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Research Article

Study on Influence of Fluid Parameters on Axial Coupled Vibration of Pipeline Conveying Multiphase Flow

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Taking a slurry reservoir-pipeline-valve system as research object, axial dynamic vibrations of pipe system were induced by coupled hydraulic transient due to rapid closure of valve at the end of pipe. The influences of fluid parameters in multiphase flow, including void fraction, density ratio, and elastic modulus ratio between solid phase and liquid phase, on vibration behaviors of pipe system were analyzed. Results of this study show that wave velocities of pressure and stress can be attenuated evidently when void fraction in multiphase fluid is increased appropriately; meanwhile, the amplitudes of pressure fluctuation and pipe vibration are also weakened obviously. With the increase of density ratio between solid phase and liquid phase, the vibrational intension of pipe system becomes stronger and stronger. In this instance, the increments of vibrational energy mainly concentrate in fluid, which leads the pressure energy of fluid to rise up quickly. When elastic modulus ratio between solid phase and liquid phase increases, the total elasticity of fluid decreases gradually. At the same time, both pressure energy of fluid and vibrational intension of pipe are enhanced but the increments are very slight.

1. Introduction

As a kind of the excellent transportation mode, piping systems are widely used in many fields such as marine engineering, nuclear industries, and petroleum engineering. In the operational process of piping system, an extreme hydraulic state, that is, water hammer, is often induced by the disturbance of dynamic or controlling system. Due to the effect of fluid-structure interaction (FSI), water hammer may cause intense coupled vibration of piping system, which decreases the reliability and performance of system and even will lead to serious disasters further. Therefore, it is of great and immediate significance to accurately analyze the coupled vibration principle of piping system for taking safety precautionary measures, ensuring reliable operation of the whole systems, reducing the loss of energy sources, and so on.

Extensive investigations have been carried out on coupled vibration of piping system in the past years. Several coupled vibration models describing nonlinear dynamic behaviors of liquid-conveying pipes were developed by Paidoussis and Li [1], Zhang and Huang [2], Gorman et al. [3], Lee and Chung [4], and Omer et al. [5], respectively. To obtain the coupled vibration response results of piping system in time and frequency domain, different numerical methods, such as MOC, FEM, MOC-FEM, traveling wave method, and transfer matrix method, were used by Wiggert and Tijsseling [6], Kochupillai et al. [7], Zanganeh et al. [8], Ren et al. [9], and Xu et al. [10], respectively.

By virtue of different theoretical models and numerical procedures, some specific researches were concerned with the influence of fluid or structural parameters on the coupled vibration characteristics of piping system. Zhang [11] conducted an investigation into the effects of fluid and shell parameters on the coupled frequencies based on wave propagation approach. Li et al. [12] analyzed the factors affecting the characteristics of FSI by changing the bend radius and angle of curved pipe. Adamkowski et al. [13] carried on their research on the influence of dynamic Poisson effect onto pressure records during hydraulic transient with FSI using experimental data and numerical computations. Yang and Fan [14] studied the influences of pipe structural damping, pipe Poisson's ratio, and pipe wall thickness on vibration responses of the RPV system. Liu et al. [15] analyzed influences of steam parameters, that is, steam pressure and velocity, on the natural characteristics of steam pipeline systems. Lin et al. [16] discussed the effect of fluid parameters, including liquid pressure, flow velocity, and axial force, on vibration characteristics of hydraulic pipe of aero-engine. Zhang et al. [17] conducted their investigation into the influences of internal flow, the changes of internal flow velocity, and top tension amplitude on coupled vibration of deep-water riser. Eslami et al. [18] studied the effect of aspect ratio of length to diameter on the dynamic response of a fluid-conveying pipe based on the Timoshenko beam model. Their results indicate that the natural frequencies decrease with the increasing of internal fluid velocity and the critical velocity decreases with the decreasing of aspect ratio. Gu et al. [19] studied vibration behavior of a fluid-conveying cracked pipe surrounded by a viscoelastic medium. In their works, the effect of open crack parameters and flow velocity profile shape inside the pipe on natural frequency and critical flow velocity of the system has been analytically investigated. Liu et al. [20] analyzed the influences of bound manner, restraint stiffness, foundation vibration parameters, and structural parameters on pipe outlet pressure fluctuation amplitude. Tian et al. [21] studied vibration characteristics of pipeline under the action of the gas pressure pulsation and the relationships between the gas column natural frequency and orders, the gas pressure pulsation and orders, the exciting force and aspect ratio, and the vibration displacement and velocity of pipeline are acquired. Meng et al. [22] developed a simple FSI model and investigated the effect of internal flow velocity on the cross-flow vortex-induced vibration of a cantilevered pipe discharging fluid.

According to the collected literatures, these researches on coupled vibration of piping system mainly focus on the development and solution of numerical models, the critical flow velocity, parameters resonance of pipe structures, and so on. Furthermore, the pure liquid is often considered as research objects, whereas the liquid containing gas phase and solid phase is rarely taken into account [23]. Actually, with the wide application of mixed transportation technology for multiphase flow or the effect of objective factors (such as interlarding the liquid with some gas or solid impurities), the actual fluid in the pipelines always exists as a kind of multiphase fluids and gas-liquid-solid three-phase mixed flow is the most general and representative in multiphase flows. Thus, this paper takes gas-liquid-solid three-phase mixed flow as research object and the influences of parameters, including void fraction, density ratio, and elastic modulus ratio between solid phase and liquid phase, on vibration characteristics of piping system are studied to illuminate coupled water hammer problems of pipelines further.

