Experimental and numerical study on transient air-water mixing flows in viscoelastic pipes

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ABSTRACT

Air-water mixing flows are commonly formed in pressurized water supply pipes due to dissolved air from the water under low pressure conditions and injected air through system controls and associates such as valves and pumps. This paper investigates transient behaviours of air-water mixing flows in viscoelastic pipes through laboratory experimental tests, numerical modelling and theoretical analysis. Two numerical schemes – the discrete vaporous cavity model (DVCM) and the discrete gas cavity model (DGCM), which are firstly calibrated and validated by the experimental data gained in this study, are adopted for comparative study for their validity and accuracy for transient air-water mixing flows in viscoelastic pipes. With the validated model, systematic analysis is then performed for understanding the influences of different factors, including unsteady friction, pipe-wall viscoelasticity and air content, on transient air-water mixing flows. Finally, the obtained results and implications are discussed through theoretical analysis conducted in this study.

Keywords: Air content; Air-water mixing flow; Transients; Unsteady friction; Viscoelasticity.

1 Introduction

Water is the basic need for human daily life and social progress, and its conveyance and distribution are more and more important to civilization advance and urban development. For this purpose, water supply pipeline becomes one of the essential elements in urban water distribution systems (UWDS). Nowadays, different types of water pipes have been developed and used commonly for UWDS, such as metallic and viscoelastic pipes. In particular, viscoelastic pipes, e.g., PE, HDPE, PVC, are more and more frequently used due to the convenience and economics of construction and management. For example, it was reported that the use of viscoelastic pipes in UWDS has attained to about 27% in USA and 43% in Canada (Folkman, 2012). In China, it has been proposed in the 10th national five-year plan that viscoelastic pipes would take over 70% in all pipe materials in UWDS (Ministry of Housing and Urban-Rural Development of the People's republic of China [MOHURDC], 2000). Therefore, understanding and investigation of flowing states (steady and unsteady) in such viscoelastic pipes are important and helpful to the effective design and operation of UWDS.

Transient flows have been widely studied in the literature for water supply pipelines in UWDS, where different models and methods have been developed for the simulation and analysis of pipe flow systems (Ghidaoui, Zhao, McInnis, & Axworthy, 2005). Among these studies, most of them are mainly focused on the elastic (metallic or concrete material) pipelines, where the effect of pipe-wall deformation or viscoelasticity has been neglected for transient flow analysis. Recently, few studies have investigated systematically the effect of pipe-wall viscoelasticity on transient pipe flows, in which the conceptual model (e.g., Kelvin-Voight model) has been commonly proposed to mimic the viscoelastic effect during transient flow process (Covas et al., 2005; Covas, Stoianov, Ramos, Graham, & Maksimovic, 2004; Duan, Ghidaoui, Lee, & Tung, 2010a, 2012a; Duan, Ghidaoui, & Tung, 2010b; Meniconi, Brunone, & Ferrante, 2012; Meniconi, Brunone, Ferrante, & Massari, 2014). Despite of full calibrations and various validations, the proposed viscoelastic transient model has only been applied to relatively simple flow and system situations. Particularly, only the pure water (single phase) flow has been commonly inspected in those previous studies. But other complex scenarios, such as air-water mixing flows, have not yet been systematically investigated for the validity and importance of the developed viscoelastic model under different systems and flow conditions (Soares, Covas, & Carriço, 2012). From this perspective, further understanding and systematic analysis of such complex factors in viscoelastic pipelines are essential and important to fill the gap and extend the applicability of current theory and practice of transient pipe flows.

Actually, air can be commonly involved in water supply pipelines such as the air release from water under low pressure conditions and air injection/trapping from system devices and associates (e.g., pumps and valves) (Escarameia, 2007; Falvey, 1980; Pothof & Clemens, 2010, 2011; Pozos, Gonzalez, Giesecke, Marx, & Rodal, 2010; Wylie, 1984). Previous studies have demonstrated from experiments and simulations that air in water supply system may cause different problems (Wiggert & Sundquist, 1979). Specifically, under steady-state condition, the trapped air may form as moveable blockages so that the water conveyance capability of pipelines can be greatly reduced (Escarameia, 2007; Lubbers, 2007; Pothof & Clemens, 2008). Meanwhile, air-water mixing can also speed up the corrosion process of metallic materials and thus shorten the span-life of pipes and devices (Cole & Marney, 2012; Mcneiill & Edwards, 2001). Under transient (highly unsteady) conditions, air content may have great influence on the transient responses, so that the simulation results by current transient models, which have not yet fully included such air-water mixing effect, could be overestimated/underestimated for transient design and management of pipe system (such as for pipe strength design and pipe condition assessment) (Duan, 2015; Duan, Tung, & Ghidaoui, 2010c; Ferrante & Brunone, 2003a, 2003b; Lee, Lambert, Simpson, Vítkovský, & Liggett, 2006; Lee, Vítkovský, Lambert, Simpson, & Liggett, 2007). Nevertheless, in the literature, the air-water mixing flows have not yet well been studied for practical water supply conditions, especially under transient flow and viscoelastic pipe conditions. Therefore, it is necessary and crucial to study and analyze the characteristics of transient air-water mixing flows in viscoelastic pipes, so as to in-depth understand the influences of different factors on transient pipe flow modelling and analysis. This is the research scope of this study.

In this paper, laboratory experiment system is firstly established for investigating the transient air-water mixing flows in viscoelastic pipes, and the test results are used for careful calibration and validation of the transient viscoelastic and friction models adopted in this study. In order to accurately simulate the air-water mixing effect in pipes, two commonly used numerical schemes from the literature – the discrete vaporous cavity model (DVCM) and the discrete gas cavity model (DGCM) are considered and examined through the comparison with experimental data from the literature and obtained in this study. The validated model is then used to systematically analyze different factors, including unsteady friction, pipe-wall viscoelasticity, and air content that are commonly shown in water supply pipes, for their influences and relative importance to the transient responses in UWDS. In the meanwhile, the validity and accuracy of the two numerical methods of DVCM and DGCM are examined for the simulation of transient air-water mixing flows in viscoelastic pipes. Finally, the results and findings of this study are discussed for the practical implications to the design and management of UWDS.

2 Laboratory Experimental Setup

Laboratory experimental test system was established for this study, which consists of water supply tank, viscoelastic pipeline, discharge water tank, air compressor, and controls and measurement facilities. The schematic of the test system is shown in Fig. 1. The testing viscoelastic pipeline is made of Plexiglas material with a total length of 36.0 m, an inner diameter of 90 mm and a wall thickness of 10 mm (i.e., 4-inch pipe). By aforehand testing, the elastic modulus of the testing pipe material is about 2.684 GPa and the Poisson ratio for this testing pipeline system is about 0.358. During the tests, the water is supplied from the upstream tank to the pipeline and discharged into the downstream tank, and then recycled by a pump system to the upstream tank in order to maintain the steady and constant supply pressure head in the system (at about 5.3 m at the upstream tank). The pipe system is well fixed onto the ground through a number of iron stands along the pipeline. For accurate measurement and comparative analysis, four pressure transducers (with precision: 0.2%, range: -10~60 m, frequency response: 1000 Hz) are installed along the pipeline as shown in Fig. 1.

