PIPELINE APPARATUS FOR INVESTIGATION OF WATER HAMMER AND COLUMN SEPARATION PHENOMENA AT THE UNIVERSITY OF MONTENEGRO

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Abstract

This paper presents recent developments in water hammer and column separation experiments conducted at the University of Montenegro. An experimental apparatus has been developed and constructed at the Laboratory for Energetic Processes. The system consists of a high pressure upstream end reservoir, a 54 m long steel pipeline with inner diameter of 18 mm, a fast closing electro-pneumatic valve that induces a transient event and a low pressure downstream end reservoir. Four dynamic pressure transducers have been installed along the pipeline for capturing high frequency pressure changes. In addition, electromagnetic and ultrasonic flow meters as well as two pressure transducers have been installed for evaluation of initial conditions. Pressure in the upstream end reservoir is kept constant during the water hammer event by compressed air. A high precision air pressure regulator is used for control of the initial pressure in the system. Transient cavitation and column separation phenomena have been observed in a number of experimental runs. A comparison between the experimental and numerical results, using the standard quasi-steady skin friction model, shows significant discrepancies in damping and timing of pressure pulses that may be contributed to unsteady friction effects. Future research priorities may be seen in the development of a numerical code for simulation of water hammer phenomena, including effects of transient cavitation and unsteady friction and its verification against results of measurements obtained in the newly developed experimental apparatus.

Introduction

The water hammer is propagation of pressure waves along liquid-filled pipelines resulting in a flow velocity change. The classical water hammer may be affected by a column separation and transient cavitation, unsteady friction, a fluid structure interaction (FSI effects) and a visco-elastic behaviour of pipe wall (Bergant *et al*., 2008). When the pressure, during the water hammer event, drops to the liquid vapour pressure, vapour bubbles occur. This effect is known as a transient vaporous cavitation. The fluid contains a small amount of free and released gas. The gas and vapour bubbles form pockets (cavities) which can break the fluid column at the system boundaries or at the high points – a phenomenon known as column separation (Wylie and Streeter, 1993; Bergant *et al*., 2006). The collapse of a vapour cavity may induce short-duration pressure pulses with values higher than the pressure initially given by the Joukowsky equation (Bergant and Simpson, 1999). The value of the friction factor during the water hammer event is different than its value during the steady flow. The friction factor can be expressed as a sum of two parts – steady and unsteady (Vardy, 1980). The unsteady part attempts to represent transient-induced changes in the velocity profile and it is important for fast transients (Bergant *et al*., 2001; Pezzinga and Brunone, 2006; He *et al*., 2008). For pipelines that are not completely fixed, FSI effects have to be taken into consideration (Tijsseling, 1996; Wiggert and Tijsseling, 2001). The viscoelastic behaviour is important in cases when the pipe is made from plastic materials such as polyethylene PE, polyvinyl chloride PVC and acrylonitrile butadiene styrene ABS (Covas *et al*., 2004, 2005; Soares *et al*., 2009). The experimental test rig at the University of Montenegro has been primarily developed for investigation of the transient cavitation, column separation and unsteady friction during the water hammer events.

Description of the Experimental Setup

The complex and flexible experimental apparatus for investigation of the water hammer effects, above all, the column separation and unsteady friction, has been developed and built in the Laboratory for Energetic Processes at the University of Montenegro. The design of the apparatus began in July 2010 and was finished by April 2011. The schematic layout of the apparatus is shown in Fig. 1. It consists of a high pressure upstream end reservoir (HPR), a 54 m long steel pipeline with inner diameter of 18 mm, a fast closing electro-pneumatic valve (EV) that induces transient events and a low pressure downstream end reservoir (LPR). In addition, the water hammer can be induced by a hand-operated valve (HV) which enables closure with different closing times. Both valves (EV and HV) are equipped with a sensor (VAS) which measures the change of the valve angle during its closing or opening. Four dynamic pressure transducers (DPT) have been installed equidistantly along the pipeline for capturing high frequency pressure changes. Dynamic pressure transducers are marked as D1 (next to the EV), D2 (18 m upstream from the EV), D3 (36 m upstream from the EV), and D4 (next to the HPR – see Fig. 1). For evaluation of initial conditions in the system, pressure transducers (SPT) are installed at the HPR and at the end of the pipeline just in front of the needle valve (NV) which has the role to define the initial system discharge. The initial discharge and consequently the average velocity are measured by electromagnetic (EF) and ultrasonic (UF) flow meters.