2. Mathematical Model

Hydraulic transportation is often used to transport concentrate and tailings in the metallurgical industry as well as cinder in the coal and power industries. To facilitate hydraulic transportation by pipeline, decreasing the wear of the equipment, reducing the conveying velocity, and lowering the operational costs, the fine solid granular materials are usually applied to maintain an even suspended motion in the effect of turbulent diffusion. In such condition, this kind of gas-liquid-solid three-phase mixed flow formed by solid granule, liquid, and some other small amount of gas mixed in is relatively stable, and the concentration of every phase is well-distributed at the cross-section of pipeline. Generally, for such kind of piping system, the flow is treated as homogeneous flow or pseudo-homogenous flow which can be analyzed on the basis of homogeneous flow theory [24].

To obtain a set of convenient FSI governing equations for piping system conveying the mentioned three-phase flow in this paper, the following assumptions are made:

(a) Gas phase, liquid phase, and solid phase are mixed evenly, and there are no velocity difference and no mass exchange among the three phases in an adiabatic state.

(b) Cross-section changes and deformations along the pipe are small; that is, $\partial A_f / \partial x \approx 0$.

(c) The material of pipe wall is isotropic and presents a linear-elastic mechanical behavior.

(d) Liquid flashing is not considered in the process of hydraulic transient, and fluid velocity is a cross-section averaged scalar value.

Because many pipes in practice have relatively thick walls, for example, high-pressure pipes in chemical and power industries, the usual assumption of thin-walled pipes is not adopted in this research. Therefore, the ratio e/R of wall thickness to pipe-radius cannot be neglected. Based on the above assumptions, the FSI model can be described by the following expression [25]:

$$\mathbf{A}\frac{\partial \mathbf{\Phi}}{\partial t} + \mathbf{B}\frac{\partial \mathbf{\Phi}}{\partial x} = \mathbf{F}, \tag{1}$$

where

$$\mathbf{\Phi} = \begin{bmatrix} V_{\mathrm{m}} \\ H \\ U \\ \sigma \end{bmatrix};$$

$$\mathbf{A} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & K^{*}\rho_{\mathrm{m}} g & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & \dfrac{2\mu R^2 \rho_{\mathrm{m}} g}{\left[\left(2Re + e^2\right) E\right]} & 0 & \dfrac{-1}{E} \end{bmatrix};$$

$$\mathbf{B} = \begin{bmatrix} 0 & g & 0 & 0 \\ 1 & 0 & -2\mu\left(1 + \dfrac{e}{R}\right) & 0 \\ 0 & 0 & 0 & \dfrac{-1}{\rho_{\mathrm{P}}} \\ 0 & 0 & 1 & 0 \end{bmatrix};$$

$$\mathbf{F}=\begin{bmatrix}-\dfrac{F_{\mathrm{m}}}{(\rho_{\mathrm{m}}A_{\mathrm{f}})}-g\sin\alpha\\ 0\\ \dfrac{F_{\mathrm{m}}}{(\rho_{\mathrm{p}}A_{\mathrm{p}})}-g\sin\alpha\\ 0\end{bmatrix};$$

$$K^{*}=\frac{1}{K_{\mathrm{m}}}+\frac{4R\left(1-\mu^{2}\right)(R+e)}{(2REe+Ee^{2})};$$

$$K_{\mathrm{m}}=\left[\frac{\nu_{\mathrm{g}}}{K_{\mathrm{g}}}+\frac{\nu_{\mathrm{s}}}{K_{\mathrm{s}}}+\frac{\left(1-\nu_{\mathrm{g}}-\nu_{\mathrm{s}}\right)}{K_{\mathrm{l}}}\right]^{-1};$$

$$\rho_{\mathrm{m}}=\rho_{\mathrm{g}}\nu_{\mathrm{g}}+\rho_{\mathrm{s}}\nu_{\mathrm{s}}+\rho_{\mathrm{l}}\left(1-\nu_{\mathrm{g}}-\nu_{\mathrm{s}}\right);$$

$$F_{\mathrm{m}}=\frac{\rho_{\mathrm{m}}f_{\mathrm{m}}A_{\mathrm{f}}V_{\mathrm{m}}\left|V_{\mathrm{m}}\right|\left\{1+\varphi\left[\nu_{\mathrm{s}}\left(\rho_{\mathrm{s}}/\rho_{\mathrm{l}}-1\right)+\nu_{\mathrm{g}}\sin\alpha\right]\right\}}{(4R)}. \tag{2}$$

The characteristic formula for (1) is $|\mathbf{B}-\lambda\mathbf{A}|=0$ and its four unequal real roots are

$$\lambda_{1,2}=\pm C_{\mathrm{m}}=\pm\sqrt{\frac{1}{2}\left[q^{2}-\left(q^{4}-4a_{\mathrm{m}}^{2}a_{\mathrm{p}}^{2}\right)^{1/2}\right]},$$
$$\lambda_{3,4}=\pm C_{\mathrm{p}}=\pm\sqrt{\frac{1}{2}\left[q^{2}+\left(q^{4}-4a_{\mathrm{m}}^{2}a_{\mathrm{p}}^{2}\right)^{1/2}\right]}, \tag{3}$$

where $q^{2}=a_{\mathrm{m}}^{2}+a_{\mathrm{p}}^{2}+(4\mu^{2}R(R+e)/(2R+e)e)(\rho_{\mathrm{m}}/\rho_{\mathrm{p}})a_{\mathrm{m}}^{2}$.

3. Numerical Scheme

To the numerical simulation of water hammer events without FSI, MOC is always regarded as an excellent numerical strategy. However, for solving FSI model, MOC may introduce excessive numerical dispersion and attenuation in the solutions, which will induce a bad influence on the accuracy of computational results [26]. To avoid the embarrassment, flux vector splitting method is used to solve the proposed FSI model.

