Journal of Fluids and Structures 83 (2018) 91–118

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

Numerical investigations of water-hammer with column-separation induced by vaporous cavitation using a one-dimensional Finite-Volume approach

F. Daude [a,b,*], A.S. Tijsseling [c], P. Galon [a,d]

[a] IMSIA, UMR EDF-CNRS-CEA-ENSTA 9219, Université Paris-Saclay, F-91762 Palaiseau, France
[b] EDF R&D, ERMES, F-91120 Palaiseau, France
[c] Eindhoven University of Technology, Department of Mathematics and Computer Science, 5600 MB Eindhoven, The Netherlands
[d] CEA Saclay, DEN-SEMT, Université Paris-Saclay, F-91191, Gif-sur-Yvette, France

ARTICLE INFO

Article history:
Received 20 February 2018
Received in revised form 16 July 2018
Accepted 24 August 2018

Keywords:
Water-hammer
Column-separation
Cavitation/condensation
HEM
Finite-volume method

ABSTRACT

Water-hammer with column-separation induced by cavitation is investigated numerically. The vapor–water flow is modeled using the Homogeneous Equilibrium Model in conjunction with the 1984 NBS/NRC Steam Tables. The discretization is done with the quasi 1-D Finite-Volume approach recently developed by the authors for compressible flows in pipelines. The ability of the present approach to tackle cavitating flows is first assessed. Then, comparisons with experimental results of water-hammer with column-separation demonstrate consistency with the present computations. Based on the obtained numerical results, focus is given to the dynamics of the liquid column-separation and to the associated physics such as cavitation, vapor growth and collapse, generation of the secondary water-hammer peak and the interaction of the primary and secondary pressure waves. The influence of the initial flow velocity before valve closure on the duration and size of the cavity and on the magnitude of the secondary water-hammer is examined.

1. Introduction

Water-hammer (WH) may occur in piping systems used in aerospace industry, hydro-power installations and nuclear reactor cooling systems. The WH phenomenon is well-studied due to its importance in designing pipe flow systems for over a century since the pioneering works of Joukowsky (1900) and Allievi (1913). Extensive reviews on WH can be found in the Refs. Wylie et al. (1993), Chaudhry (2014), Ghidaoui et al. (2005) and Bergant et al. (2006). WH is the result of a sudden change of the liquid's flow velocity due to valve/pump operations or other reasons. The induced pressure variations propagate along the pipe and can damage pipes or supports disturbing the operation of the flow system. As the motion or deformation of the pipes forced by the fluid transient may strongly influence the flow in the pipe, the dynamic fluid–structure interaction should be taken into account in critical cases. In addition, the cavitation phenomenon may take place during the fast transient event when the pressure falls to the saturation value of vapor. As a consequence, the liquid starts to evaporate and column-separation may occur. Bergant et al. (2006) present a comprehensive review on the WH phenomenon with liquid column-separation. As the authors explained in this review, the collapse of vapor may induce large and steep pressure rises. In certain situations, this leads to a pressure amplitude which can be higher than the one obtained in the single liquid-phase situation given by the classical Joukowsky formula. The cause of this phenomenon is the superposition of the

---

[*] Corresponding author at: EDF R&D, ERMES, F-91120 Palaiseau, France.
E-mail address: frederic.daude@edf.fr (F. Daude).

