-liquid flow water hammer model is used in computing the working conditions with the gas storage tank installed and the working conditions with the check and pressure-relief valves installed.

4.1 Without any protective measures in pipeline

When the reciprocating pump stops, the outflow discharge from the pump Q_p reduces to zero after a time interval t_p. The interval t_p is correlated to pump types and practical operations. Because of the lack of practical data, several possible values are assumed in the computations. According to the computed results, the t_p that corresponds to the most dangerous condition is used in the sequential computations and analyses. Computations are carried out for t_p= 0, 1 s, 2 s, 5 s, and 10 s, respectively, and the computed results are shown in Fig. 4.

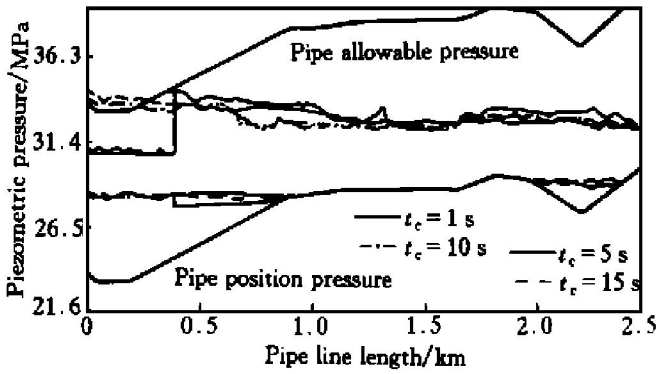

Fig. 4 Maximum and minimum piezometric pressure with different t_c

Fig. 4 shows that, with increasing t_p, the variation rate of Q_p decreases and the corresponding difference between maximum and minimum piezometric pressure becomes smaller. It suggests that the longer the pump stops, the less the entire water hammer wave flunctuates along the pipeline. Moreover, from Fig. 4, we can learn that the piezometric pressure has exceeded the pipeline allowable water pressure in part of the upstream segment of the pipeline when $t_p < 2$ s. If $t_p > 5$ s, the piezometric pressure falls below the position pressure of the pipeline in the highly elevation of downstream segments, and fluid column separation happens in some pipe segment.

4.2 With check valve installed on pipeline

The main control parameter for check valves on pipelines is t_c, the time for closing. According to the control objectives of water hammer, changes of water hammer pressure are studied for different t_c. Fig. 5 shows the computational results. From Fig. 5, it is found that, in the upstream of check valve in the pipeline, the bigger t_c is, the higher the maximum piezometric pressure is. The minimum piezometric pressure is lower than the position head of the pipeline and the liquid column separation occurs, which produces new irregular pressure wave in the pipeline.

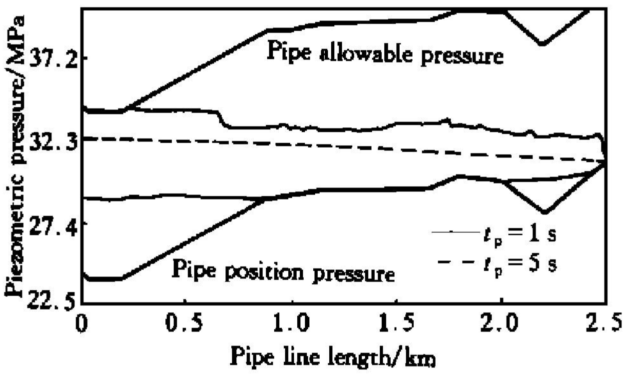

Fig. 5 Maximum and minimum piezometric head lines for different t_c

4.3 With surplus pressure-relief valve

Surplus pressure-relief valves are generally fixed on the lower segment of pipelines. The figure showing pipeline longitudinal profiles indicates that the segment between 58 m and 202 m from the pump has the lowest position and is relatively close to the pump, and the surplus pressure-relief valve may be fixed on this segment. Fig. 6 shows the computed results of the maximum and minimum piezometric pressure of the pipeline when the valve is fixed on different positions. From the figure, we can see that the maximum piezometric pressure at several positions fall below the allowable pressure of the pipe and the valve has the remarkable effects of reducing pressure.

4.4 With gas storage tank at exit

The gas volume V_t in the tank before water hammer happens is one of important control parameters.