For testing, the water flow in the pipeline can be controlled and adjusted by the electric ball valve at the downstream end, and the initial steady state flow rate can be accurately measured by an ultrasonic flowmeter installed at the outlet of the supply tank at the upstream. Meanwhile, for testing air-water flows, the air is compressed by the air compressor installed through a side pipe branch (as shown in Fig. 1) and injected into the pipeline at the upstream of testing pipeline with its velocity (air content) measured by a gas rotameter. To mimic the real-life water supply system and to achieve the air-water mixing flows in this study, the air injected into the pipeline are fully mixed with water flow from the upstream, which results in uniformly distributed bubbly flows with different air contents in the pipeline under the pressurized state. The cases of relatively large air cavities or air columns are not considered in this study, and therefore will not be shown (by mixing control in the system) in the tests under both steady and transient conditions concerned in this paper.

The transients in the test system are caused by the fast and complete closure of the butterfly valve located at the downstream of the testing viscoelastic pipeline. At the same, the air injection from the air compressor is ceased for the induced transient flow system. The duration of valve closure is estimated at about 0.90 s for all tests in this study, which is recorded and calibrated by a high-speed camera with precision of 15 FPS (Frame per Second). The pressure signals from the four transducers are collected by the Advantech USB-4711A data acquisition card with sampling frequency of 1000 Hz. In this paper, only the measurements at T4 (close to downstream end) are used and discussed for this study.

3 Transient Models & Numerical Methods

3.1 1DTransient Model

As designed in laboratory experimental tests above, the air content (also termed as void fraction in the literature) of air-water mixing flows is relatively small for all tests concerned in this study (e.g., 0~3%). Therefore, the air-water mixing flows can be modelled as bubbly flows with the assumption that the air-water mixture is a type of homogeneous pseudo-fluid, in which all the physical properties of this pseudo-fluid are the weighted average values of these two phases (air and water). Taking the pipe-wall viscoelasticity into consideration, the governing equations of one-dimensional (1D) transient model used for expressing such air-water mixing flows can be expressed as (Covas et al., 2005):

$$\frac{\partial H}{\partial t}+V\frac{\partial H}{\partial x}+\frac{a^2}{g}\frac{\partial V}{\partial x}+\frac{2a^2}{g}\frac{\partial \varepsilon_r}{\partial t}=0, \quad (1)$$

$$\frac{\partial H}{\partial x}+\frac{1}{g}\left(V\frac{\partial V}{\partial x}+\frac{\partial V}{\partial t}\right)+h_f=0, \quad (2)$$

where H is the piezometric head, x is the spatial coordinate, g is the gravitational acceleration, V is the fluid (mixture) velocity, t is the temporal coordinate, h_f is the pipe frictional loss, a is the wave speed, ε_r is the retarded strain of viscoelastic pipe-wall. Since the wave speed for air-water mixing transient flow can usually be greatly affected by the air content, i.e., becoming much smaller than original single phase water flow (Duan et al., 2010c; Wylie, Streeter, & Suo, 1993), the convective terms in Eq. (1) and (2) are included for the analysis so as to improve the accuracy of numerical simulation. The traditional method of characteristics (MOC) with fixed grid interpolation scheme is applied in this study to solve the above 1D transient model. The details of the friction and viscoelastic models will be presented later in this paper.

To represent the air-water interaction during transient flow process, two commonly used simulation schemes for expressing air cavity dynamics – DVCM and DGCM are adopted in this study with the expressions of wave speed (a) of air-water mixture defined respectively as follows (Wylie et al., 1993):

- For the scheme of DVCM:

$$a = \frac{1}{\sqrt{\rho_l \left(1-\alpha\right)\left(\frac{1}{K_l}+\frac{\alpha}{K_g}+\frac{D}{Ee}C_1\right)}}, \tag{3}$$

where ρ_l is the density of water phase, α is the instantaneous air content (void fraction), K_l is the bulk modulus of water, K_g is the bulk modulus of air, D is the pipe inner diameter, e is the pipe wall thickness, E is the elastic modulus of pipe material, and C_1 is a parameter related to the pipe constraints, and in this study, for completely fixed pipeline,

$$C_1 = \frac{2e}{D}\left(1+\mu\right)+\frac{D}{D+e}\left(1-\mu^2\right) . \tag{4}$$

- For the scheme of DGCM:

$$a = \frac{1}{\sqrt{\rho_l \left(1-\alpha_0\right)\left(\frac{1}{K_l}+\frac{\alpha}{P}+\frac{D}{Ee}C_1\right)}}, \tag{5}$$

where α_0 is the initial air content (void fraction), P is the absolute pressure, and $P = \rho gH$, and H_v the vacuum pressure.

3.2 *Friction Model*

As indicated in the literature (e.g., Duan et al., 2012a; Vardy & Brown, 1996), pipe friction effect during transient flow process is usually divided into two parts: (1) the quasi-steady friction, which is modelled by Darcy-Weisbach formula in this study, and (2) the unsteady friction, which can be simulated by different types of models (Ghidaoui et al., 2005), and in this study, the weighting function based unsteady friction by Vardy and Brown (1996) is used for the demonstration. Thus, the total frictional losses due to these two friction components can be expressed as follows:

$$h_{fs} = \begin{cases} \dfrac{fV|V|}{2gD} & (\mathrm{Re} > 2000) \\ \dfrac{32\nu V}{gD^2} & (\mathrm{Re} \le 2000) \end{cases}, \tag{6}$$

$$h_{fu} = \frac{16\nu}{gD^2}\int_0^t \frac{\partial V}{\partial t^*} W\left(t - t^*\right) dt^*, \tag{7}$$

in which h_{fs} and h_{fu} are frictional loss components from quasi-steady and transient friction effects respectively; f is the Darcy friction factor; Re is the Reynolds number of initial flow state; v is the kinematic viscosity of fluid mixture; W is the weighting function that represents the historical flow effect, with its expression shown in Vardy and Brown (1996). To efficiently implement the convolutional unsteady friction model into the MOC-based numerical scheme, the following iterative form is applied for Eq. (7) (Vítkovský, Stephens, Bergant, Lambert, & Simpson, 2004):

$$h_{fu} = \frac{16\nu}{gD^2}\sum_{k=1}^{N} y_k(t), \tag{8}$$

$$y_k(t+\Delta t) = e^{-n_k\frac{\Delta\tau}{2}}\left\{ e^{-n_k\frac{\Delta\tau}{2}} y_k(t) + m_k\left[V(t+\Delta t) - V(t)\right]\right\}, \tag{9}$$

Where Δt is the time step of the iterative calculation, $\Delta\tau = K\Delta t$, $K = 4v/D^2$, m_k and n_k are the parameters obtained through experimental calibrations shown in Vítkovský et al. (2004).