Make (1) flux splitting and numerical discretization based on Lax-Wendroff central difference scheme and Warming-Beam upwind difference scheme, both of which possess second-order precision in time and space [27]. According to the literature [28], (1) can be written as the following difference form:

$$\mathbf{W}_{j}^{n+1}=\mathbf{W}_{j}^{n}-\frac{\Delta t}{\Delta x}\left(\mathbf{D}^{n}_{j+\frac{1}{2}}-\mathbf{D}^{n}_{j-\frac{1}{2}}\right)+\Delta t\mathbf{T}\mathbf{F}_{j}^{n},$$

$$\mathbf{D}_{j+1/2}=\mathbf{Y}_{j+1/2}^{+}+\mathbf{Y}_{j-1/2}^{-},$$
$$\mathbf{D}_{j-1/2}=\mathbf{Y}_{j-1/2}^{+}+\mathbf{Y}_{j-3/2}^{-},$$
$$\mathbf{Y}_{j+1/2}^{+}=\mathbf{Y}_{j}^{+}+\frac{1}{2}\left(\mathbf{I}-\frac{\mathbf{\Lambda}^{+}\Delta t}{\Delta x}\right)*\mathrm{MINMOD}\left(\Delta\mathbf{Y}_{j-1}^{+},\Delta\mathbf{Y}_{j}^{+}\right),$$
$$\mathbf{Y}_{j-1/2}^{-}=\mathbf{Y}_{j+1}^{-}-\frac{1}{2}\left(\mathbf{I}+\frac{\mathbf{\Lambda}^{-}\Delta t}{\Delta x}\right)*\mathrm{MINMOD}\left(\Delta\mathbf{Y}_{j}^{-},\Delta\mathbf{Y}_{j+1}^{-}\right),$$
$$\Delta\mathbf{Y}_{j-1}^{\pm}=\mathbf{Y}_{j}^{\pm}-\mathbf{Y}_{j-1}^{\pm},$$
$$\Delta\mathbf{Y}_{j}^{\pm}=\mathbf{Y}_{j+1}^{\pm}-\mathbf{Y}_{j}^{\pm},$$
$$\Delta\mathbf{Y}_{j+1}^{\pm}=\mathbf{Y}_{j+2}^{\pm}-\mathbf{Y}_{j+1}^{\pm}, \tag{4}$$

where $\mathbf{W}=\mathbf{T}\mathbf{\Lambda}\mathbf{\Phi}$; $\mathbf{T}=[t_{ij}]_{4\times4}$; for $i=1$ or 2, $t_{i1}=1$, $t_{i2}=\lambda_{i}$, $t_{i3}=2\mu(1+e/R)\lambda_{i}^{2}/(C_{\mathrm{p}}^{2}-\lambda_{i}^{2})$, $t_{i4}=2\mu C_{\mathrm{p}}^{2}(1+e/R)\lambda_{i}/(C_{\mathrm{p}}^{2}-\lambda_{i}^{2})$; for $i=3$ or 4, $t_{i1}=(2\mu R^{2}\rho_{\mathrm{m}}/(2Re+e^{2})E)(C_{\mathrm{m}}^{2}\lambda_{i}^{2}/(C_{\mathrm{m}}^{2}-\lambda_{i}^{2}))$, $t_{i2}=(2\mu R^{2}\rho_{\mathrm{m}}/(2Re+e^{2})E)(C_{\mathrm{m}}^{2}\lambda_{i}^{3}/(C_{\mathrm{m}}^{2}-\lambda_{i}^{2}))$, $t_{i3}=1-(4\mu^{2}(R^{2}+Re)\rho_{\mathrm{m}}/(2Re+e^{2})E)(C_{\mathrm{m}}^{2}\lambda_{i}^{2}/(C_{\mathrm{m}}^{2}-\lambda_{i}^{2}))$, $t_{i4}=\lambda_{i}$; $\mathbf{Y}^{+}=\mathbf{\Lambda}^{+}\mathbf{W}$, $\mathbf{Y}^{-}=\mathbf{\Lambda}^{-}\mathbf{W}$; $\mathbf{\Lambda}^{+}=\mathrm{diag}(\lambda_{1}^{+},\lambda_{2}^{+},\lambda_{3}^{+},\lambda_{4}^{+})$, $\mathbf{\Lambda}^{-}=\mathrm{diag}(\lambda_{1}^{-},\lambda_{2}^{-},\lambda_{3}^{-},\lambda_{4}^{-})$, $\lambda_{i}^{+}=(\lambda_{i}+|\lambda_{i}|)/2$, $\lambda_{i}^{-}=(\lambda_{i}-|\lambda_{i}|)/2$; $\mathbf{I}$ is an identity matrix; MINMOD(a,b) function is described as follows: when $ab\le0$, the value of function equals zero; when $ab>0$, the value of function equals the lesser one of absolute values of a and b.

The stability condition of the above difference schemes is $Cr=\max(C_{\mathrm{m}},C_{\mathrm{p}})\Delta t/\Delta x\le1$. These equations are solved subject to boundary conditions at the upstream and downstream ends of the pipeline and initial conditions. For a pipeline connected to a reservoir with constant piezometric head H_{up} and an unfixed valve at the upstream and downstream ends, respectively, the boundary conditions can be derived from Rankine-Hugoniot condition [29]:

For upstream end,

$$\mathbf{\Phi}_{0}^{n+1}=\begin{bmatrix}V_{\mathrm{m0}}^{n+1}\\ H_{0}^{n+1}\\ U_{0}^{n+1}\\ \sigma_{0}^{n+1}\end{bmatrix}=\begin{bmatrix}V_{\mathrm{m1}}^{n}+\dfrac{\left(H_{\mathrm{up}}-H_{1}^{n}\right)g}{C_{\mathrm{m}}}\\ H_{\mathrm{up}}\\ 0\\ \sigma_{1}^{n}+C_{\mathrm{p}}\rho_{\mathrm{p}}U_{1}^{n}\end{bmatrix}. \tag{5}$$

For downstream end,

Table 1: Physical parameters of the RPV system.