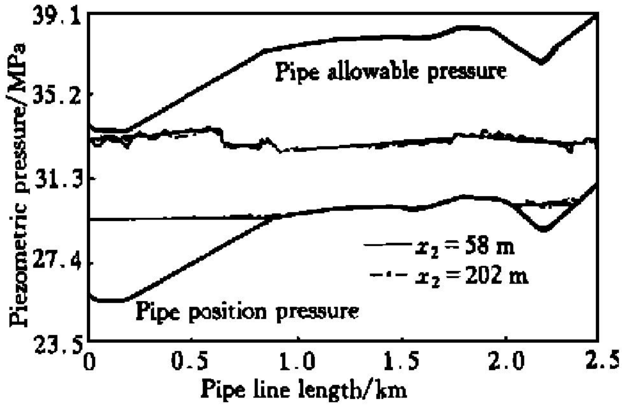

Fig. 6 Maximum and minimum water hammer pressure distribution along pipeline with different x_2

The volume of the tank can be determined based on V_t and the technical requirements of the tank. This example problem is computed using V_t = 0.05 m^3, 0.1 m^3, 0.15 m^3, and 0.2 m^3, respectively, and the results are given in Fig. 7. In this figure the maximum and minimum piezometric pressure, with V_t being different values, along the pipeline are shown. The working pressure at the upstream end of the tank with V_t being different values are shown in Fig. 8. Fig. 7 indicates that the pressure-relief effect of tank is remarkable. It can not only make the maximum piezometric pressure fall below the allowable pressure of the pipe, but also, except for the situation of V_t = 0.05 m^3, make the minimum piezometric pressure rise above the position pressure of the pipe and avoid liquid column separation. Fig. 8 indicates that the fluctuation of working pressure decreases as V_t increases. To further verify Eqn. (6), the gas volumes are recomputed by substituting the parameter ρ_m obtained from solid-liquid flow model into Eqn. (6). Here, the absolute pressure of steady flow in the pipeline is 6.96 MPa. Table 3 gives computed results. From Table 3, it can be seen that the gas volumes computed by Eqn. (6) have relatively high precision.

Based on the above comparisons of several mea-

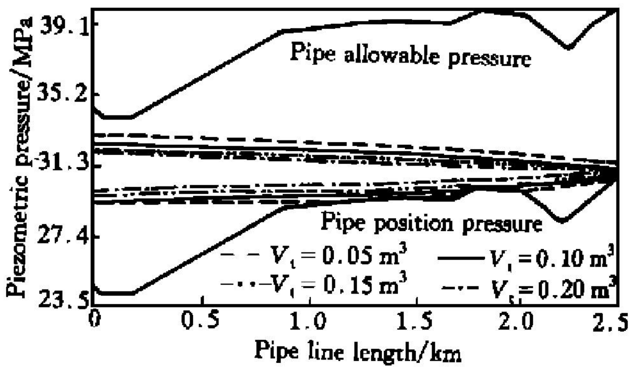

Fig. 7 Water hammer pressure distribution along pipes with gas tank equipped

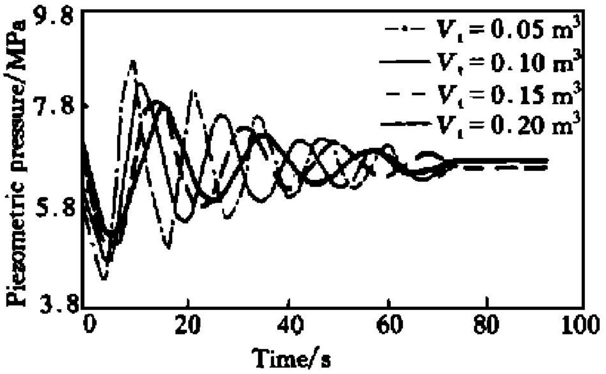

Fig. 8 Pressure pulsation in upstream cross-section with gas in tank being different volumes

Table 3 Computation results of gas volumes

Volume in model calculating/ m^3	Max pressure calculated/ 10^6 Pa	Gas volume calculated with Eqn. (6) / m^3
0.05	8.16	0.054
0.1	7.63	0.095
0.15	7.37	0.152
0.2	7.25	0.214

sures, it can be seen that, for the pipeline transporting by reciprocating pumps, the most effective method for controlling water hammer pressure is to fix the gas storage tank with appropriate volume at the exit of the reciprocating pump. It not only controls the maximum working pressure being lower than permissible working pressure of the pipeline, but also controls the minimum working pressure not producing liquid column separation. In designing the gas storage tanks, the results obtained from the simple equation given by Eqn. (6) are coincident with those computed using the mathematical model. Therefore, the water hammer Eqn. (6) can be utilized in the practical engineering project with satisfactory precision.

5 CONCLUSIONS

1) The occurrence of water hammer mainly depends on the layout and operating procedure of pipelines. Similar to the situation of clear water, there are three possible cases of water hammer in pipelines transporting solid-liquid two-phase flows: a) the water hammer occurring during the closure of the end valve; b) the vacuum close water hammer; c) the inverse flow water hammer.

2) For Eqn. (6) is deduced from the law of conservation of energy, it can be applied to both solid-liquid two-phase flow and clear water. Same as the water hammer computational equations (continuity Eqn. (7), momentum Eqn. (9)), with the concentration of the solid equals to 0, the solid-liquid two-phase flow equations can be turned into clear water equations.

3) The experiments show that the gas storage tank can effectively adjust and decrease pressure. The initial gas volume equation given by Eqn. (6) deduced theoretically is consistent with the experimental results and can be used in the design of gas storage tank in practical engineering.

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(Edited by LONG Huai-zhong)