Investigation of transient vaporous cavitation: experimental and numerical analyses

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Abstract

The current paper aims at the experimental and numerical analysis of the cavitating pipe flow during the occurrence of hydraulic transients in a quasi-horizontal straight copper pipe rig. Transient events were simulated by the quasi-instantaneous closure of a pneumatically actuated ball valve located at the downstream end of the pipe. A hydraulic transient model has been developed for describing cavitating pipe flow by means of two approaches – the discrete vapour cavity model (DVCM) and the discrete gas cavity model (DGCM). Firstly, the model has been calibrated by using transient data without cavitation. Numerical results have been compared with collected data and a good agreement has been observed as long as the unsteady friction losses are considered. Secondly, DVCM and DGCM have been used to describe cavitating flows. Results of both models have been compared, and the DGCM model has shown to better describe transient events with cavitation.

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Keywords: Cavitating flow; Fluid transients; Pipe-rig; Experimental data; Column separation.

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Peer-review under responsibility of the Scientific Committee of CCWI 2015
doi:10.1016/j.proeng.2015.08.881
1. Introduction

The literature describes two main types of transient cavitation occurrence in fluid systems: *gaseous cavitation* (two-component two-phase flow) and *vaporous cavitation* (single-component two-phase flow). In the former the pressure drops below the saturation pressure but keeps above the liquid vapour pressure. The flow is characterized by the presence of micro-bubbles of free gas distributed along the pipeline and, thus, the wave speed is pressure-dependent. Gas cavities increase their volume due to the pressure drop and dissolved gas is released. The added compressibility of the gas reduces the mixture celerity and gives rise to significant pressure wave dispersion [1-8]. Experimental investigations have shown that the energy dissipation is higher in gas-liquid mixtures than in pure liquid flow. In the vaporous cavitation, the local fluid pressure falls to its vapour pressure and a sudden growth of air cavities containing vapour occurs. This is the basis of column separation regimes in which the liquid flow is completely separated by its vapour phase when the cavity is formed [9-18]. Bergant et al. [19] distinguishes two types of vaporous cavitation in pipelines: local column separation (large void fraction – the ratio of the volume of the vapour to the total volume of the liquid/vapour mixture) and distributed vaporous cavitation (small void fraction), which occurs over an extended length of the pipe. Actually, a combination of both phenomena is produced during low pressure transients in existing systems [5]. The response may involve column separation and subsequent re-joining, vaporization and condensation, air release, dispersion of wave fronts and shock waves. As shown by Adamkowski and Lewandowski [16] the phenomenon can have a distributed nature, which means that gas-vapour zones may be spread along the pipeline length.

The current paper focuses on the analysis of transient cavitating flow in pressurized pipes. A hydraulic transient solver that incorporates the description of dynamic effects related to unsteady friction losses and the cavitating pipe flow has been developed. The discrete vapour cavity model (DVCM) and the discrete gas cavity model (DGCM) have been used to describe transient cavitating flow. Such models assume that discrete air cavities are formed at fixed sections of the pipeline and consider a constant wave speed in pipe reaches between these cavities. An extensive experimental programme has been carried out in an experimental set-up composed of a straight copper pipeline. Numerical results obtained for the cavitating flow for both cavity models have been compared with collected data and a very agreement has been obtained, being the DGCM the one that describes more accurately physical measurements. The contribution of unsteady friction losses on pressure dampening has also been analysed.

2. Mathematical models

2.1. Elastic model

One-dimensional transient flows in elastic pipes are described by the following momentum and continuity equations [20-22]:

\[
\frac{\partial H}{\partial x} + \frac{1}{gA} \frac{\partial Q}{\partial t} + h_f = 0
\]  
\(1\)

\[
\frac{\partial H}{\partial t} + \frac{a^2}{gA} \frac{\partial Q}{\partial x} = 0
\]  
\(2\)

where \(x\) = coordinate along the pipe axis; \(t\) = time; \(H\) = piezometric-head; \(Q\) = discharge; \(A\) = pipe cross-sectional area; \(a\) = celerity (or elastic wave speed); \(g\) = gravity acceleration; and \(h_f\) = head loss per unit length.