Parameter name	Parameter unit	Parameter value
Length of pipe	m	20
Outer diameter of pipe	m	0.813
Pipe wall thickness	m	0.008
Young's modulus of pipe material	GPa	210
Density of the pipe material	kg/m^3	7900
Poisson's ratio	—	0.3
Initial velocity of internal flow in pipe	m/s	1
Pressure behind valve	MPa	0

$$\Phi_N^{n+1} = \begin{bmatrix} V_{mN}^{n+1} \\ H_N^{n+1} \\ U_N^{n+1} \\ \sigma_N^{n+1} \end{bmatrix} = \begin{bmatrix} U_N^{n+1} \\ H_{N-1}^n - \dfrac{C_m\left(U_N^{n+1} - V_{mN-1}^n\right)}{g} \\ \dfrac{\left(A_f\rho_m g H_{N-1}^n + A_f C_m \rho_m V_{mN-1}^n + A_p C_p \rho_p U_{N-1}^n - A_p \sigma_{N-1}^n\right)}{\left(C_m\rho_m A_f + C_p\rho_p A_p\right)} \\ \dfrac{A_f\rho_m g H_N^{n+1}}{A_p} \end{bmatrix}. \quad (6)$$

4. Discussion about the Influence of Correlative Parameters

A slurry reservoir-pipeline-valve system shown in Figure 1 is taken as a research object in this paper. The pipe and valve are allowed to move freely in the axial direction. The physical parameters of this RPV system are listed in Table 1.

In the multiphase fluid, water is taken as liquid phase, where the density is 1000 kg/m^3 and bulk modulus equals 2.14 GPa. The coupled water hammer event is induced by instantaneous closure of valve at downstream end.

4.1. The Influence of Void Fraction on Vibration Characteristics of Piping System. Void fraction is one of the most important parameters of multiphase fluid. The bulk modulus of gas phase is usually 4~6 quantity grades less than that of liquid phase and solid phase. So even if the change of void fraction is very inconspicuous, the influence on vibration characteristics of piping system cannot be ignored. Assume the solid phase in the slurry is iron concentrate, whose dry density is 4760 kg/m^3, elasticity modulus is 105 GPa, solid particulate diameter is about 0.071 mm, and bulk concentration equals 0.168. The gas phase is air bubble, whose bulk modulus is obtained by [30]

$$K_g = \rho_m g H \gamma. \quad (7)$$

The curves of pressure wave velocity with the change of void fraction are shown in Figure 2. Pressure wave velocity decreases sharply in the process of void fraction increasing from 0 to 0.001. When void fraction exceeds 0.2, pressure wave velocity tends toward stabilization. Before and after considering fluid-structure interaction, the difference between two curves of pressure wave velocity is not obvious. When void fraction equals zero, pressure wave velocity without FSI is 861 m/s, exceeding the value of pressure wave velocity with FSI, that is, 839 m/s. The curves of stress wave velocity with the change of void fraction are shown in Figure 3. According to Figure 3, the variational trend of stress wave velocity is similar to that of pressure wave velocity when FSI is considered. However, when FSI is not considered, stress wave velocity is a constant. This is because stress wave velocity is only related to elastic modulus and density of pipe material in the equation for stress wave velocity without FSI.

The pressure response and pipe structure vibration at valve are analyzed with the void fraction in the slurry equaling 0.000035, 0.00035, and 0.0035, respectively, as shown in Figures 4 and 5. As void fraction increases, the amplitudes of pressure and structure vibration decrease obviously and the fluctuation frequency also reduces. Such situations are similar to system energy dissipation induced by structure damp of piping system. So the gas phase can be regarded as a kind of energy dissipation damp. Increasing appropriately void fraction in the conveyed medium may effectively weaken the fluctuations of fluid pressure and pipe vibration on the premise of maintaining the current flow pattern.

4.2. The Influence of Density Ratio between Solid Phase and Liquid Phase on Vibration Characteristics of Piping System. At present, in the industrial production, many kinds of solid material particulates can be conveyed by hydraulic

Figure 1: Sketch of slurry reservoir-pipeline-valve system.

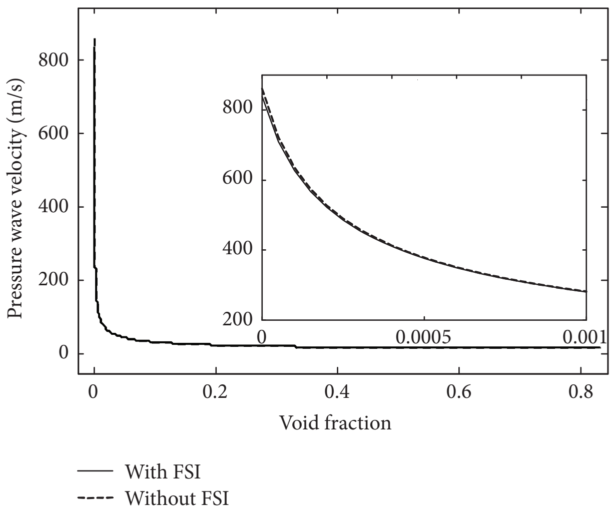

Figure 2: Variation of pressure wave velocity with void fraction.