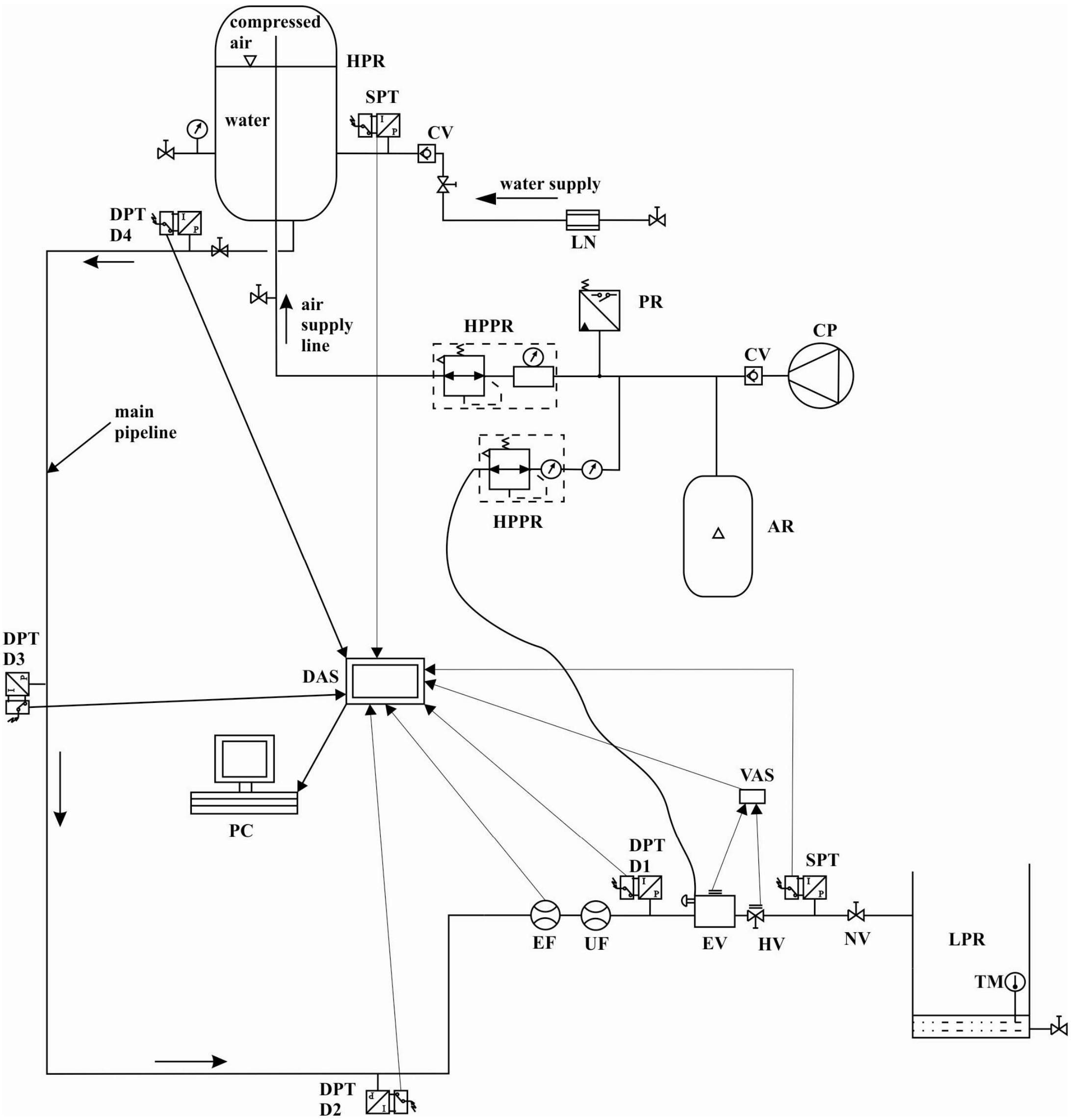

Figure 1: Schematic layout of the experimental setup

Pressure in the HPR is kept constant during the transient event by compressed air that is supplied from the compressor (CP) and the air reservoir (AR). The high precision air pressure regulator (HPPR) is used for control of the initial pressure in the system as well as for control of the EV closing and opening pressure. All measured data are collected by the data acquisition system (DAS) that is connected with PC. HPR is supplied with water from the tap water supply system. The lime-scale neutralizer (LN) and check valve (CV) are installed in the water supply line. The water temperature is continuously monitored by a thermometer (TM) installed in LPR.

The detailed description of the experimental apparatus and its components can be found in Jokić (2011).