3.3 Viscoelastic Model

The retarded strain of viscoelastic pipe-wall deformation is usually described by the Kelvin-Voigt (K-V) model which derived from a conceptual model consisting of a combination of spring and dashpot elements to mimic the viscoelastic behavior. As a result, after appropriate discretization in MOC-based numerical scheme, the term of $\partial\varepsilon_r/\partial t$ in Eq. (2) can be calculated as follows (Covas et al., 2005; Duan et al., 2010a, 2010b):

$$\frac{\partial\varepsilon_r(x,t)}{\partial t} = \sum_{k=1,\ldots,N} \frac{\partial\varepsilon_{rk}(x,t)}{\partial t}, \tag{10}$$

$$\frac{\partial\varepsilon_{rk}(x,t)}{\partial t} = \frac{J_k}{\tau_k}\frac{C_1\rho g D}{2e}\left[H(x,t) - H_0(x)\right] + \frac{\varepsilon_{rk}(x,t)}{\tau_k}, \tag{11}$$

$$\begin{aligned}\varepsilon_{rk}(x,t) = J_k F(x,t) - J_k e^{-\Delta t/\tau_k} F(x,t-\Delta t) \\ - J_k \tau_k \left(1 - e^{-\Delta t/\tau_k}\right) \frac{F(x,t) - F(x,t-\Delta t)}{\Delta t} \\ + e^{-\Delta t/\tau_k} \varepsilon_{rk}(x,t-\Delta t)\end{aligned} \quad , \qquad (12)$$

Where N is the number of Kelvin-Voigt elements; ρ is the weighted average density of air-water mixture, J_k is the creep-compliance of the spring in the k-element, τ_k is the retardation time of the dashpot in the k-element. Particularly, the parameters of J and τ represent the viscoelastic behavior of plastic pipes, which are determined by experimental calibrations in this study.

With the implementation of above friction and viscoelastic models into the MOC-based 1D transient model, the numerical schemes of DVCM and DGCM for expressing the air dynamics in air-water flows can be comparatively studied for their validity and accuracy based on the laboratory experimental data obtained in this study. After the verification and validation, the numerical model is then used to systematically investigate the transient air-water mixing flows in viscoelastic pipes so that different influence factors can be quantified for their importance to the pipe fluid transients in UWDS, which is the objective of this study.

4 Model Calibration and Validation

4.1 Viscoelastic Parameters Calibration

Prior to the application of viscoelastic model for transient pipe flows, it is necessary to calibrate and validate the model parameters, in order to examine and confirm the reliability and accuracy of the used model and method. In this study, the numerical program framework of 1D transient model is firstly validated by the worked case in the literature and then the viscoelastic parameters (J & τ) of the used pipeline in this study are calibrated by the experimental data from the measurement in Fig. 1. The cases of single water phase only (without air in the pipe flow) are adopted for this validation and calibration purpose. Particularly, the MOC-based numerical scheme for the transient model in Eq. (1) and (2), where the convective terms are included, under the developed program framework of DVCM and DGCM schemes, is validated by the experimental test from Covas et al. (2005). The comparative results of the selected test case from Covas et al. (2005) are shown in Fig. 2. The results confirm the reliability and accuracy of the developed numerical framework. Meanwhile, the results also demonstrate that the two schemes of DVCM and DGCM can provide the very similar accuracy for the case of single water phase only (almost on the top of each other in Fig. 2). While for the situation of transient air-water mixing flow, further validation of these two schemes is performed later in this paper.

Furthermore, the developed method framework is then applied to the viscoelastic pipe condition tested in the experiment system of this study. By applying the similar calibration process in the literature (e.g., Covas et al., 2005; Duan et al., 2010a), the viscoelastic parameters of the used viscoelastic pipe under the test condition of initial velocity $V = 0.9$ m/s (see Fig. 1, and case no. 1 in Table 1 later in this study), are obtained as follows: $\tau_1 = 0.05$s, $\tau_2 = 0.5$s and $\tau_3 = 1.5$ s; $J_1 = 0.00839\times10^{-9}$ Pa^{-1}, $J_2 = 0.3504\times10^{-9}$ Pa^{-1} and $J_3 = 0.3552\times10^{-9}$ Pa^{-1}.

The comparative results of experimental test and numerical simulation are shown in Fig. 3. Similarly, for the case of single water phase only considered herein, the results of the two schemes of DVCM and DGCM are almost the same, and thus only the result of DVCM is plotted in Fig. 3 for illustration. The results of Fig. 3 confirm again the reliability and accuracy of the developed framework and the calibrated viscoelastic parameters in this study.

It is also noted that in Fig. 3 the small difference is still shown between the experimental data and the numerical result, especially for the late stage of transient process (e.g., after 5 wave periods in Fig. 3 for this test case). By inspection, this discrepancy may be attributed to: (i) the accuracy of calibration process of viscoelastic parameters where the initial drastic transient data may play dominant role for the fitness evaluation; (ii) the accuracy of numerical model and method such unsteady friction model and MOC scheme; and (iii) the accuracy of experimental measurement, especially under the relatively small amplitude transient condition. More analysis and discussion about the accuracy and reliability of these viscoelastic transient models and numerical methods are conducted later in this study.

4.2 Numerical Scheme Validation

To validate and apply the developed transient model, the wave speed of test pipeline is a crucial parameter, which is verified by the comparison of experimental data and theoretical results in Eq. (3) for DVCM scheme and Eq. (4) for DGCM scheme. For different test scenarios concerned in this study, the values of wave speed determined by these three different ways are shown in Table 1. Particularly, for the case of pure or quasi-pure water case, the air content is set to 10^{-7} in the DVCM and DGCM schemes (i.e., almost zero air content), in order to implement and evaluate these two schemes. From the results of test case no. 1 in Table 1, which was used for the calibration of viscoelastic parameters in above section, the obtained results are nearly the same for these three methods. This good agreement result demonstrates the reliability and accuracy of the numerical implementation of the DVCM and DGCM schemes, and at the same time, confirms again the validity of the calibrated viscoelastic parameters in above section of this study.

Furthermore, the results of air-water mixing cases (i.e., no. 2 through no. 6 in Table 1) reveal that the theoretical result by the DVCM scheme agrees well with the experimental result (exact value), but obvious difference exists between the DGCM and measured data. Specifically, the result by the DGCM scheme is much higher than the exact value (or the result of the DVCM scheme), which means the formulation of the DVCM scheme is much more suitable (than the DGCM scheme) for capturing the characteristics of transient air-water mixing flows in viscoelastic pipes concerned in this study. This is mainly due to the possible vacuum/cavitation phenomenon during the transient process so that the DGCM scheme with Eq. (4) is not so accurate for the evaluation of average wave speed in the system. To explain and compare, the results of transient pressure head for test case no. 6 are used for detailed analysis and shown in Fig. 4. Similar results have been obtained for other air-water flow cases in this study.

