DEVELOPMENTS IN PIPELINE FILLING AND EMPTYING EXPERIMENTATION IN A LABORATORY PIPELINE APPARATUS

Uroš KARADŽIĆ*, Filip STRUNJAŠ

University of Montenegro, 81000 Podgorica, Montenegro, uros.karadzic@ac.me,

fillip.strunjas@gmail.com

Anton BERGANT, Rok MAVRIČ

Litostroj Power d.o.o., 1000 Ljubljana, Slovenia, anton.bergant@litostrojpower.eu,

rok.mavric@litostrojpower.eu

Samuel BUCKSTEIN

University of Toronto, Toronto, Canada, M5S 1A4, samuel.buckstein@mail.utoronto.ca

ABSTRACT

A flexible, unsteady friction dominated, experimental apparatus for investigating water hammer events has been developed and designed at the University of Montenegro. The apparatus has recently been modified for investigating pipeline filling and emptying events. The apparatus consists of an upstream end high-pressurized tank, horizontal steel pipeline (length 55.37 m, inner diameter 18 mm, pipe wall thickness 2 mm), four valve units positioned along the pipeline including the end points, and a downstream end tank. This paper presents preliminary experimental results obtained during filling and emptying of the pipeline. The filling of an initially empty pipeline is performed by a sudden opening of the valve unit positioned at the high-pressurized tank filled with water. The pipeline emptying process is accomplished by high-pressurized air supplied from the air reservoir installed at the high-pressurized tank filled with water. The high-pressurized tank is closed and the downstream end valve is opened, thereby starting the emptying process. Experimental runs have been performed at a number of different initial values of pressure in the pressurized tank from zero (gravitational filling and emptying) up to 5 bar. Experimental results indicate that pressure fluctuations are larger for pipeline filling compared to pipeline emptying, which makes for a more dangerous transient regime, at least for the cases investigated. From comparisons of measured data obtained by a piezoelectric transducer and a strain-gauge transducer it follows that the piezoelectric transducer with a fixed relatively low discharge time constant is not quite appropriate for accurate low frequency pressure measurements. The paper is intended to serve as reference for further investigations on pipeline filling and emptying.

KEYWORDS

Pipeline Apparatus; Pipeline Filling and Emptying; Experimental Results.

* *Corresponding author:* University of Montenegro, Dzordza Vasingtona nn, 81000 Podgorica, Montenegro, phone: +382 20 268 682, email: uros.karadzic@ac.me

1. INTRODUCTION

The filling with liquid of an initially empty pipeline and the emptying of an initially liquid-filled pipeline are of great interest due to the many practical applications. Rapid pipe filling and emptying occur in various hydraulic applications, such as water-distribution networks, storm-water and sewage systems, fire-fighting systems, oil transport pipelines and pipeline cleaning. During rapid filling of an empty pipeline, while the water column is driven by a high head, air is expelled by the advancing water column. For emptying of a pipeline initially filled with water, water is expelled out of the system while the air is blown into the pipeline [1]. Rapid filling and emptying of the pipeline may be considered as a specific case of water hammer with column separation in which both vaporous and gaseous cavities may be present [2]. The filling and the emptying of the large-scale pipelines has been experimentally studied [1], [3], [4], [5]. Developers and users of computational codes (in-house, commercial) need measured data with which to compare their theoretical models. Unfortunately such data are limited and fragmented elsewhere. There is a strong need for enhanced well-controlled measurements of the water hammer, column separation, fluid-structure interaction, and pipeline filling and emptying. To address these needs, a flexible experimental apparatus has been developed and installed at the University of Montenegro [6]. The small-scale apparatus consists of an upstream end high-pressurized tank, horizontal steel pipeline (length 55.37 m, inner diameter 18 mm), four valve units positioned along the pipeline including the end points, and a downstream end tank (outflow tank). The first preliminary tests of filling and emptying have been performed in an early June, 2015. Key results of the measurements are presented and discussed in this paper.