Comparison of Experimental and Numerical Results

The experimental setup has been tested for a number of steady and transient flow conditions. Experiments have been performed for different initial pressures in the HPR and velocities in the pipe system. Each experiment has been carried out as follows: the initial pressure in HPR was adjusted and maintained during the transient test by a high precision air pressure regulator. After that, the initial discharge (velocity) in the pipe was adjusted by an appropriate opening of the needle valve. The water hammer was initiated by fast closing or opening using either the electro-pneumatic valve or the manual valve.

In this paper two different experimental tests results, with the corresponding numerical simulations, are presented. The first experimental run is a fast closing of the EV valve from the initial pressure in the HPR of p_r = 1 bar and the initial velocity in the system of V_0 = 1.24 m/s (Test DP1EVI1C). The flow for the Test DP1EVI1C is turbulent with Reynolds number Re = 22,320. The second run represents the fast opening of the EV valve with the adjusted pressure in the HPR of p_r = 4 bar and the final pipe velocity of V_f = 2.1 m/s (Test DP4EVI3O).

The water hammer is fully described by two hyperbolic partial differential equations, the continuity and the momentum equation (Eqs. 1 and 2).

$$\frac{\partial H}{\partial t}+\frac{a^2}{gA}\frac{\partial Q}{\partial x}=0 \qquad (1)$$

$$\frac{\partial H}{\partial x}+\frac{1}{gA}\frac{\partial Q}{\partial t}+\frac{fQ|Q|}{2gDA^2}=0 \qquad (2)$$

in which, H = piezometric head, Q = discharge, a = wave speed, A = pipe area, t = time, x = distance along the pipe, g = gravitational acceleration, D = pipe diameter. The water hammer equations are numerically solved by the Method of Characteristics (MOC). The occurrence of cavitation and column separation is simulated with Discrete Gas Cavity Model (DGCM) (Wylie, 1984; Wylie and Streeter, 1993). The calculated pressure wave speed in the piping system is a = 1402.7 m/s. The measured value of the pressure wave speed that is used in the numerical model is a = 1408.0 m/s. With this value adopted, an even number of pipeline reaches of N = 108 has been selected. The numerical time step is equal for both tests, Δt = 3.55x10^{-4} s. The friction losses in the pipe system are modeled by a standard quasi-steady friction factor with its initial value f_q = 0.025.

Figure 2 shows comparisons of heads at dynamic pressure transducer positions D1, D2 and D3 for Test DP1EVI1C. The EV valve measured closing time is t_c=0.023 s, which is shorter than the water hammer wave reflection time of $2L/a$ = 0.0767 s. The fast closing of the EV valve induces the water hammer with a liquid column separation. The existance of the a large vapour cavity at the valve is represented by a constant vapour pressure line. The maximum calculated head at the EV valve (DPT D1) H_{maxD1} = 179.0 m occurred when the first reflected wave arrived back to the valve. On the other hand, the maximum measured head of 181.5 m occured as a short duration pulse after the first cavity at the valve collapsed. The numerical model accurately demonstrates the experimental results of measurements of the first three pressure pulses.

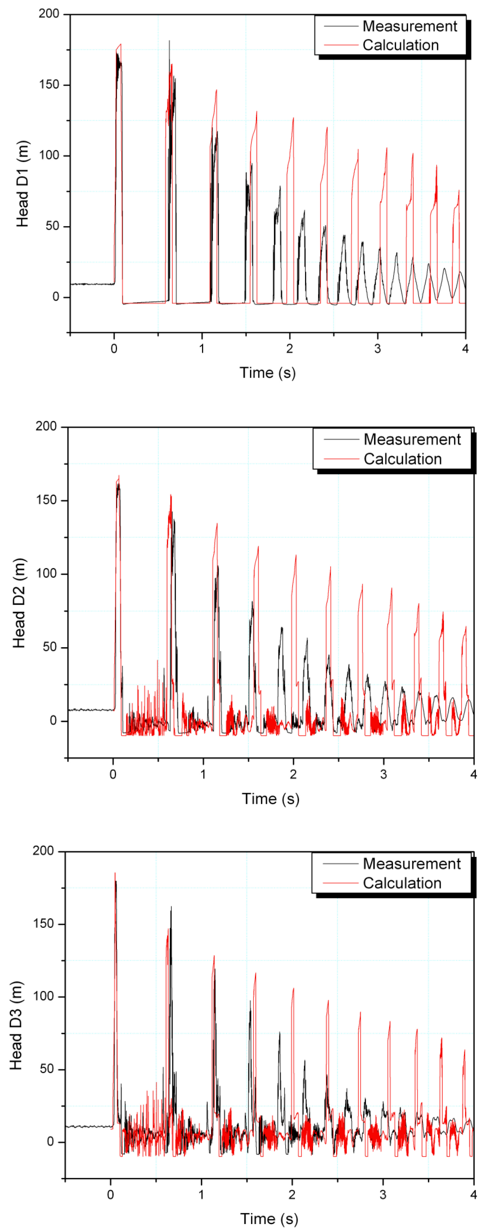

Figure 2: Comparisons of heads at D1, D2 and D3 for Test DP1EVI1C: p_r = 1 bar, V_0 = 1.24 m/s, Δt = 3.55x10^{-4} s.