On one hand, the results of Fig. 4 show clearly that the DVCM scheme can provide more accurate transient response result than the DGCM scheme, under the comparison of experimental data. Specifically, the result of DVCM agrees well with the experimental measurement data for both the phase and amplitudes of the transient trace, while the result of DGCM has overestimated the maximum positive amplitudes and wave period (phase) but underestimated the maximum negative amplitudes. On the other hand, the instantaneous wave speed by the DGCM in Fig. 4 indicates the obvious variation trend of wave speed induced by the local air content dependent pressure changes as expressed in Eq. (4), which results in the over-estimation of transient amplitude and wave period. From this perspective, the DVCM scheme is more reliable and accurate than the DGCM scheme to simulate the transient air-water mixing flow in viscoelastic pipes, which will be adopted in the following study.

It is also necessary to point out that the above comparison and validation of the used two schemes (DVCM and DGCM) is conducted under the condition of relatively mild air dynamics. That is, some drastic and extreme situations of air-water interaction have not yet been considered, such as complete column separation with large air cavities during the transient process. Consequently, the validity and accuracy of these two schemes for such extreme phenomena is out of the scope of this study, which needs further investigation in the future work.

5 Further Numerical Applications and Results Analysis

With the validation and calibration of the used numerical models and methods by experimental data, it is necessary to further investigate the influence and important of different practical factors to the transient air-water mixing flow responses (amplitude damping and phase/frequency shifting). To this end, the common factors of unsteady friction, pipe-wall viscoelasticity, and air content in water supply pipelines are analyzed in this study. Based on the above comparative analysis, only the numerical scheme DVCM is adopted for the numerical simulation in the following study.

5.1 Effects of Different Factors on Transient Amplitude Damping

The relative importance of the effects of steady friction (SF), unsteady friction (UF) and viscoelasticity (VE) on pressure damping has been investigated for pure water-phase flows in previous studies (e.g., Covas et al., 2005; Duan et al., 2010a). In this section, the influence of air content on such relative importance of these two common factors is further analysed for transient air-water mixing flows. To this end, three numerical simulation models by considering and including different factors (SF, UF, VE, and air content) are applied for the investigation, in order to highlight and separate the effect of each factor on transient responses. That is, Model I is for the combined effect of all three factors (SF, UF and VE); Model II for the combined effect of SF and UF only; and Model III for the combined effect of SF and VE only. The test cases no. 1 and no. 4 in Table 1 are adopted for comparative study, and the numerical results are plotted in Fig. 5. Note that the pressure head in Fig. 5 represents the relative value to the initial steady state pressure head.

On one hand, the results of Fig. 5(a) show that, under pure water-phase flow condition, the Model III (only SF and VE effects) can provide very close result of transient amplitude damping as the Model I (all SF, UF and VE effects), which indicates the UF effect has much less influence than the VE effect to the transient damping. The result is also confirmed by the relatively large discrepancy between the results of Model I and Model II, which is also consistent with the results and findings in the previous study of Duan et al. (2010a). From this perspective, it is indicated that the VE effect plays dominant and important role in transient flows of the viscoelastic pipeline investigated in this study (Fig. 1).

On the other hand, the result comparison of Fig. 5b reveals the very similar accuracy of the Model II and Model III under air-water mixing flow condition, with comparison to the full model I. The result demonstrates clearly the influence of air content in transient flows on the relative importance of UF and VE effects. In other words, the existence of air content in transient water flows may reduce greatly the influence of VE effect (and meanwhile increase relatively the importance of UF effect) on transient damping. This is mainly due to the compressibility of air component, which may offset partial pressurized effect on viscoelastic deformation of pipe-wall under transient condition. Therefore, it is necessary to systematically analyse and quantify the influence of air content on the relative importance of UF and VE to transient damping in pipe fluid transients.

With similar numerical analysis method, the results of transient responses can be obtained for different air content situations in transient pipe flows. In this study, to visualize and quantify such influence of air content, the relative importance of UF and VE for each specific air content condition is evaluated by the following expression defined in Duan et al. (2010a),

$$\text{UF/VE}\left(\%\right) = \frac{\text{Peak attenuation by UF}}{\text{Peak attenuation by VE}} \times 100 \;, \tag{13}$$

Based on Eq. (12), the relative importance of UF and VE is calculated for different air content cases and the results are plotted in Fig. 6, where Fig. 6a presents the results for relatively low air content cases (0~0.5%), and Fig. 6b for relatively high air content cases (0.6~1.0%). Actually, the similar influence trend has been obtained as in Fig. 6b from extensive numerical applications of higher air contents (e.g., 1.0~5.0%) in this study, which has been neglected due to the similarity of the analysis and conclusion as presented below.

The overall comparison between results of Fig. 6a and Fig. 6b implies the different variation trends of relative importance of UF and VE. Specifically, under relatively low air content condition in Fig. 6a, the relatively importance of UF and VE is decreasing with wave time (or peak number) (but except the first peak), while under relatively high air content condition in Fig. 6b, this relative importance value is increasing with wave time (or peak number). This is mainly because of gradual air escaping of air content from the transient air-water mixing flow, and thus the decreasing air content in the mixing flow, with wave propagation time. As a result, for relatively small value of initial air content (e.g., < 0.5% in the test pipeline in this study), the transient air-water mixing flow becomes quickly the pure or quasi-pure water-phase flow again after 2~3 wave cycles.

Furthermore, both results of Fig. 6a and Fig. 6b reveal the increasing trend of relative importance of UF and VE with air content, which indicates the effect of VE is decreasing with an increase of air content in transient pipe flows, which is mainly due to the increasing capacity of flow compressibility resulted from the air component under the pressurized flow condition. In other word, the existence of air content in transient pipe flows may greatly suppress the damping effect of VE. Particularly, the results of Fig. 6 show that the UF effect becomes relatively more dominant than VE effect on the overall transient amplitude damping when air content is larger than 0.8% in the viscoelastic pipeline of interest in this study (see Fig. 1). Consequently, the consideration and inclusion of air content influence is crucial to the modelling and analysis of transient pipe flows.

5.2 Effects of Different Factors on Transient Frequency Shifting

In addition to the transient amplitude damping, it has been shown in former studies the effect of VE on transient frequency shifting, and the frequency-dependent methods, such as the system frequency response function (FRF) method for pipe leakage and blockage detection (e.g., Duan, 2015; Duan, Lee, Ghidaoui, & Tung, 2012b). On this point, it is necessary to examine the influence of air content on such frequency shifting effect of VE in transient air-water mixing flows. To evaluate the frequency shifting effect, the peak frequencies of the FRF results obtained from the transient simulations are extracted and compared with the theoretical frequency of the elastic pipeline with equivalent settings as the test pipeline in this study, which can be defined as below (Duan et al., 2012b):

$$f_{Theo} = \frac{(2n-1)a}{4L} \ , \tag{14}$$

where f_{Theo} is the theoretical frequency, L is the length of pipeline, and n (n = 1, 2, 3…) is the number for the resonant peaks in the frequency domain. For illustration, the first five peaks from the FRF results are extracted and plotted in Fig. 7 for the case no. 1 in Table 1. The comparative results in Fig. 7 show clearly the frequency shifting effect from the VE from the original elastic pipe situation.