2. EXPERIMENTAL APPARATUS

A small-scale unsteady friction dominated pipeline apparatus has been designed and constructed at the Faculty of Mechanical Engineering, University of Montenegro [6] for investigating rapid water hammer events including column separation and fluid-structure interaction (pressure changes last for few seconds only) [6]. Recently the apparatus has been modified for performing pipeline filling and emptying events that are characterized both by rapid and gradual pressure changes [4], [5]. The apparatus is comprised of a horizontal pipeline that connects the upstream end high-pressurized tank to the outflow tank (steel pipe of total length L = 55.37 m; internal diameter D = 18 mm; pipe wall thickness e = 2 mm; maximum allowable pressure in the pipeline $p_{max, all}$ = 25 MPa) – see Fig. 1.

Four valve units are positioned along the pipeline including the end points. Valve units at the upstream end tank (position 0/3) and at the two equidistant positions along the pipeline (positions 1/3 and 2/3) are comprised of two hand-operated ball valves (valves Vi/3U and Vi/3D; i = 0, 1, 2) that are connected to the intermediate pressure transducer block. A T-section with an on/off air inlet valve (V0/3A) and a compressed-air supply valve (V0/3AS) is installed between upstream end valve unit (position 0/3) and the high-pressurized tank to facilitate pipeline emptying tests. At the T-section there is also an air vent valve (V0/3AV) and a vertical pipe upstream end service valve (V0/3SV). Horizontal pipe upstream end service valve (V0/3SH) is installed between the T-section and the high-pressurized tank in order to isolate upstream end tank during emptying tests. There are four 90° bends along the pipeline with radius R = 3D. The pipeline is anchored against the axial movement at 37 points (as close as possible to the valve units and bends). The anchors are loosed for fluid-structure interaction tests. The air pressure in the upstream end tank (total volume $\forall_{HPT}$ = 2 m^3; maximum allowable pressure in the tank $p_{HPTmax, all}$ = 2.2 MPa) can be adjusted up to 800 kPa.

Pressure in the tank is kept constant during each experimental run by using a high precision air pressure regulator in the compressed air supply line [6]. The upstream end tank is used for the pipeline filling experiment where the valve V0/3A is closed thus enabling isolation of the compressed air supply into the horizontal steel pipeline.