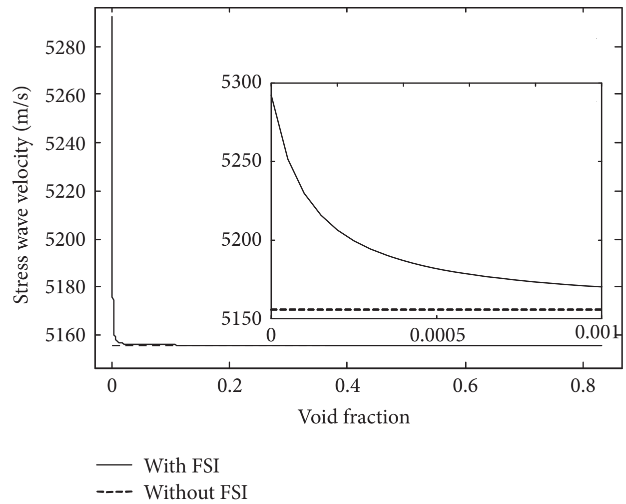

Figure 3: Variation of stress wave velocity with void fraction.

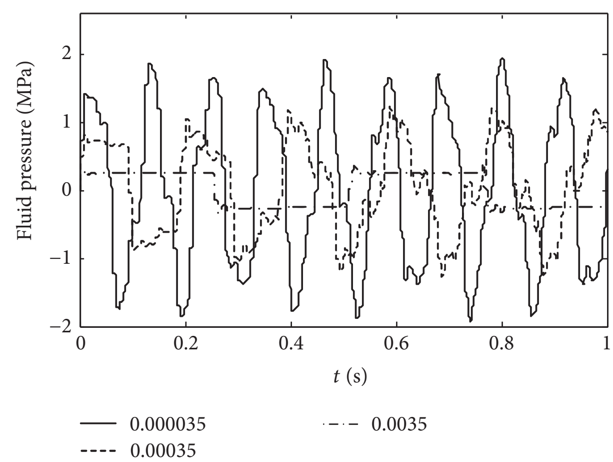

Figure 4: Comparison among pressure responses at valve with the different void fraction.

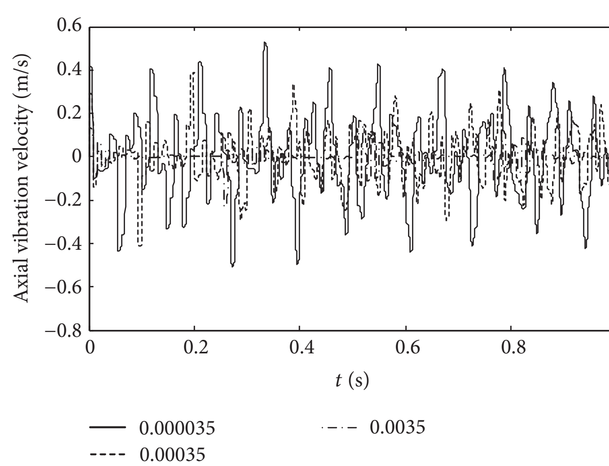

Figure 5: Comparison among axial vibration velocity responses at valve with the different void fraction.

transportation in pipeline. With the further investigation, it can be pointed out that the influence of density ratio between solid phase and liquid phase (density ratio for short in the following content) on dynamic behaviors of piping system is quite conspicuous. The influence of slurry concentration (i.e., solid phase content in the fluid) on pressure wave velocity shows some obvious discrepancies because of different density ratios.

Assume the content of void fraction in the slurry maintains 0.00035. The influences of slurry concentration on pressure wave velocity are shown in Figure 6 with different density ratios. According to Figure 6, the density ratio has a critical value (it is about 1.15 in this instance). When density ratio is less than the critical value, pressure wave velocity will quicken with increase of slurry concentration, whereas pressure wave velocity will decrease. The curves of stress wave velocity with density ratios are shown in Figure 7. According to Figure 7, the changing trends of stress wave velocity with the slurry concentration are not affected by density ratios. Only under different density ratios, increasing extent of stress wave velocities varies.

Let slurry concentration equal 0.568 and density ratios equal 0.5~5.0 with an interval of 0.3. Then the maximum values and virtual values of fluid pressure and vibration velocity at valve are shown in Figures 8 and 9.

According the computational curves in Figures 8 and 9, the maximum values and virtual values of fluid pressure are enhanced with the increase of density ratio, and due to junction coupled effect, the axial vibration velocity has same

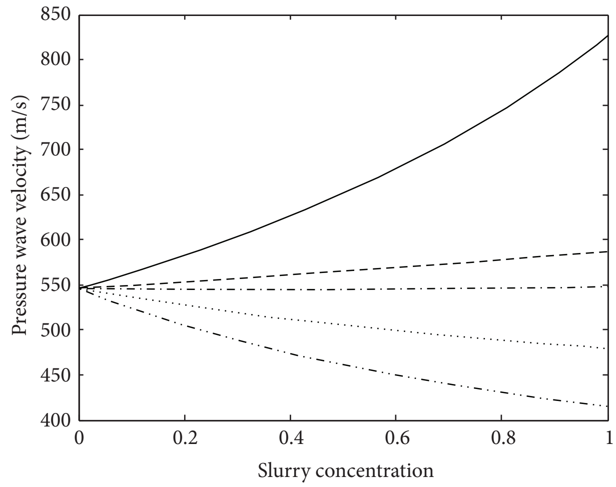

Figure 6: Influence of density ratio on pressure wave velocity.

