Developments in multiple-valve pipeline column separation control

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Abstract. This paper investigates novel multiple-valve pipeline column separation control. Experimental investigations have been performed in a laboratory pipeline apparatus. The apparatus consists of an upstream end high-pressure tank, a horizontal steel pipeline (total length 55.37 m, inner diameter 18 mm), four valve units positioned along the pipeline including the end points, and a downstream end tank. The transient event is induced by downstream-end or/and upstream-end valve closures (single- or multiple-valve action). A multiple-valve induced closure event may significantly attenuate the severity of pressure oscillations in the pipeline system. Discrete gas cavity model (DGCM) predictions and measured results for two typical cases including single- and multiple-valve closures are compared and discussed.

1. Introduction

State-of-the-art hydraulic pipelines undergo a broad range of operating regimes. Unsteady pipe flows may induce severe loads in the piping systems, including large pressure pulsations and pipeline vibrations [1]. Water hammer is the propagation of pressure waves along liquid-filled pipelines (water, oil), and it is induced by a change in flow rate (flow velocity). Vaporous cavitation occurs when the pressure drops to the liquid vapour pressure [2]. There are two distinct types: (1) column separation, where a localized (discrete) vapour cavity with a large void fraction separates two liquid columns (or one column and a dead end) and (2) flashing, where a region of distributed vaporous cavitation with a small void fraction extends over long sections of the pipeline. A discrete vapour cavity may form at a boundary (valve, pump, water turbine), at a knee or at a high point in the pipeline. Distributed vaporous cavitation occurs when a rarefaction wave progressively drops the pressure in an extended region of the pipe to the liquid vapour pressure. The collapse of vapour cavities may induce large pressures. Engineers try to avoid column separation, although there are some systems in which column separation is accepted. Most of the column separation research has been done for a classical case with single-valve closure in a simple reservoir-pipeline-valve system [1], [2]. However, there are a number of typical industrial pipelines with multiple-valves, at least with two of them (upstream- and downstream-end valves). Multiple closing or opening of valves may induce very large or low pressure waves due to superposition of the waves [3], [4]. The associated phenomena are well understood, but accurate predictions are problematic because of uncertainties in wave speeds and reflection

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coefficients; therefore engineers try to avoid multiple valve action in the system. There are reports, for example, on the usage of single or even multiple-check valves to attenuate column separation effects and this has been addressed theoretically by Karney and Simpson [5] and practically applied by Dudlik et al. [6]. To even better understand the phenomena associated with these types of transient events, and to create an experimental database, a large number of tests have been performed in a laboratory pipe system at the University of Montenegro [4]. The small-scale apparatus consists of an upstream end high-pressurized tank, horizontal steel pipeline (total 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). This paper investigates the effects of vaporous cavitation caused by the single-valve closure (downstream-end valve) and by the multiple-valve closure (nearly simultaneous closure of upstream-end and downstream-end valves). Comparisons between the results of two distinct column separation tests and numerical simulations using a discrete gas cavity model (DGCM) are presented and discussed.

2. Discrete gas cavity model

The classical discrete gas cavity model (DGCM) is based on simplified water hammer equations (the convective transport terms are neglected) [1], [2]. The DGCM allows gas cavities (with the vapour pressure set as bottom pressure) to form at all computational sections in the method of characteristics (MOC) grid. A liquid phase with a constant wave speed \( c \) is assumed to occupy the reaches connecting the computational sections. A discrete gas cavity is described by two water hammer compatibility equations, the continuity equation for the gas cavity volume, and the ideal gas equation. Detailed description of the DGCM is given in [1]. The DGCM model can be successfully used for the simulation of unsteady pure liquid pipe flow by utilizing a very low gas void fraction and for transient cavitating flow with void fractions up to 1. The MOC based DGCM algorithm in this paper incorporates a convolution-based (with quasi-2D weighting function) unsteady friction model [7].

3. Laboratory pipeline apparatus

A small-scale pipeline apparatus has been designed and constructed at the University of Montenegro for investigating rapid water hammer events including column separation. 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 \( e = 2.0 \) mm; maximum allowable pressure in the pipeline \( p_{\text{max, all}} = 25 \) MPa) – see Fig. 1. The symbols are defined as they first appear in the paper. Four valve units are positioned along the pipeline including the end points (valves \( V*/3* \) at positions 0/3, 1/3, 2/3 and 3/3). The air pressure in the upstream end tank can be adjusted up to 800 kPa. The pressure in the tank is kept constant during each experimental run by using a high-precision fast-acting air pressure regulator (precision class: 0.2%) in the compressed air supply line. 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)). The water temperature is continuously monitored by the thermometer installed in the outflow tank. The water hammer wave speed was determined as \( a = 1340 \pm 10 \) m/s. The test procedure is as follows. The steady-state flow conditions (in advance of a dynamic test) are controlled by a set pressure in the upstream end tank and by a set opening of the downstream end control needle valve (valve V3/3C in Fig. 1). The water level in the upstream end pressurized tank can be adjusted. From initial steady flow conditions (flow, no-flow), a transient event is initiated by downstream-end (V3/3H) or/and upstream-end (V0/3U) valve closures (single- or multiple-valve action).
4. Numerical and experimental results