Similar to the transient amplitude damping analysis above, the frequency shift rate can be approximately assessed by following equation:

$$\text{Frequency deviation rate } (\%) = \frac{f_{Theo} - f_{Exp}}{f_{Theo}} \times 100 , \tag{15}$$

where f_{Exp} is the peak frequency extracted from the numerical simulation or experimental data. Meanwhile, the averaged value of frequency shifting rate for the first five peaks is used for the evaluation. Accordingly, the average frequency shifting rate of VE effect only for the test case no. 4 in Fig. 7 is about 2.11%. In comparison with the transient damping results in Fig. 5a, this frequency shifting rate of VE effect is relatively small, which is mainly due to relatively short length of testing pipeline in this study (Fig. 1), and thus results in the time scale of wave propagation is much smaller than that of viscoelastic deformation based on the understanding of physical mechanism of viscoelasticity provided in Duan et al. (2010b).

Applying the same analysis procedure and evaluation method in Eq. (15), the results of frequency shifting rate for the cases of different air content are obtained and plotted in Fig. 8 for comparison. The results demonstrate clearly the significant influence of air content on the transient frequency shifting. Specifically, the frequency shifting effect of air content, from 30% to 75% in Fig. 8, is much more dominant than that of VE effect only (about 2.11% in Fig. 7). Moreover, the results in Fig. 8 also indicate that, with the existence of air content, the frequency shifting effect of VE is negligible for the viscoelastic pipeline considered in this study (Fig. 1). Consequently, by combining with the former results in terms of amplitude damping, it can be concluded that the existence of air content in transient pipe flow may suppress significantly the influence of VE effect on both transient amplitude damping and frequency shifting.

To explain, the variation of wave speed during the transient process can be calculated from the DVCM model and is also shown in Fig. 8 for the analysis. The result shows clearly the significant reduction trend of wave speed due to the existence of increasing air content in the pipe flows, which therefore induces the significant transient phase change in the time domain and the large transient frequency shifting in the frequency domain (Duan et al., 2012b; Wiggert & Sundquist, 1979). Consequently, this result confirms again the necessity and importance of including air content for transient modelling and utilization (e.g., leakage and blockage detection).

Furthermore, the variation of the influence of air content on wave speed and thus on the frequency shifting can be explained through the analytical analysis for Eq. (3) in this study. It is also clear from Eq. (3) that the dependence of average wave speed on different parameters of fluid and pipe properties (e.g., air content α, and size-thickness ratio $\beta = D/e$) can expressed as follows:

$$\frac{\partial a}{\partial \alpha} = -\frac{1}{2}\rho_l a^3 \left[\left(\frac{1}{K_g} - \frac{1}{K_l} - \frac{DC_1}{Ee}\right) - \frac{2\alpha}{K_g}\right], \quad (16)$$

$$\frac{\partial a}{\partial \beta} = -\frac{\rho_l (1-\alpha)(1-\mu^2)(\beta^2 + 2\beta) a^3}{2E(1+\beta)^2}. \quad (17)$$

It is concluded from Eq. (16) and (17) herein that $\partial a/\partial \alpha \leqslant 0$ when $\alpha \leqslant 50\%$, $\partial a/\partial \alpha \geqslant 0$ when $\alpha \geqslant 50\%$ and $\partial a/\partial \beta < 0$ with considering that $\alpha \leqslant 1$ and $\mu \leqslant 1$.

These analytical results clearly demonstrate the different variation trends of wave speed (and thus the frequency shifting from the original elastic pipe case) with different parameters in the system. In details, the wave speed is decreasing (and thus the frequency shifting rate is increasing) with air content when $\alpha \leqslant 50\%$, which is the situation inspected formerly in this study (Fig. 6). This result is consistent with the former numerical results observed in Fig. 8. On the other hand, it is also indicated from this analytical analysis that for some extreme cases with $\alpha \geqslant 50\%$, the opposite variation trend of wave speed and frequency shifting rate will be achieved. Particularly, the frequency shifting rate will be decreasing with air content when $\alpha \geqslant 50\%$, which is however out of this scope of this study because the used numerical model (DVCM & DGCM) may not be valid for such extreme cases. Meanwhile, the results also provide useful implications that the frequency shifting rate under the existence of air content is affected by pipe size scales (D, e), which has been indicated similarly in the previous study of Duan et al. (2010b). Specifically, the extent of frequency shifting in transient air-water mixing flows is increasing with size-thickness ratio (β), which means more severe frequency will be resulted from relatively larger pipes under same other system and flow conditions. Moreover, the analytical results of Eq. (16) and Eq. (17) also imply that the importance and influence of air content (α) and pipe size scale (β) on the transient responses of air-water mixing flows are dependent on each other.

6 Summary and Conclusions

This paper investigates transient air-water mixing flows in viscoelastic pipes through laboratory experimental tests and numerical simulations. The numerical models with different simulation schemes for representing the air content effect are firstly calibrated and validated by the experimental data obtained in this study. The results show that the calibrated viscoelastic model is valid for accurately reproducing the transient flow responses for the viscoelastic pipeline tested in this study. Meanwhile, the two numerical schemes (DVCM and DGCM) can be successfully implemented and applied into the proposed MOC-based transient simulation framework. The comparison of results from the numerical simulation by the validated models and the experimental test data demonstrates that the DVCM scheme is more suitable and accurate than the DGCM scheme for the simulation of transient air-water mixing flows in the viscoelastic pipeline considered in this study.

The validated model and the DVCM scheme are then applied for further numerical analysis, in order to examine the influences of different factors, including unsteady friction (UF), viscoelasticity (VE) and air content, on transient amplitude damping and frequency shifting. On one hand, the systematic numerical analysis implies the significantly decreasing trend of VE effect (relative to UF effect) with the increase of air content, due to the additionally induced compressibility of air component in transient pipe flows. On the other hand, the results and analysis indicate that frequency shifting rate of VE effect is negligible in comparison with that of air content. Furthermore, the analytical analysis regarding to the dependent of wave speed on different parameters in viscoelastic pipe flow systems demonstrates that frequency shifting effect is increasing with the pipe size scale (size-thickness ratio), but not always monotonically varying with air content.

The results and analysis of this study demonstrate that the existence of air content can greatly influence and suppress the effect of VE in both aspects of transient amplitude damping and frequency shifting in transient pipe flows. The findings of this study may provide additional implications to the design and management of water supply pipe systems where air is usually unavoidable in the system. Finally, it is also noted that only the homogenous air-water mixing flows are considered in this study, and further experimental and numerical investigations are required in the future work for more complex air-water two phase flows in urban water supply systems.