In order to take into account unsteady friction effects, the friction losses, \(h_f\), have been separated into two components:

\[
h_f = h_{fs} + h_{re} = \frac{fQ^2}{2gDA^2} + h_{re}
\]  
\(3\)
where \( h_{fs} \) = head loss for steady-state conditions (expressed in terms of square discharge for turbulent flows); \( h_{fu} \) = head loss for unsteady-state conditions; \( f \) = Darcy-Weisbach friction factor; and \( D \) = pipe inner diameter. The unsteady-state component, \( h_{fu} \), is herein calculated by using Vítkovský et al. [23] formulation, in which the head loss component \( h_{fu} \) is function of both local and convective accelerations as firstly proposed by Brunone et al. [24]:

\[
h_{fu} = \frac{k'}{gA} \left( \frac{\partial Q}{\partial t} + aSGN(Q) \frac{\partial Q}{\partial x} \right)
\]

where \( k' \) = empirical decay coefficient; and \( SGN \) = the operator for the sign of the average discharge.

2.2. Transient pipe cavitation flow models

The discrete vapour cavity model (DVCM) is based on the column separation hypothesis. It assumes that discrete air cavities are formed at fixed pipe sections by considering a constant wave speed in pipe reaches between these cavities [19]. This model is particularly adequate if the pipe profile has sections with higher elevation, where air tends to be entrapped, forming air pockets, or if only a portion of the system is subjected to vapour pressure. The Method of Characteristics (MOC) is used to solve basic equations with a fixed grid and, whenever a particular section of the pipe reaches a pressure below vaporization pressure, it is treated as an internal boundary condition with the absolute pressure in a cavity set equal to the vapour pressure.

An alternative to model vaporous cavitation is the discrete gas cavity model (DGCM), also solved by the MOC. As in DVCM, between each computing section and concentrated gas volume, pure liquid with a constant wave speed is assumed. Each isolated small volume of gas isothermally expands and contracts as the pressure varies, according to the perfect gas law [22]. The DGCM is able to simulate vaporous cavitation by using a low initial gas void fraction \( \alpha_0 \leq 10^{-7} \), in which \( \alpha_0 = g/m \), with \( g \) = gas cavity volume and \( m \) = mixture volume [9, 25].

3. Experimental data collection

An experimental pipe-rig has been assembled at the Instituto Superior Técnico of Lisbon, Portugal. It has the typical reservoir-pipeline-valve system configuration in which a steady state flow is stopped by a quasi-instantaneous valve closure. The pipeline is composed of a straight copper pipe (Fig. 1a) with a total length of 15.22 m, an inner diameter of 0.02 m and a pipe wall thickness of 0.001 m. The system is supplied by a centrifugal pump with a nominal flow rate of 1 L/s and a nominal head of 46 m. Immediately at downstream of the pump, there is a hydropneumatic tank with 60 L of total volume (Fig. 1b). Two valves are located at the downstream end of the pipeline: a pneumatically actuated quarter turn ball valve (Fig. 1c), which is used for generating the water hammer, and a manually operated quarter turn ball valve, which is used to control the initial discharge.

A data acquisition system has been set to collect and store transient data. It is composed of an oscilloscope, a trigger-synchronizer, a power source for the solenoid actuator, a laptop computer and two strain-gauge type pressure transducers (0-25 bar). The transducers are located at the downstream end (T1) and at mid-length of the pipeline (T2 \( \approx 7.60 \) m from downstream end) in order to collect transient pressure data at high frequency acquisition (3 kHz).

Figure 2 shows the pressure traces for non-cavitating flow (initial discharge, \( Q_0 \), of 0.133 L/s and Reynolds number, \( R \), of 8,467) acquired by the transducers T1 (Fig. 2a) and T2 (Fig. 2b) as well as the transient pressure data for cavitating flow (\( Q_0 = 0.156 \) L/s and \( R = 9,931 \)) acquired by the transducers T1 (Fig. 2c) and T2 (Fig. 2d).
Fig. 1. Pipe-rig: (a) straight copper pipe; (b) hydropneumatic tank; (c) pneumatically actuated ball valve.