After that, the discrepancies in the phase shift and pressure wave attenuation are evident. These discrepancies may be attributed to the unsteady friction effects. A similar behaviour may be observed along the pipe at the transducer positions D2 and D3. In the cavitation regions along the pipeline the collapse of a number of vapour bubbles causes small pressure fluctuations that are registered in the experiments and simulated in the numerical calculations.

Figure 3 shows comparisons of heads at the dynamic pressure transducer positions D1, D2 and D3 for Test DP4EVI3O.

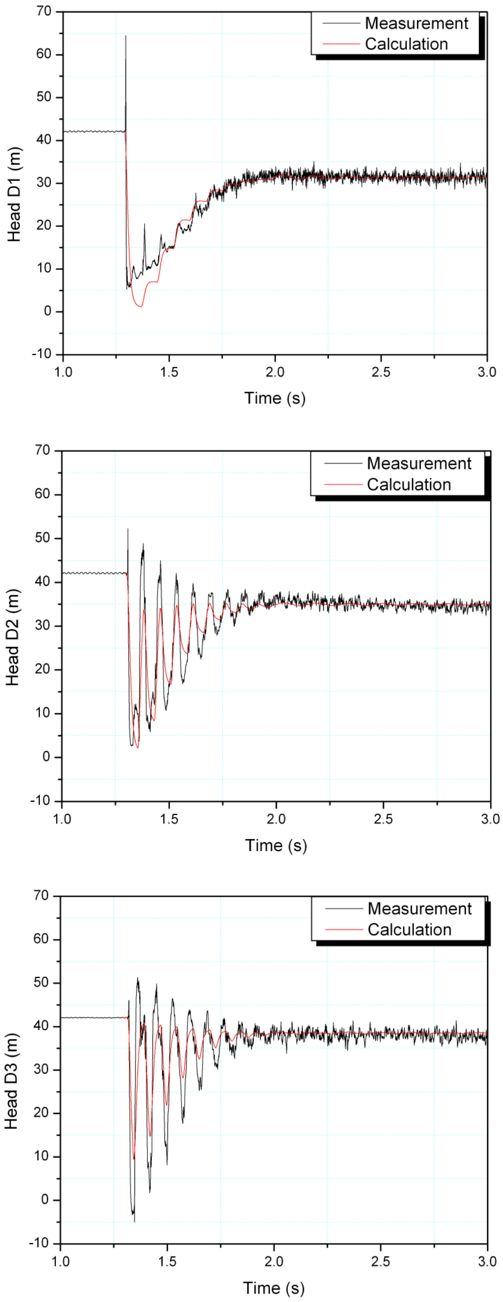

Figure 3: Comparisons of heads at D1, D2 and D3 for Test DP4EVI3O: $p_r = 4$ bar, $V_f = 2.1$ m/s, $\Delta t = 3.55\text{x}10^{-4}$ s.

The EV valve measured opening time is t_o=0.011 s. The experimental results show a characteristic appearance of the high frequency pressure peak at the beginning of the valve opening that is not simulated by the numerical model. The peak may be attributed to FSI effects of the EV. Except for this, the numerical model accurately demonstrates the measurement results for the valve opening case. After the valve is opened the pressure at the D1 drops and, without significant oscillations attains a new steady state. On the other hand, pressure fluctuations at the D2 and D3 positions, after the valve is opened, are much larger. The maximum measured head has a higher value than the initial system's head. This is not the case in the numerical model where the maximum head is lower than the initial one. The cavitation does not occurr in the considered case of the valve opening.

Conclusions

In this paper the experimental apparatus for investigation of water hammer phenomena including unsteady friction and column separation is described in detail. Occurrence of the transient cavitation and column separation has been observed in a number of experiments. The numerical results obtained by the DGCM with a standard quasi-steady friction model for the fast closing and opening of the electro-pneumatic valve are compared with the results of measurements. The comparisons show significant discrepancies in the phase shift and attenuations of pressure history traces between the experimental and numerical data that may be attributed to the effects of unsteady friction. Future research priorities may be seen in the further improvements of the developed numerical code with included effects of the unsteady friction and transient cavitation as well as its verification against the experimental results obtained in the recently developed laboratory apparatus.

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