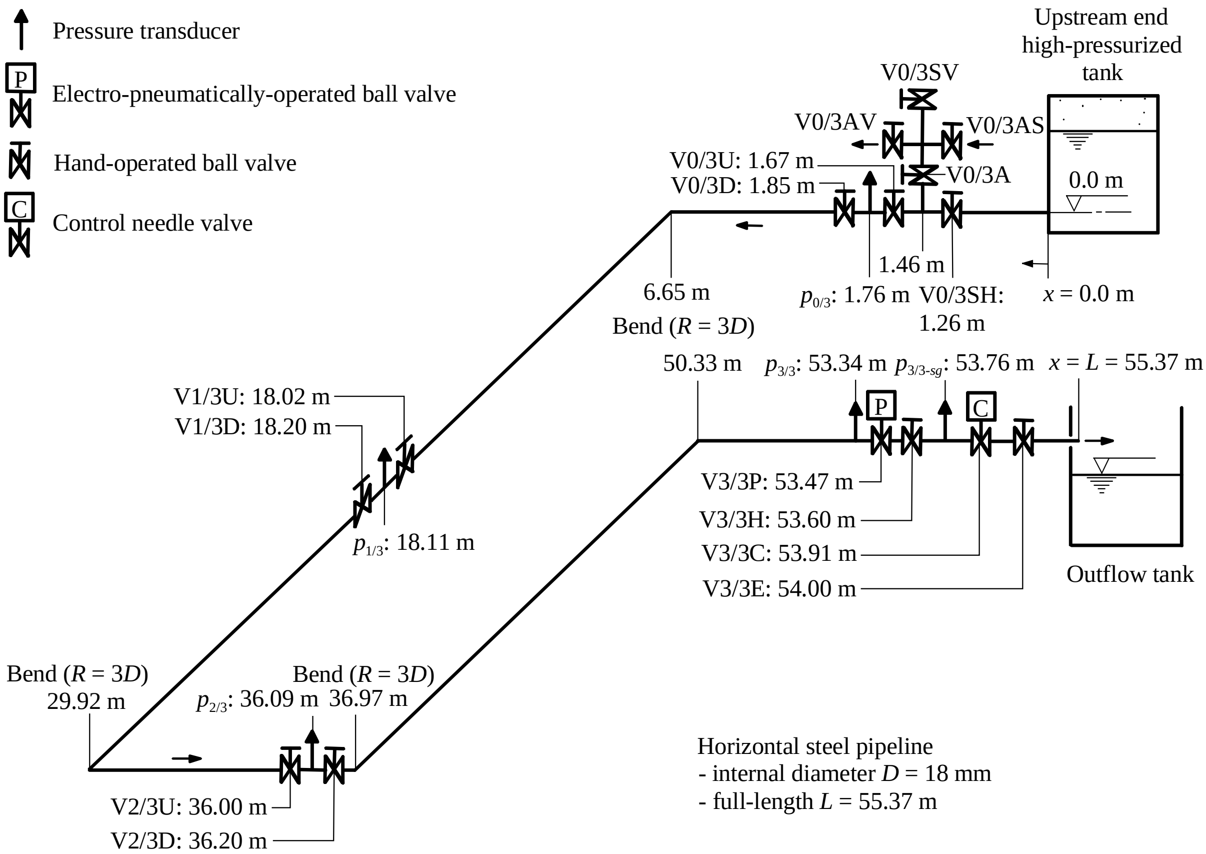

Fig. 1 Layout of small-scale pipeline apparatus

2.1 Instrumentation

Four dynamic high-frequency pressure transducers are positioned within the valve units along the pipeline including the end points (see Fig. 1). Pressures $p_{0/3}$, $p_{1/3}$, $p_{2/3}$ and $p_{3/3}$ are measured by Dytran 2300V4 high frequency piezoelectric absolute pressure transducers (pressure range: from 0 to 6.9 MPa; resonant frequency: 500 kHz; acceleration compensated; discharge time constant: 10 seconds (fixed)). All four piezoelectric transducers were flush mounted to the inner pipe wall. These transducers perform accurately for rapid water hammer events including column separation and fluid structure interaction [6]. In these events the water hammer pressure pulse in the apparatus (Fig. 1) lasts about or less than the wave reflection time $2L/a$ = 0.08 seconds, which is less than 10/100 of a second event during which the sensor will discharge 1% of the voltage. Because of the relatively short discharge time constant of these transducers which cannot be adjusted, a question is posed on their applicability for measurements of 'rapid' filling and emptying events. Therefore, Endress+Hauser PMP131 strain-gauge pressure transducer has been installed at the control valve V3/3C (pressure $p_{3/3\text{-}sg}$; pressure range: from 0 to 1 MPa). This transducer does not discharge the voltage (analogue output); consequently, it can be used for measurement of 'slow' events (low frequency). The datum level for all pressures measured in the pipeline and at the tank is at the top of the horizontal steel pipe (elevation 0.0 m in Fig. 1). For initial flow velocities larger than 0.3 m/s an electromagnetic flow meter Khrone OPTIFLUX 4000F IFC 300C is used. The water temperature is continuously monitored by the thermometer installed in the outflow tank. The water hammer wave speed was determined as a = 1340 m/s.

2.2 Test procedure for pipeline filling

Test procedure for the pipeline filling is as follows. The pressure in the upstream end high-pressurized tank is adjusted to a desired value using a high precision air pressure regulator. The control needle valve (V3/3C) is opened to appropriate position. The upstream end valve (V0/3U) at the pressurized tank (position 0/3 in Fig. 1) is closed. All other valves of the four valve units are fully opened. The air inlet valve (V0/3A) is closed (isolation of the compressed air supply into the pipeline), and the horizontal pipe upstream end service valve (V0/3SH) and the downstream end emptying valve (V3/3E) are opened. The filling of the initially empty pipeline is initiated by quickly opening valve V0/3U. When a steady state is achieved, the final flow velocity (V_f) is measured using an electromagnetic flowmeter.