Fig. 2. Transient pressure traces (a) at the downstream end of the pipe, T1, and (b) at mid-length of the pipe, T2, for $Q_0 = 0.133$ L/s, and (c) at T1 and (d) at T2 for $Q_0 = 0.156$ L/s.
4. Numerical results

In order to determine the contribution of unsteady friction losses on transient pressure traces, tests were carried out by closing the downstream end valve for non cavitating flows (Figs. 2a and 2b). Elastic wave speed was estimated as 1,255 m/s ($\Delta x = 1.0 \text{ m}$; and $\Delta t = 0.0007968130 \text{ s}$). The decay coefficient, $k'$, of the unsteady friction model [23] has been estimated as 0.016 based on transient pressure data collected at transducer T1.

Numerical results obtained by using the elastic model are presented in Fig. 3 ($Q_0 = 0.133 \text{ L/s}; R = 8,467$). The classic elastic model (considering steady state friction only) reproduces well the first pressure peak (Fig. 3b), but the attenuation is not well described (Fig. 3a). Numerical results fitted to pressure data observed extremely well when unsteady friction losses were taken into account, namely the attenuation (Fig. 3c) or the pressure peaks (Fig. 3d).

![Fig. 3. Transient pressure traces for $Q_0 = 0.133 \text{ L/s (without cavitation): (a) and (b) at the downstream end of the pipe (T1) considering steady state friction losses; (c) and (d) at the downstream end of the pipe (T1) taking into account for unsteady friction losses.}]
Fig. 4. Transient pressure traces for $Q_0 = 0.156$ L/s (with cavitating flow): (a) and (b) at the downstream end of the pipe (T1) considering DVCM and steady state friction losses; (c) and (d) at the downstream end of the pipe (T1) considering DVCM and unsteady friction losses.

The DGCM was tested to analyse if the results were better to describe the system behaviour considering a small initial void fraction of $D_0 = 10^{-7}$. Numerical results obtained are presented in Fig. 5 ($Q_0 = 0.156$ L/s; $R = 9,931$). For only steady state friction losses, DGCM reproduces well the overpressure due to the valve closure (Fig. 5b), but it calculates a higher pressure peak after the water column re-joining (Fig. 5b) and the attenuation is not described (Fig. 5a), similarly to DVCM results. By taking into account unsteady friction losses, DGCM can describe the pressure peak after the water column re-joining (Fig. 5d) as well as the pressure attenuation (Fig. 5c). The calibrated unsteady friction decay coefficient for non cavitating flows, $k' = 0.016$, has been used in DGCM simulations.

In comparison with DVC, DGCM can describe better the system behaviour in terms of pressure attenuation and phase shifting (Fig. 5d). In this research, the calculation of unsteady friction losses has also been essential to describe observed transient pressures for cavitating flows.
Fig. 5. Transient pressure traces for $Q_0 = 0.156$ L/s (with cavitating flow): (a) and (b) at the downstream end of the pipe (T1) considering DGCM and steady state friction losses; (c) and (d) at the downstream end of the pipe (T1) considering DGCM and unsteady friction losses.

5. Conclusions

The current paper presented experimental tests and numerical analyses of water hammer with cavitation in a pressurized straight copper pipe-rig. Pressure data in turbulent conditions were collected during transient events caused by the downstream valve closure. A hydraulic transient solver that takes into account unsteady friction losses and cavitation has been developed. Measured data were used to calibrate and verify two developed mathematical models to the description of cavitating pipe flow: discrete vapour cavity model (DVCM), and discrete gas cavity model (DGCM).

Obtained numerical results showed that the assumption of the ideal gas law (DGCM) is more appropriate than the simple adoption of attained vapour pressure (DVCM) and induces more attenuation and dispersion of transient pressures. The calculation of unsteady friction losses has also been essential to describe observed transient pressures for cavitating flows.

Considering the numerical analysis carried out in this work, cavitation flows in pressurized systems have to be better analysed. The use of advanced Computational Fluid Dynamics for describing the 3D nature of transient flow in pipes is definitively important for better understanding and numerically describing transient cavitating pipe flow.

With regard to the experimental analysis, several transient tests are currently being carried out in the pipe-rig in order to cover different initial Reynolds numbers as well as to study other phenomena, such as unsteady friction and fluid-structure interaction.
Acknowledgements

The first author gratefully acknowledges the financial support of the Brazilian National Council for Scientific and Technological Development (CNPq: Conselho Nacional de Desenvolvimento Científico e Tecnológico).

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