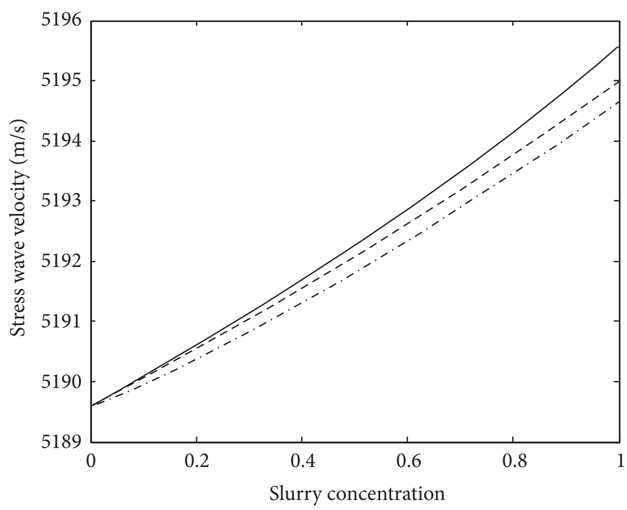

Figure 7: Influence of density ratio on stress wave velocity.

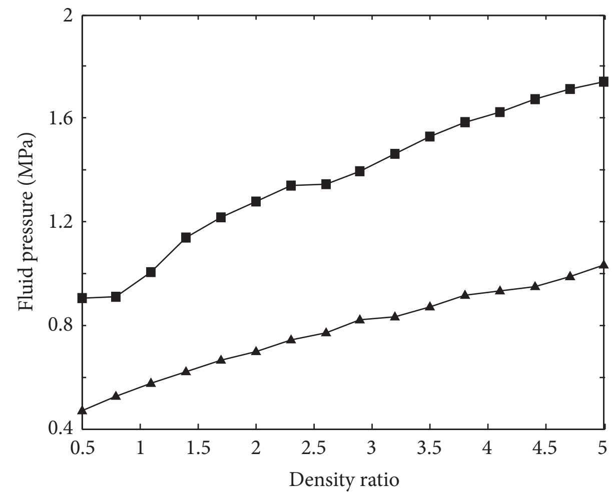

Figure 8: Pressure responses of fluid at valve.

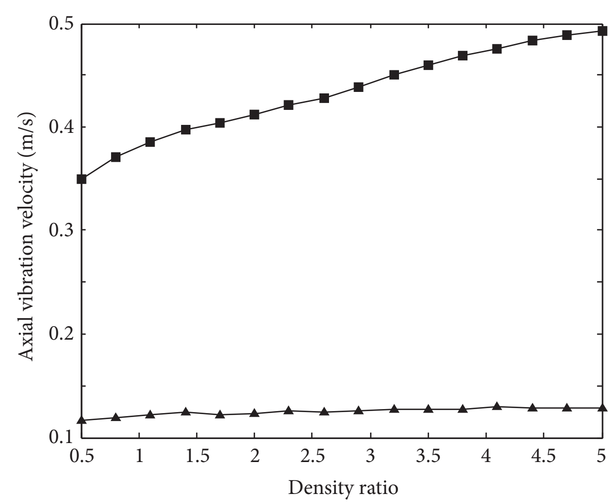

Figure 9: Axial vibration velocity responses of pipe at valve.

changing trend. The phenomenon explains that the vibration extent of piping system will be enhanced with the increase of density ratio. Combined with the computational curves in Figure 6, pressure wave velocity is decreased because of the increase of density ratio, but the total density of fluid gains more enhancement. Then the inertia of unit volume of fluid is stronger and the intensity of water hammer pressure will be enhanced correspondingly from the principle of inertial water hammer. The increasing extent of virtual values of pipe vibration velocity (i.e., vibration energy) is less than that of virtual values of fluid pressure (i.e., pressure energy), which indicates that the increments of systemic vibration energy mainly centralize in the slurry with the increase of density ratio. Hence the pressure energy in the slurry can get a more rapid rise.

4.3. The Influence of Elastic Modulus Ratio between Solid Phase and Liquid Phase on Vibration Characteristics of Piping System. As the slurry concentration changes, different elastic modulus ratio between solid phase and liquid phase (elastic modulus ratio for short in the following content) may lead to different transformation of overall bulk modulus of multiphase fluid and further influences the changing trend of pressure and stress wave velocity. The influence of different elastic modulus on pipe stress wave velocity is shown in Figure 10, in which solid line and broken line denote density ratio equaling 4.76 or 0.76, respectively. According to Figure 10,

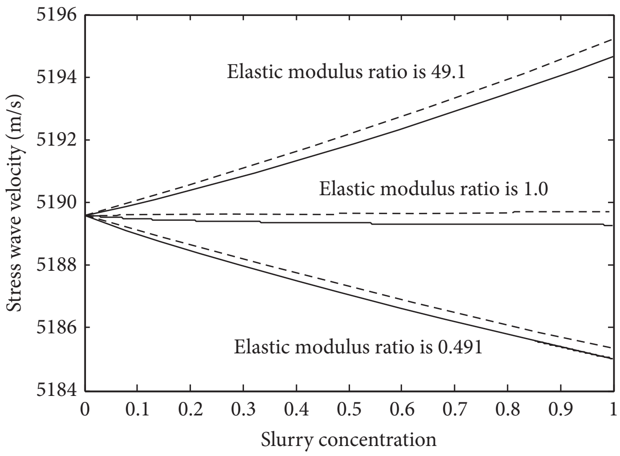

Figure 10: Influence of elastic modulus ratio on stress wave velocity.