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Notation

a = wave speed (m)

D = pipe diameter (m)

e = pipe-wall thickness (m)

E = Young's modulus of elasticity of the pipe (Pa)

f = Darcy friction factor (-)

f_{Theo} = theoretical frequency of the test pipeline (Hz)

f_{Exp} = peak frequency extracted from the numerical simulation (Hz)

g = gravity acceleration (ms^{-2})

h_f = frictional loss per unit length (-)

h_{fs} = frictional loss due to quasi-steady friction (-)

h_{fu} = frictional loss due to transient unsteady friction (-)

H = piezometric head (m)

J_k = creep-compliance of the spring in the k-element in K-V model (Pa^{-1})

K_g = bulk modulus of the air (Pa)

K_l = bulk modulus of the water (Pa)

L = length of the pipeline (m)

Re = Reynolds number of initial flow (-)

t = temporal coordinate (s)

V = velocity of fluid mixture (ms^{-1})

x = spatial coordinate (m)

α = air content (-)

α_0 = initial air content (-)

β = size-thickness ratio (-)

ε_r = retarded strain of pipe-wall (mm^{-1})

μ = Poisson ratio of the pipe (-)

ρ = weighted average density of fluid mixture (kgm^{-3})

ρ_l = density of the water (kgm^{-3})

v = kinematic viscosity of the fluid mixture (m^{2}s^{-1})

τ_k is the retardation time of the dashpot in the k-element in K-V model (s)

Δt = time step of the iterative calculation (s)

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Figure & Table

Table 1 Comparison between experimental and theoretical wave speeds

Case No.	Air Content (m^3h^{-1})	Water Velocity (ms^{-1})	Void Fraction	Experimental Wave Speed (ms^{-1})	Wave Speed of DVCM (ms^{-1})	Average Wave Speed of DGCM (ms^{-1})
1	0	0.90	0%	492.19	492.81	492.75
2	0.5	0.90	2.37%	65.35	65.63	70.83
3	0.5	1.11	1.93%	73.16	72.41	80.33
4	0.5	1.30	1.65%	79.23	78.01	88.26
5	0.5	1.56	1.38%	86.07	85.01	100.45
6	0.5	1.73	1.25%	90.25	89.26	107.88

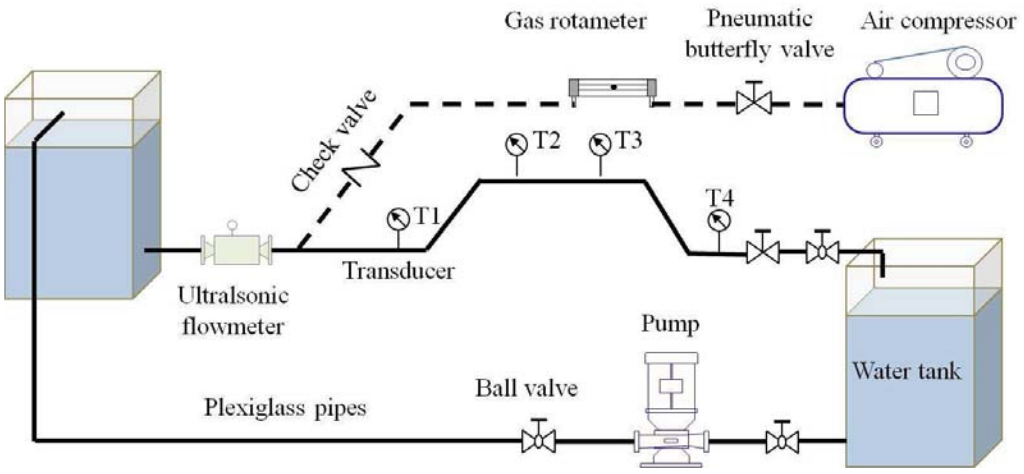

Fig. 1 Schematic diagram of the laboratory experiment system and measurement facilities