2.3 Test procedure for pipeline emptying

The pipeline is emptied using compressed air supplied from the air reservoir connected with a high precision air pressure regulator. The air pressure for the pipeline emptying is firstly adjusted to a desired value as well as the opening of the control needle valve. All valves of the four valve units and the horizontal pipe upstream end service valve (V0/3SH) are fully opened. The air inlet valve (V0/3A) (isolation of T-section) and the downstream end emptying valve (V3/3E) are closed. Then the high-pressurized tank is isolated from the system by shutting the horizontal pipe upstream end service valve (V0/3SH) and after that the compressed-air supply valve (V0/3AS) and the air inlet valve (V0/3A) are opened. The process of emptying is started by quickly opening the downstream end emptying valve (V3/3E).

3. EXPERIMENTAL RESULTS

This paper presents measured results from pipeline filling and emptying runs in a small scale experimental apparatus. All experimental runs have been carried out for the 'same' initial conditions at least three times in order to achieve repeatability of experiments. The following case studies are investigated in this work: the filling and the emptying runs with different initial values of the pressure (p = {3, 4} bar) in the high-pressurized upstream tank (filling procedure) and air supply line (emptying procedure).

3.1 Pipeline filling

Figure 2 shows comparison of heads at the two end valve sections and along the pipeline for the case of pipeline filling with the 'same' initial conditions (tests DP4FILL_1 and DP4FILL_2). The pressure in the upstream end tank is p = 4 bar, the control needle valve is fully opened and the final flow velocity in the pipe after the filling process is completed is V_f = 2.21 m/s. From the Fig. 2 it may be seen that general patterns of pressure history during filling events are similar for both tests. As explained in Section 2.1 Dytran 2300V4 dynamic pressure transducers accurately measure high-frequency pressure changes. Therefore, when a new steady state is attained, these transducers do not show the final value of the pressure because the signal discharges to its initial state (63% discharge drop in 10 seconds). Figure 3 shows comparison of heads at the downstream end of the pipeline (position 3/3 in Fig. 1) measured both by the Dytran 2300V4 piezoelectric pressure transducer and by the E+H PMP131 strain-gauge pressure transducer for the test DP4FILL_1. It may be seen that E+H transducer, after filling process is completed, shows steady state (actual) value of the pressure which is not the case with the Dytran transducer (step like pressure pulse).

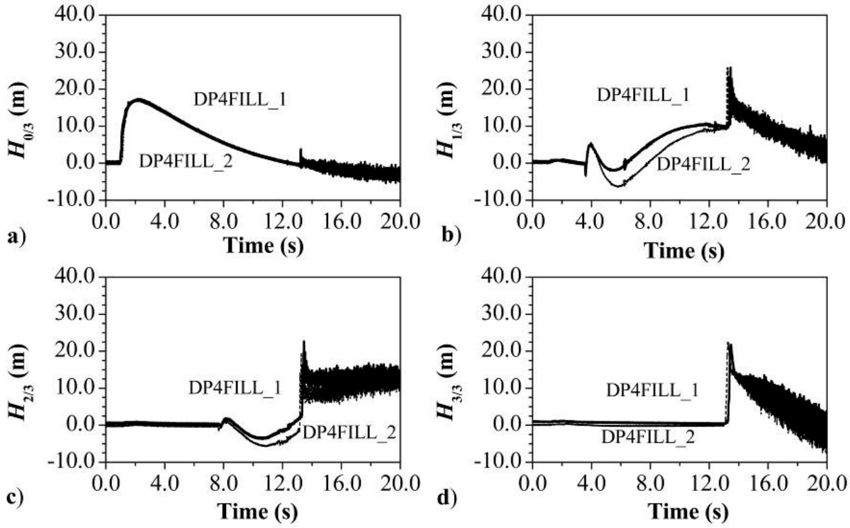

Fig. 2 Comparison of heads at the end valves ($H_{3/3}$ and $H_{0/3}$) and along the pipeline ($H_{2/3}$ and $H_{1/3}$) for the same initial conditions: pipeline filling