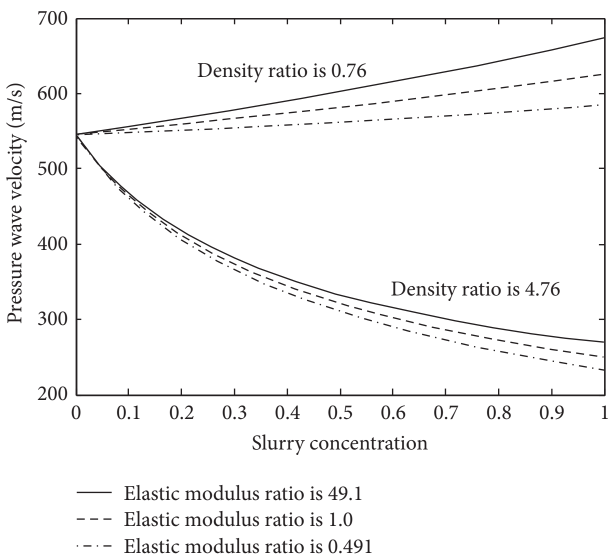

Figure 11: Influence of elastic modulus ratio on pressure wave velocity.

the influence of elastic modulus ratio on stress wave velocity is obvious, whereas density ratio has a less effect on stress wave velocity comparatively. Similarly there exists a critical value (it is about 1.0 in this instance) in elastic modulus ratio. When elastic modulus ratio is less than the critical value, stress wave velocity will decrease with the increase of slurry concentration. Otherwise stress wave velocity will quicken with the increase of slurry concentration.

The influence of elastic modulus ratio on pressure wave velocity is shown in Figure 11. As presented in this figure, with the transformation of slurry concentration, the changing trend of pressure wave velocity is not affected by elastic modulus ratio but the changing extent of pressure wave velocity is influenced. In general, its influence on pressure wave velocity is less than that of density ratio. In addition, according to Figure 11, the pressure wave velocity grows with the increase of elastic modulus ratio at the same slurry concentration. This is because the increase of elastic modulus ratio can make the total bulk modulus of multiphase fluid augment. It means that the slurry becomes harder gradually and its elasticity decreases and rigidity increases. So the pressure wave velocity travels faster and faster. If bulk modulus of the slurry is infinite, pressure wave velocity will become infinite too.

Let the slurry concentration equal 0.568 and density ratio equal 0.76 or 4.76, respectively. The values of elastic modulus ratio are assigned between 0.1 and 50. Then the maximum and virtual values of pressure and vibration velocity at valve are shown in Table 2.

According to the data as shown in Table 2, although density ratio takes different values, the maximum and virtual values of slurry pressure always grow with the increase of elastic modulus ratio. But the growth is low. When elastic modulus ratio exceeds a certain value (it is about 1.0 in this instance), the changing extent of slurry pressure response decreases and tends to be stable. Due to the junction coupled effect, the change of pipe axial vibration velocity is similar to that of slurry pressure response. The result shows that when the elasticity of slurry decreases to certain extent with the increase of elastic modulus ratio, its influence on pressure energy and vibration intensity of pipe can be ignored.

5. Conclusions

The slurry reservoir-pipeline-valve system is taken as a research object in this paper and the influences of physical parameters of multiphase fluid on system vibration response are analyzed. The main conclusions are as follows:

(1) With the increase of void fraction, the wave velocities of pressure and stress decrease rapidly then tend to be stable. At the same time, the amplitudes of slurry pressure and pipe vibration decline obviously. So the gas phase can be regarded as a kind of energy dissipation damp. Increasing moderately void fraction can weaken slurry pressure and pipe vibration effectively if the current flow pattern is maintained.

(2) For pressure wave velocity in the slurry, density ratio has a critical value. When density ratio is less than the critical value, pressure wave velocity will grow with the increase of slurry concentration; otherwise the pressure wave velocity will decrease. The changing trend of stress wave velocity with slurry concentration is not affected by density ratio. Just the increasing extent of stress wave velocity is dissimilar to the different density ratio. When density ratio increases, the vibration intensity of piping system grows too. The increment of vibration energy of pipe system is mainly concentrated in the slurry.

(3) For stress wave velocity of pipe, there also exists a critical value in elastic modulus ratio. When elastic modulus ratio is less than the critical value, stress wave velocity decreases with the increase of slurry concentration. On the contrary, stress wave velocity will grow. However, the changing trends of pressure wave velocity with slurry concentration are not affected obviously by elastic modulus ratio and only small variations of its changing extent are shown with

Table 2: Numerical results with the different elastic modulus ratio.

Elastic modulus ratio	Slurry pressure/MPa (density ratio is 0.76)		Vibration velocity/m/s (density ratio is 0.76)		Slurry pressure/MPa (density ratio is 4.76)		Vibration velocity/m/s (density ratio is 4.76)	
	Maximum values	Virtual values	Maximum values	Virtual values	Maximum values	Virtual values	Maximum values	Virtual values
0.1	0.7053	0.3796	0.3059	0.0865	1.1811	0.7338	0.4240	0.0936
1.0	0.8605	0.4962	0.3620	0.1136	1.6601	0.9692	0.4833	0.1242
5.0	0.8978	0.5149	0.3671	0.1190	1.7122	0.9952	0.4885	0.1286
10.0	0.8992	0.5151	0.3677	0.1191	1.7164	0.9969	0.4891	0.1287
30.0	0.9008	0.5157	0.3682	0.1191	1.7192	0.9982	0.4895	0.1291
50.0	0.9011	0.5159	0.3682	0.1192	1.7193	0.9984	0.4895	0.1292

different elastic modulus ratio. The increase of elastic modulus enhances the pressure energy and vibrational intension slightly. When elastic modulus ratio grows to a certain extent, its influence on pressure energy and vibrational intension of pipe system can be ignored.