https://doi.org/10.1016/j.jfluidstructs.2018.08.014
0889-9746/

first and the secondary pressure waves (Bergant et al., 2006). The cavitation/condensation phenomena and the interaction of several pressure waves clearly increase the complexity and severity of the fluid transient. According to Bergant and Simpson (1999), this kind of transient cavitating flow is classified as active column-separation. As reported in Bergant et al. (2006), column-separation can have a destructive effect as in the burst pipe accident at Oigawa hydropower station in 1950 in Japan (Bonin, 1960). Both experimental and numerical studies have investigated the column-separation phenomenon (Bergant et al., 2006). The existing methods for the simulation of WH with liquid column-separation are almost all 1-D and based on the Discrete Vapor Cavity Model (DVCM) using the method of characteristics as originally proposed by Wylie et al. (1993). Strong assumptions are made in the derivation of the DVCM. In particular, the vapor generated when the pressure falls to the saturation value is concentrated at the grid points and between the grid points pure liquid is assumed. As a consequence, the precise position of cavities along the pipe cannot be estimated. Another limitation lies in the inability of the cavity to move with the flow. In addition, spurious pressure spikes can be obtained using the DVCM when the mesh is sufficiently fine (Bergant et al., 2006). To alleviate this difficulty, a small amount of non-condensable gas is introduced which provides damping. This approach is referred as the Discrete Gas Cavity Model (DGCM) presented by Wylie (1984). However, the calculations are known to be sensitive to the initial assumed amount of gas. Zhou et al. (2017, 2018) recently proposed a second-order Finite-Volume approach for the water-hammer equations in which cavitation is modeled using either DVCM (Zhou et al., 2017) or DGCM (Zhou et al., 2018). This avoids the unrealistic artificial spikiness appearing on finer meshes, noting that unfiltered measurements show “spikiness” too. The first applications of Finite-Volume methods for water-hammer equations are described in Guinot (2000), Hwang and Chung (2002) and Zhao and Ghidaoui (2004). Chaiko (2006) proposed a Finite-Volume approach considering the classical conservation laws of mass and momentum instead of the linear water-hammer equations to take into account the non-linear convective terms which are significant for low wave speeds due to vapor and free gas, and thus necessary for a large range of Mach numbers. In addition, the Finite-Volume formulation ensures the discrete conservation of mass and momentum as well as the correct jump relations at discontinuities (Hirsch, 1988; Toro, 2009). Moreover, only isothermal or isentropic fluids are considered in the papers mentioned above. In this paper, non-isothermal compressible flows are considered as in realistic pipe systems the fluid temperature may vary due to heat exchange with the environment.

The numerical modeling of the cavitation phenomenon has received a lot of interest in the literature. In recent years, two-phase flow models have become popular in the modeling of cavitating flows. For example, the one-fluid model based on the assumption of mechanic, kinematic and thermodynamic equilibria treats the two-phase mixture as a single-fluid, see for example Liu et al. (2004), Zheng et al. (2013), Dumbser et al. (2013) and the references therein. As a consequence, any non-equilibrium effect cannot be taken into account and cavitation is assumed to be instantaneous. In the present paper, the one-fluid approach is retained through the use of the Homogeneous Equilibrium Model (HEM) (Clerc, 2000). The next modeling issue is to provide an adequate equation of state (EOS) for the water that covers the subcooled liquid region (where, at a given pressure, the water temperature is lower than the saturation temperature), the pure steam region (where, at a given pressure, the water temperature is higher than the saturation temperature) and the (saturated) two-phase mixture. For this purpose, the Steam Tables based on the 1984 NBS/NRC (National Bureau of Standards/National Research Council of Canada) formulation for the EOS (Haar et al., 1984) are considered herein to represent steam–water flows. In addition, the simulation of fast transients in pipe systems is usually performed using a one-dimensional approach. The quasi 1-D numerical approach presented in Daude and Galon (2018) is based on a Finite-Volume method using Godunov-type solvers and it is used for the simulation of compressible flows in flexible pipelines. In particular, the influence of the pipe hoop elasticity on the effective pressure wave speed is taken into account. Several air and water shock-type problems were tackled, involving pipe junctions, sudden changes of duct cross-section and elastic/plastic deformation of pipe walls. For example, the highly nonlinear propagation of a pressure wave in a liquid-filled pipe experiencing plastic deformation was computed and compared satisfactorily with experiments (Daude and Galon, 2018). In addition, skin friction, gravity and non-instantaneous valve closure, which are known to affect two-phase water-hammer wave evolution, are also considered here. The aim is to assess this Finite-Volume methodology through the simulation of water-hammer with column-separation and the comparison with published experimental data.

The paper is organized as follows. First, the governing equations and, then the associated numerical schemes used for the discretization are presented. Afterwards, the computation of the cavitation phenomenon is considered for 1-D theoretical Riemann problems. The numerical method is then assessed via comparison with experiments involving water-hammer with column-separation. A particular focus is on the dynamics of the water-column-separation in order to better understand where the cavitation occurs along the pipeline, how the largest vapor pocket interacts with the primary pressure wave, how the vapor pocket collapses thereby leading to a secondary water-hammer, and how the primary and the secondary WH waves interact. The influence of the initial flow velocity before valve closure on the duration of the cavity and on the severity of the secondary water-hammer is examined.

2. Governing equations

The Homogeneous Equilibrium Model (HEM) is used to represent two-phase flows under the following assumptions. The slip between phases is neglected and instantaneous thermal, mechanical and chemical equilibria are assumed. As a consequence the two phases share the same velocity, the same pressure, the same temperature and the same Gibbs free energy. In order to improve the modeling of the physical phenomena involved in the water-hammer events, the effect of