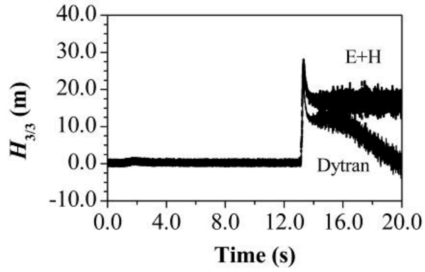

Fig. 3 Comparison of heads at the position 3/3 measured by Dytran and E+H pressure transducers: pipeline filling

Figure 4 shows comparison of heads at the two end valve sections and along the pipeline for the case of pipeline filling with the two different values of pressure in the upstream end high-pressurized tank (tests DP3FILL and DP4FILL with pressure p = {3, 4} bar, respectively). The control needle valve is fully opened and the final flow velocity in the pipe is V_f = {1.93; 2.21} m/s for p = {3, 4} bar, respectively. As expected the head rise at the position 0/3 is higher for the tank pressure p = 4 bar and it is ΔH = 17.1 m. The corresponding value of the head rise for p = 3 bar is ΔH = 12.6 m. The head rise at the end of the system at position 3/3 is ΔH = {12.5; 21.8} m for p = {3; 4} bar, respectively. During pipeline filling the head rise along the pipeline is practically of the same order. The measured maximum heads along the pipeline are to be considered with caution because of the Dytran transducer behaviour. Our objective is to add miniature strain-gauge pressure transducers at all four transducer blocks fitted with existing piezoelectric transducers. However, the timing of the propagation of pressure wave fronts and the values of first sharp pressure shocks are correct. The timing of pressure pulses in later times is correct too but not the magnitude of the instantaneous pressure (head) due to discharge leakage.

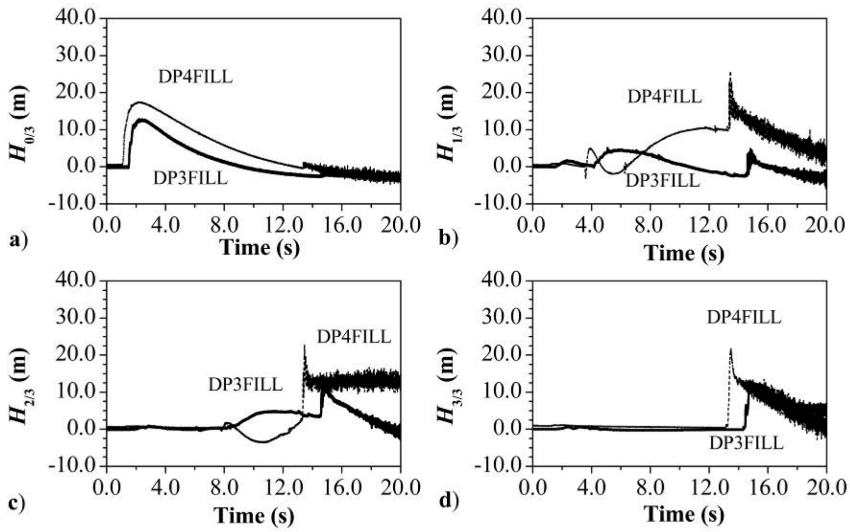

Fig. 4 Comparison of heads at the end valves ($H_{3/3}$ and $H_{0/3}$) and along the pipeline ($H_{2/3}$ and $H_{1/3}$) for the different pressure values: pipeline filling

3.2 Pipeline emptying

Figure 5 shows comparison of heads at the end valve sections and along the pipeline for the case of pipeline emptying using the 'same' initial conditions (tests DP4EMPT_1 and DP4EMPT_2). The pressure in the air supply line is p = 4 bar and the control needle valve is fully opened. The process of emptying is started by quickly opening the downstream end emptying valve (V3/3E in Fig. 1). From the Fig. 5 it may be concluded that head change for the same initial conditions during pipeline emptying is similar. The time for the complete emptying of the pipeline is about 17 s. The initial head drop along the pipeline is about 40 metres.