The following two distinct experimental runs in the test apparatus (Fig. 1) are presented and analyzed theoretically in this section: (1) the first case study investigates single-valve (V3/3H) closure only and (2) the second case study investigates the closure of two valves (first V3/3H and then V0/3U with a time delay of $9.5L/a$). Numerical results from the DGCM (see Section 2) are compared with results of laboratory measurements at the upstream end-valve (pressure $p_{0/3}$ in Fig. 1), along the pipeline (pressures $p_{1/3}$ and $p_{2/3}$) and at the downstream end-valve (pressure $p_{3/3}$). The computational time step for all runs is $\Delta t = 0.0004$ s. Water and surrounding temperatures were about 25 and 30 °C, respectively.

4.1 Single-valve closure induced column separation test

Numerical and experimental results for the single-valve closure (valve V3/3H in Fig. 1) are shown in Fig. 2. This case is a classical example of passive column separation [8] with a maximum head rise equal to the Joukowsky head rise caused by valve closure (and not by cavity collapse). The initial flow velocity was $V_0 = 2.19$ m/s. The effective valve closure time of 20 ms is much less than the wave reflection time $2L/a$ of 0.08 seconds, and it is about 50% of the total closure time. A rapid valve closure generates a column separation event with severe repeated column separations at the valve. The valve closure first induced a Joukowsky head rise at the valve and subsequently, at time $t = 0.09$ s, first severe column separation at the valve. The negative pressure wave travels along the pipeline and makes the head drop to the vapour head at all measured positions along the pipeline. The maximum measured head at the valve of $H_{3/3} = 295$ m after the first cavity collapsed at $t = 0.4$ is less than the Joukowsky head of $H_{3/3} = 330$ m (including friction) just before first column separation. The datum level for all heads in the pipeline and at the tank is at the top of the horizontal steel pipe (elevation 0.0 m in Fig. 1). Pressure histories along the pipeline enable accurate tracing of distributed vaporous cavitation zones and intermediate large cavities. The computational results give pressure histories that are in good agreement with the measured results.
4.2 Multiple-valve closure induced column separation test

Figure 3 presents measured and computed head traces in the system ($H_{3/3}$, $H_{2/3}$, $H_{1/3}$ and $H_{0/3}$) for the fast but not simultaneous closure of the two valves $V_{3/3}$ and $V_{0/3}$ for the same initial flow velocity $V_0 = 2.19$ m/s as for the single-valve closure case [4]. Again, the valve closure times were less than the wave reflection time $2L/a = 0.08$ seconds ($V_{3/3}$: 60 ms and $V_{0/3}$: 20 ms). The initial fast closure of the downstream end valve ($V_{3/3}$) produces the classical Joukowsky head of $H_{3/3} = 330$ m. The second but delayed fast closure of the downstream end valve ($V_{0/3}$) produces the pressure head drop from the reservoir head to the vapour head of -10.1 m. The time delay between the two end valve closures is 0.38 s. At the time of the pressure drop at $V_{0/3}$ the water moves towards the downstream end (away from the reservoir). The pressure heads along the pipeline (at least at the $H_{3/3}$, $H_{2/3}$, $H_{1/3}$ and $H_{0/3}$ positions) remain practically constant at the vapour head for a longer period. We may conclude that for the case considered the system’s dynamic response in terms of long-term pressure pulsations is less violent (one pressure pulse) than the response of a similar classical column separation case with the downstream end valve closure only (large number of pressure pulses; Section 4.1). The number of pressure pulses during a transient event is important for the assessment of the system lifetime. The effect of reopening of one of the valves is the topic of current authors’ research. Again, the results obtained using the DGCM give pressure histories that are in favourable agreement with the experimental results.

5. Conclusions

Experimental investigations have been performed in a laboratory pipeline apparatus. Dynamic pressures were investigated at the pipe end points and at one- and two-third points along the pipe. Transient events were induced by downstream-end or/and upstream-end valve closures (single- or multiple-valve action). Comparison between single- and multiple-valve closures showed that multiple-valve induced closure event may significantly attenuate the severity of column separation induced oscillations in the pipeline system. Discrete gas cavity model (DGCM) predictions and measured results for the two typical cases including single- and multiple-valve closures are in good agreement.
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