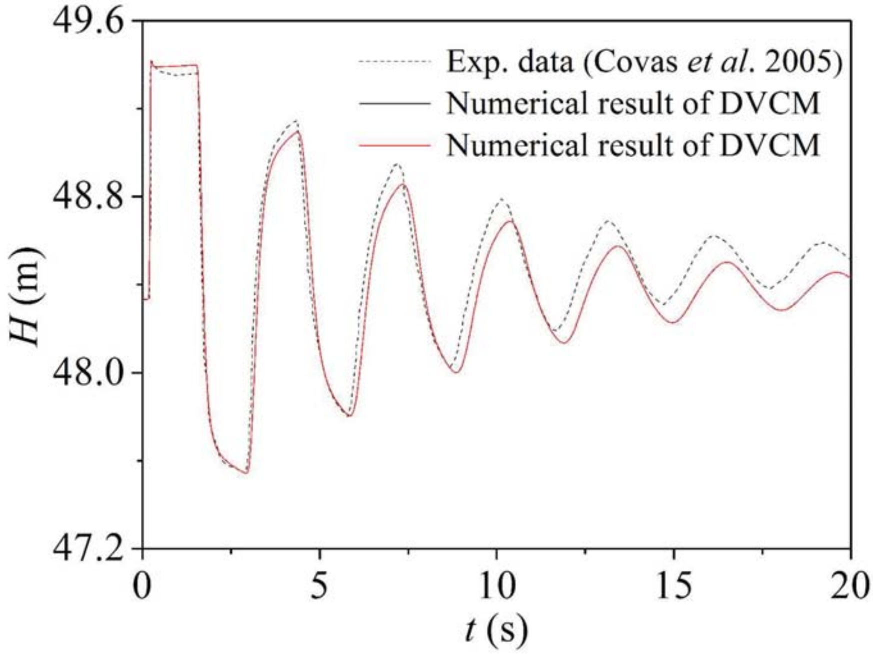

Fig. 2 Model calibration by experimental data in reference

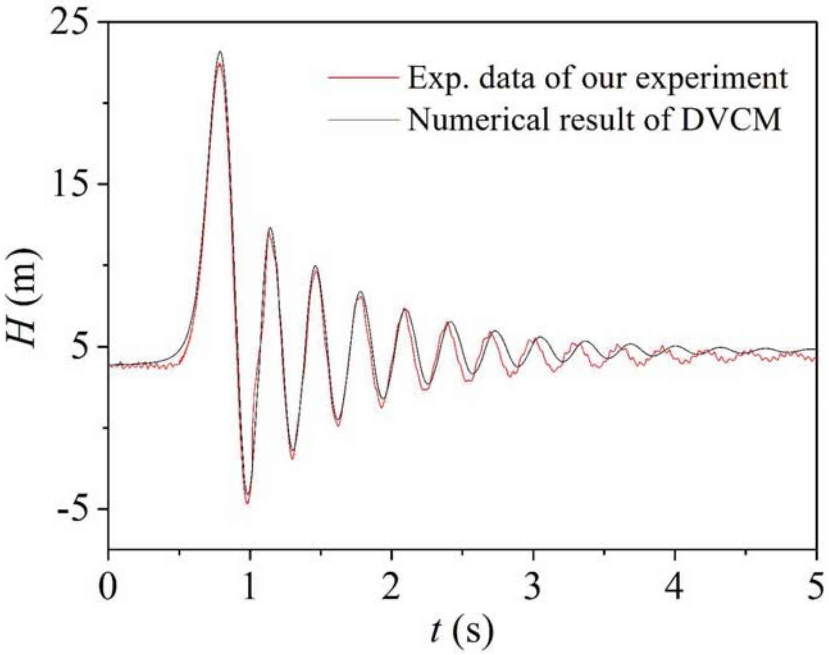

Fig. 3 Viscoelastic parameters calibration by single water transient flow

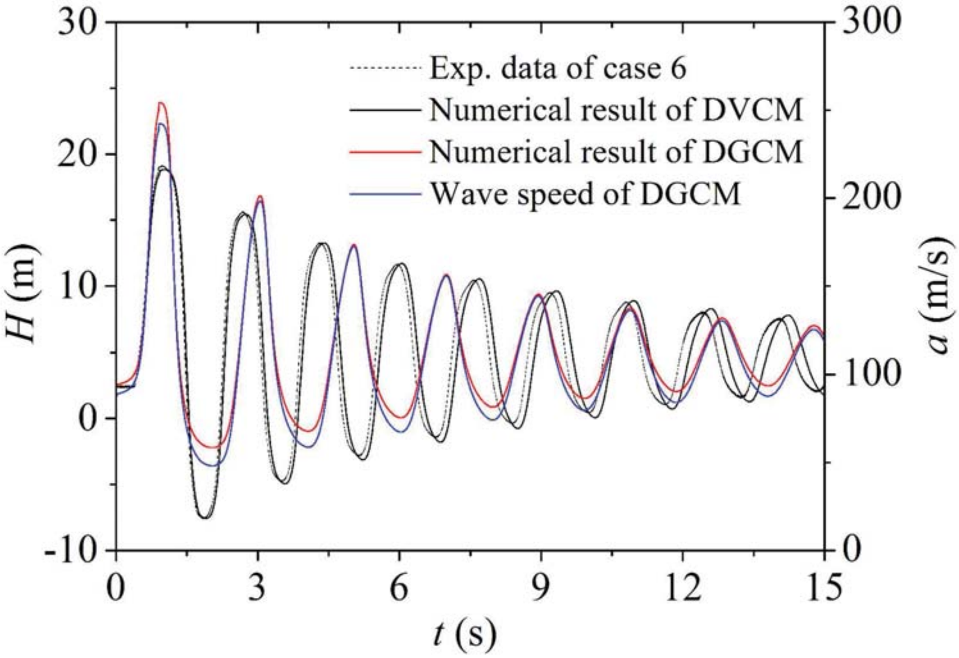

Fig. 4 Comparison among experimental and numerical results

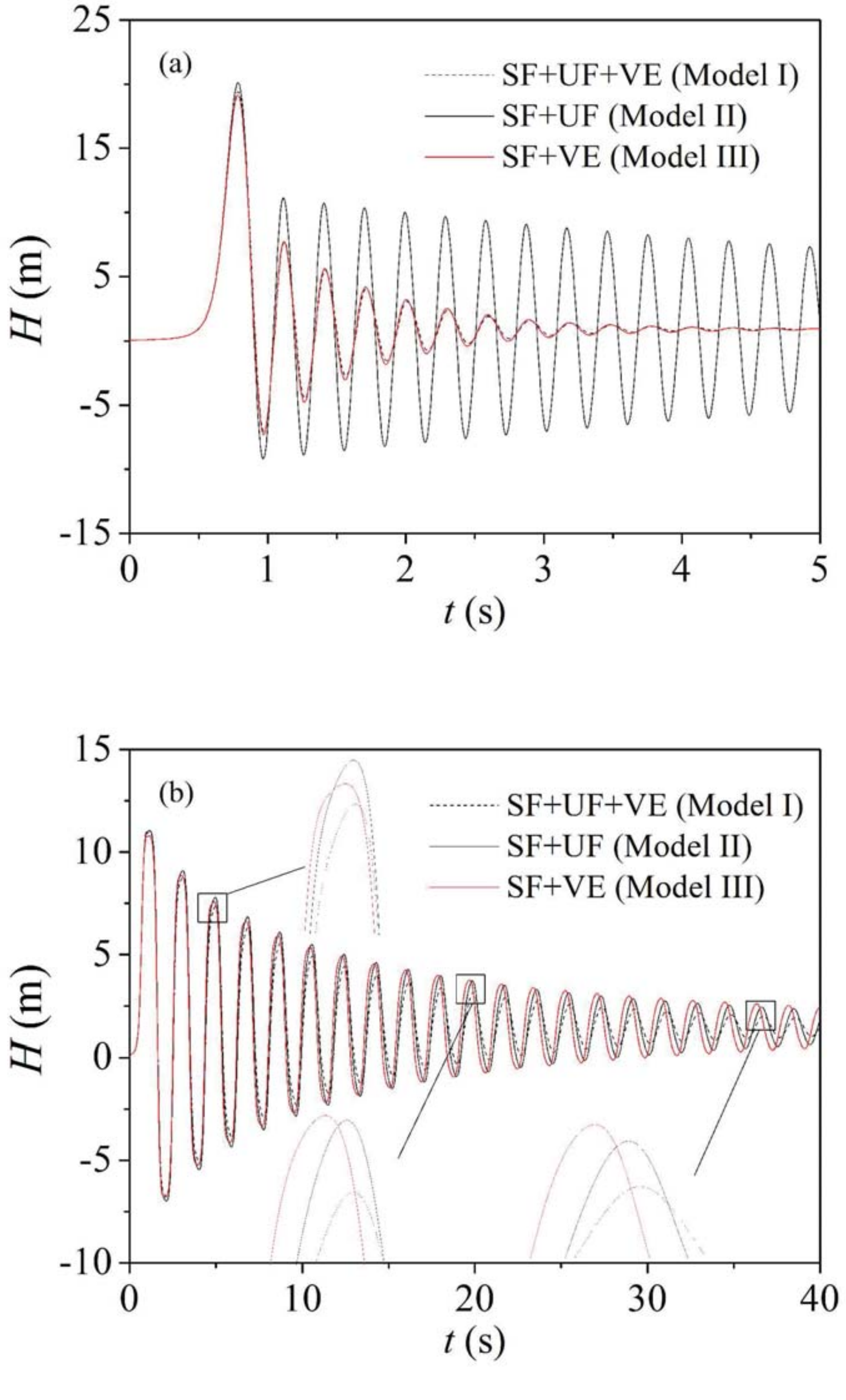

Fig. 5 Numerical results of transient responses by considering different influence factors for:

(a) case 1 (b) case 4

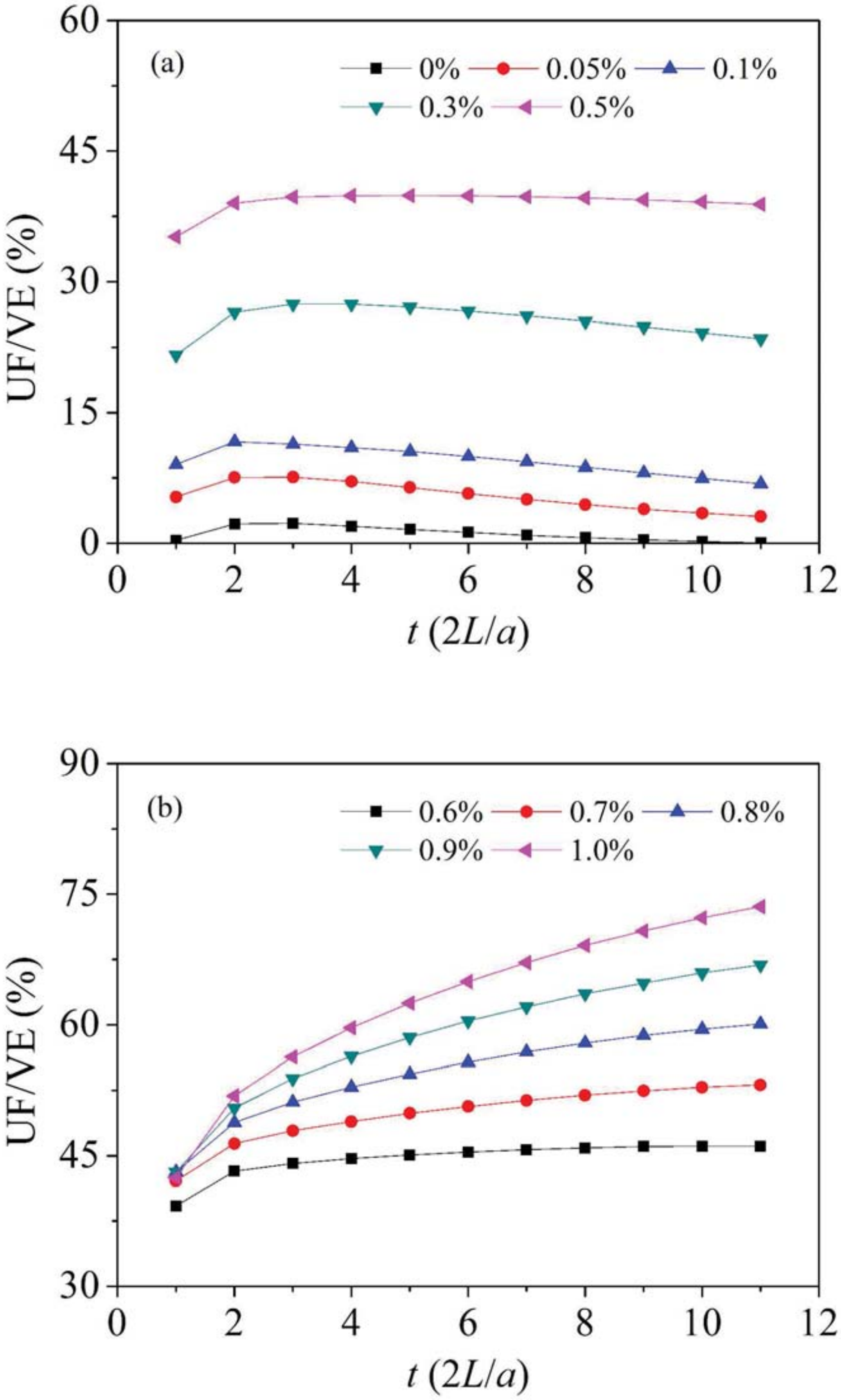

Fig. 6 Relative importance of UF and VE under different air content conditions: (a) for relatively low air content; (b) for relatively high air content

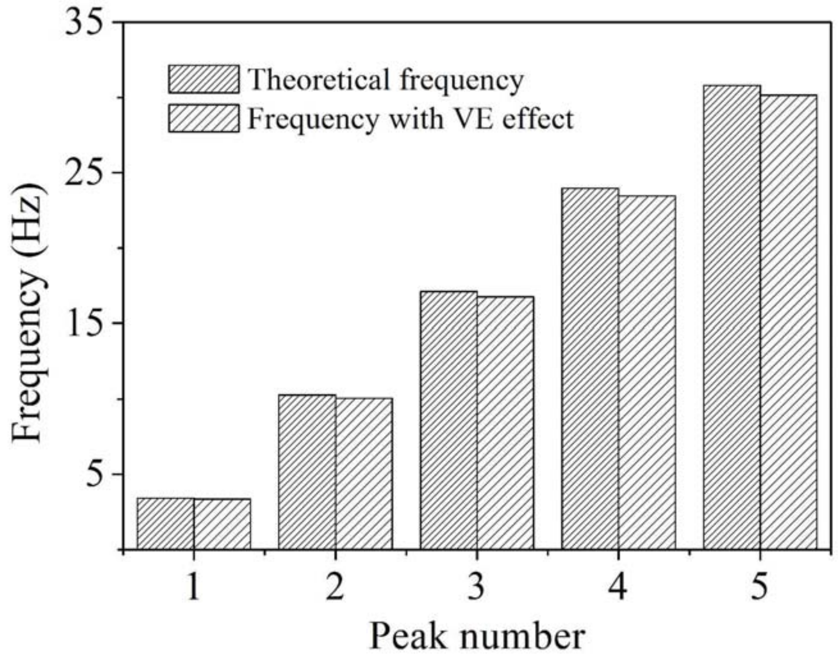

Fig. 7 Comparison between theoretical frequencies and frequencies with VE effect

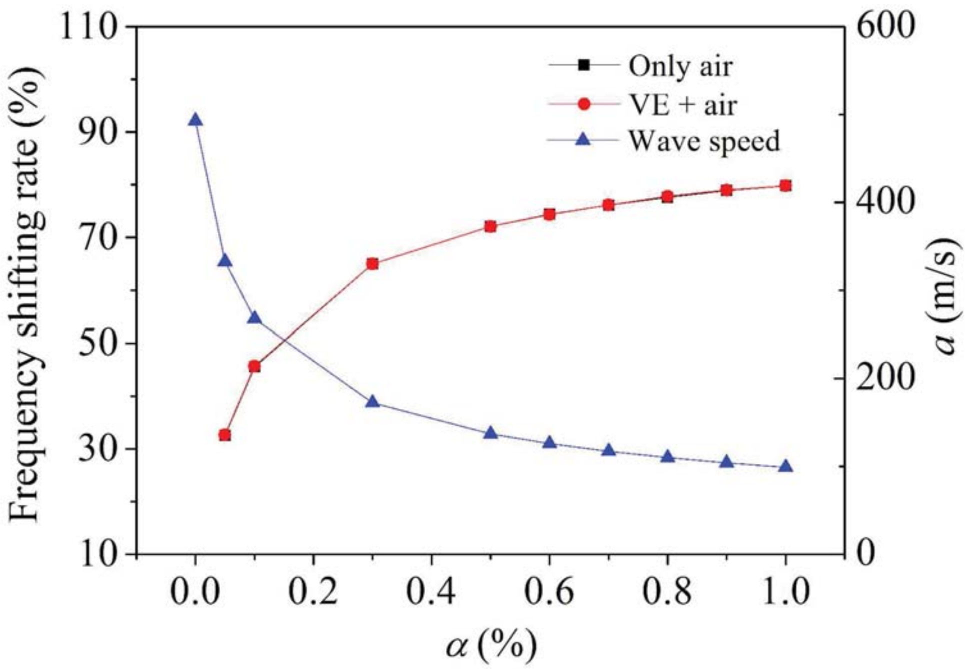

Fig. 8 Variation of frequency shifting rate and wave speed with air content