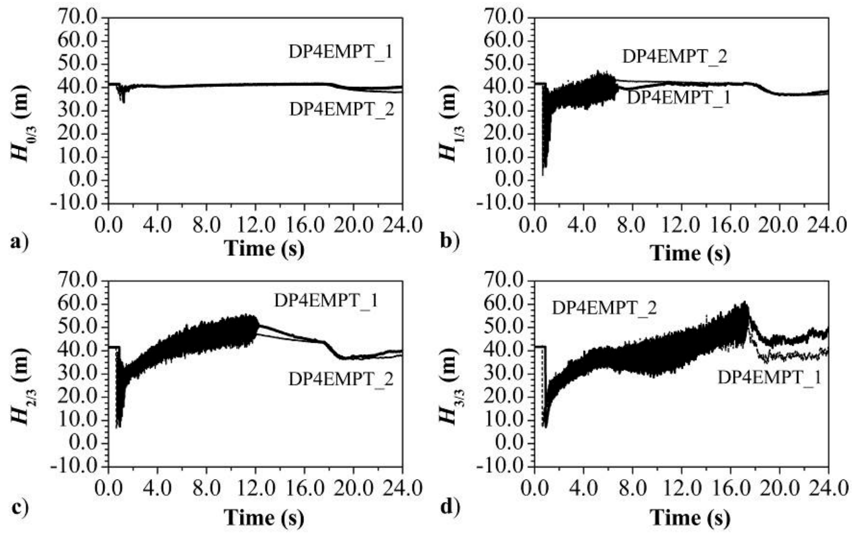

Fig. 5 Comparison of heads at the end valves ($H_{3/3}$ and $H_{0/3}$) and along the pipeline ($H_{2/3}$ and $H_{1/3}$) for the same initial conditions: pipeline emptying

Figure 6 shows comparison of heads at the position 3/3 measured by the Dytran 2300V4 piezoelectric pressure transducer and the E+H PMP131 strain-gauge pressure transducer for the test DP4EMPT_1. Due to the nature of pressure pulses the Dytran transducers exhibit better behavior for the case of the pipeline emptying in contrast to the case of pipeline filling

(Fig. 3). However, the conclusions regarding the transducers are the same as those in Section 3.1. In future experiments, the authors are planning to develop a numerical code for simulation of filling and emptying of pipelines which will be validated against measured data using appropriate pressure transducers that cover low and high-frequency pressure pulses accurately.

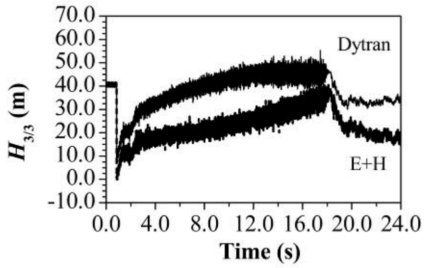

Fig. 6 Comparison of heads at the position 3/3 measured by Dytran and E+H pressure transducers: pipeline emptying

Figure 7 depicts comparison of heads at the end valve sections and along the pipeline for the case of pipeline emptying with two different values of pressure in the air supply line (tests DP3EMPT, DP4EMPT with pressures p = 3 and 4 bar, respectively). Again, the control needle valve is fully opened. The compressed air/water interface (front) at p = {3; 4} bar needs $t_{0/3}$ = {0.9; 1.4} s to pass position 0/3, $t_{1/3}$ = {6.9; 6.2} s, to pass position 1/3, $t_{2/3}$ = {13.1; 11.7} s to pass position 2/3 and finally, it needs $t_{3/3}$ = {19.0; 17.4} s to expel water from the pipeline.