Nomenclature

V_{m}: Average velocity of multiphase fluid (m/s)
H: Pressure head of multiphase fluid (m)
U: Axial velocity of the pipe (m/s)
σ: Axial normal stress of the pipe wall (Pa)
E: Young's modulus of pipe wall material (Pa)
μ: Poisson's ratio of pipe material
R: Internal radius of the pipe (m)
e: Thickness of pipe wall (m)
A_{P}: Cross-sectional area of pipe wall (m^2)
A_{f}: Internal cross-sectional area of the pipe (m^2)
ρ_{p}: Density of pipe wall material ($\mathrm{kg/m}^3$)
g: Gravity acceleration ($\mathrm{m/s}^2$)
α: Inclination angle of the pipe ($^\circ$)
ρ: Density of each phase in multiphase fluid ($\mathrm{kg/m}^3$)
ν: Volume percentage of each phase in multiphase fluid
K: Bulk modulus of each phase in multiphase fluid (Pa)
x: Axial direction of the pipe (m)
t: Time (s)
f_{m}: Friction factor between pipe wall and multiphase fluid
φ: Pressure coefficient
a_{m}: Pressure wave velocity without FSI ($= (K^* \rho_{\mathrm{m}})^{-0.5}$) (m/s)
a_{p}: Axial stress wave velocity without FSI ($= (E/\rho_{\mathrm{p}})^{0.5}$) (m/s)
Δt: Time step (s)
Δx: Pipe element length (m)
γ: Adiabatic exponent of air.

Superscripts

n: Time step number.

Subscript

j: Node number of the difference grid, $j = 0, 1, \ldots, N$
g: Gas phase
s: Solid phase
l: Liquid phase
m: Mixed phase.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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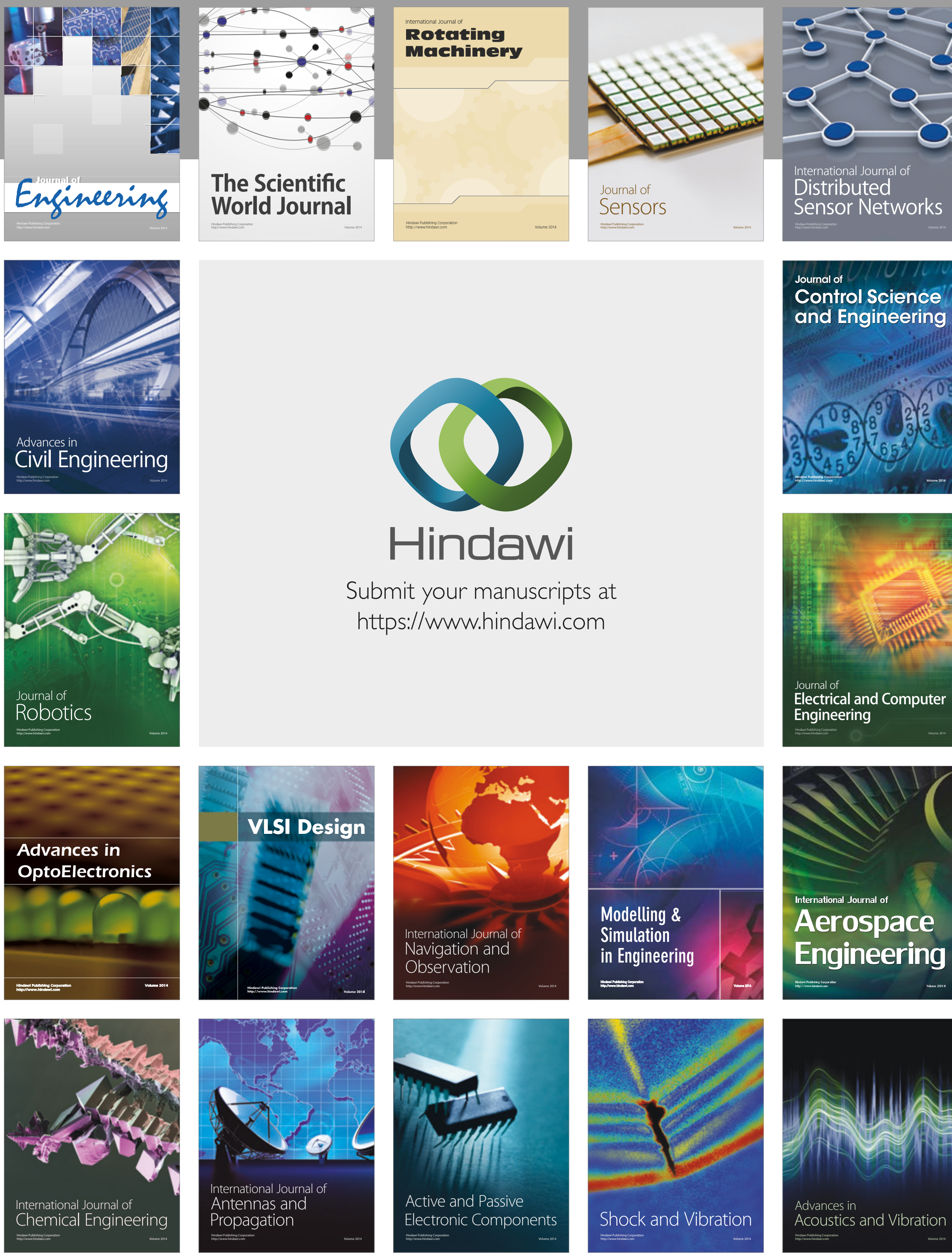
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