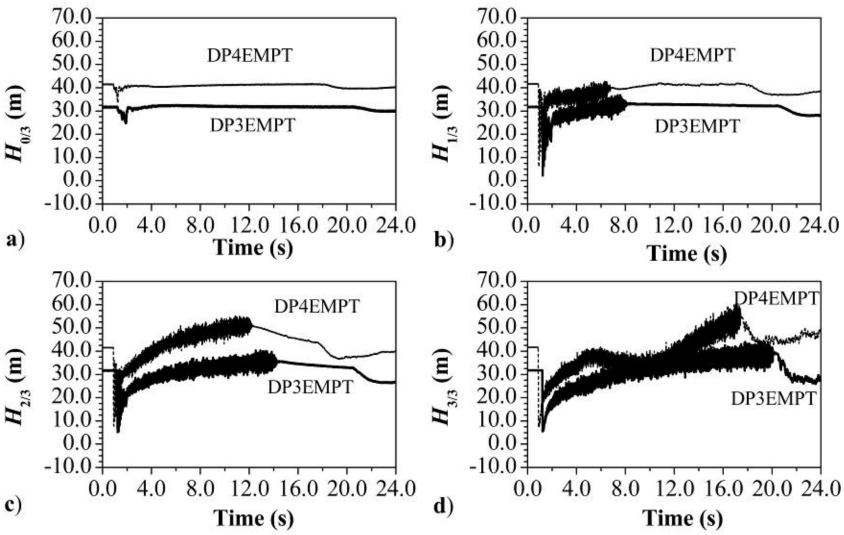

Fig. 7 Comparison of heads at the end valves ($H_{3/3}$ and $H_{0/3}$) and along the pipeline ($H_{2/3}$ and $H_{1/3}$) for the different pressure values: pipeline emptying

4. CONCLUSIONS

A flexible experimental apparatus for investigating rapid water hammer events including column separation and fluid-structure interaction has been designed and constructed at the University of Montenegro. The apparatus has been recently modified for performing pipeline filling and emptying runs that are characterized both by rapid and gradual pressure changes in the pipeline. The first tests of pipeline filling and emptying have been performed in an early June, 2015. The main objective of the paper was to investigate effects of pipeline filling and emptying on head changes along the pipeline for different initial values of the pressure in high-pressurized upstream end tank (filling) and air supply line (emptying). Higher initial pressure in the upstream end tank produces higher head rise during filling process. The minimum head along pipeline is practically the same regardless the magnitude of the initial pressure in the air supply line during the emptying process. From comparisons of measured data obtained by a piezoelectric transducer and by a strain-gauge transducer it follows that the piezoelectric transducer with a fixed relatively low discharge time constant is not fully suitable for low frequency pressure measurements. New miniature strain-gauge pressure transducers are going to be employed for the next set of the pipeline filling and emptying tests in order to get more accurate data that are needed as a reference for validation of numerical models.

5. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of the Slovenian Research Agency (ARRS) and of the Ministry of Science of Montenegro (MSM) conducted through the projects BI-ME/14-15-016 (ARRS, MSM) and L2-5491 (ARRS).

6. REFERENCES

[1] Hou, Q. et al.: *Experimental study of filling and emptying of a large-scale pipeline*, CASA Report 12-15, Eindhoven University of Technology, The Netherlands, 2012.

[2] Malekpour, A., Karney, B.W.: Profile-induced column separation and rejoining during pipeline filling, *Journal of Hydraulic Engineering*, ASCE, 140(11), 2014, pp. 04014054–1-12.

[3] Vasconcelos, J. G., Wright, S. J. and Guizani, M.: *Experimental investigations on rapid filling of empty pipelines*, Report UMCEE-05-01, University of Michigan, Ann Arbor, USA, 2005.

[4] Laanearu, J. et al.: Emptying of large-scale pipeline by pressurized air, *Journal of Hydraulic Engineering*, ASCE, 138(12), 2012, pp. 1090-1100.

[5] Hou, Q. et al.: Experimental investigation on rapid filling of a large-scale pipeline, *Journal of Hydraulic Engineering*, ASCE, 140(11), 2014, pp. 04014053–1-14.

[6] Karadžić, U., Bulatović, V., Bergant, A.: Valve-induced water hammer and column separation in a pipeline apparatus, *Strojniški vestnik – Journal of Mechanical Engineering*, 60(11), 2014, pp. 742-754.

7. NOMENCLATURE

a	(m/s)	wave speed	V	(m/s)	flow velocity
D	(m)	diameter	x	(m)	axial distance
e	(m)	pipe wall thickness	$\forall$	(m^3)	volume
H	(m)	head	*Subscripts:*		
L	(m)	length	f		final
p	(Pa)	pressure	HPT		pressurized tank
R	(m)	pipe bend radius	max		maximum value
t	(s)	time			