

Numerical investigation of homogeneous equilibrium model and fluid-structure interaction for multiphase water flows in pipes



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ABSTRACT

To simulate fast transient phenomena, one must consult realistic compressible fluid models that take into consideration phase change, shock wave generation and its propagation. In an industrial framework, such phenomena occur mostly near industrial apparatuses such as pumps, propellers, impellers and control valves. The rapid collapse of cavitation produces strong shock waves that may harm the interacting structure. In this paper, we present a numerical methodology to solve three-dimensional complex industrial problems through the combination of Homogeneous Equilibrium Model (HEM) phase change model proposed by Saurel et al. (1999), Arbitrary-Lagrangian-Eulerian (ALE) formulation and Fluid Structure Interaction (FSI). The HEM model is implemented in the LS-DYNA® software where the ALE and FSI capabilities were co-developed by the third co-author. To validate the proposed numerical methodology in order to extend the past one-dimensional solution, we consider the study of Tijsseling et al. (1996) on fluid structure interaction and cavitation in a single elbow pipe system that provides both numerical and experimental results.

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1. Introduction

Under certain configurations, water in pipes may be put into tension, and the local pressure may fall below the saturated pressure that gives rise to cavitation, small liquid-free zones (“bubbles” or “voids”). To simulate fast transient phenomena such as Water Hammers (WHs) or underwater explosions (UNDEX), one must consult realistic compressible fluid models that take into consideration phase change, shock wave generation and its propagation. From the existing approaches, we can distinguish two major categories:

- The “Two-Fluid Models” (Ahuja et al., 2001; Senocak and Shyy, 2002; Venkateswaran et al., 2002), where each material (liquid and vapor) has its own set of governing equations that include additional closing relations and coupling process at the interface between the two materials.
- The “One-fluid Models”, where only the average flow is considered by solving a unique set of governing equations and it can be based on a pure phase model (Vacuum Model (Tang and Huang, 1996) and Cut-off Model (Aanhold et al., 1998))

or a mixture model (Schmidt model (Schmidt et al., 1999), Isentropic model (Liu et al., 2004), modified Schmidt model (Xie et al., 2006) or Saurel et al. model (Saurel et al., 1999)).

In this paper, we numerically investigate the one-fluid models due to their simplicity, easy implementation within existing ALE and Lagrangian codes, and finally, their ability to model water phase changes in many industrial applications. From “numerical methods” point of view, the set of governing equations (in the continuum domain) solved are the same for both applications whether or not a phase change takes place. Except that for the phase change model, the solved density and energy variables are mixture quantities expressed in function of the saturated vapor fraction. An adequate equation of state (EOS) must be defined based on the mixture quantities, and furthermore, it must describe the kinematic and the thermodynamic behaviors of the phase change phenomenon and the continuous transition between liquid and vapor phases (creation of the cavitation and its collapse).

Schmidt et al. (1999) proposed the barotropic phase change model, which was originally designed for high-speed nozzle cavitating flows in diesel injectors. When the Schmidt model is applied to water, it was observed that when the vapor fraction is larger than a small quantity $O(10^{-2})$, the pressure cannot remain positive, and thus leads to unphysical results (Xie et al., 2006). In order to overcome the limitations of the Schmidt model,

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Xie et al. (2006) proposed to add a small positive cut-off pressure that prevents the cavitation pressure from reaching negative values. However, this modification is limited to small scale cavitation and cannot model properly the full transition from liquid to vapor phases. The isentropic model proposed by Liu et al. (2004), is another barotropic model that overcomes the limitations of Schmidt's model but it requires an empiric parameter that depends on the physical properties of the flow and the cavitation number which makes the model problem dependent. A numerical procedure for obtaining a value of the isentropic model parameter is given in detail in Liu et al. (2004).

In this work, we decided to investigate the model proposed by Saurel et al. (1999), which was designed to model high-velocity compressible flows including phase change caused by low pressure. This last model has the advantages of being

- a one fluid HEM model and easy to implement in existing codes,
- based on the water physical properties and thus physically consistent,
- and independent from any empiric parameter.

In an industrial framework, such phenomena occur mostly near industrial apparatuses such as pumps, propellers, impellers and control valves. The rapid collapse of cavitation produces strong shock waves that may harm the interacting structure. During the fluid structure interaction process, the fluid's pressure deforms the structure and the resulting deformation of the structure will modify the fluid's properties such as the shock wave pressure and the shock speed (Simpson, 1986), it is thus mandatory to consider FSI.

In this paper, we present the performance of the combination of the HEM phase change model and the LS-DYNA® software ALE-FSI capabilities that have been developed by the third co-author of this paper. In Section 2, the governing equations of the ALE formulation and fluid structure coupling method are described. Section 3 describes the HEM phase change model that have been implemented in LS-DYNA® software for the purpose of modeling fully coupled industrial problems. Section 4 is dedicated to the numerical validation of cavitation and FSI considering the benchmark test proposed by Tijsseling et al. (1996) who provide both experimental and numerical results.

2. ALE Multi-material formulation and FSI

To solve fluid-structure interaction problems, a Lagrangian formulation is considered for the structure and an ALE formulation for the fluid materials, where the fluid mesh can move to an arbitrary position. In general, the fluid nodes at the fluid-structure interaction are set to be Lagrangian and follow the interacting structure. The Lagrangian motion of the interface fluid nodes may cause high mesh distortion inside the fluid domain inducing a loss of accuracy in numerical solution, and even stop the run before reaching termination time, due to negative Jacobian in the highly distorted elements. To overcome those limitations, additional remeshing (smoothing) algorithms are triggered to redefine the new arbitrary fluid nodes position that maintains a good element aspect ratio for the sake of the numerical accuracy and stability.

We present in this section a brief description of the ALE formulation considered in this paper (more details are provided in Aquelet et al. (2005)) and the constrain-based FSI algorithm that constrains the Lagrangian fluid nodes motion with respect to the structural motion and computes the effort resulting from the FSI. The Equipotential smoothing algorithm is used to define the ALE internal fluid nodes position, more details are provided in Winslow (1963) and Hallquist (2015).

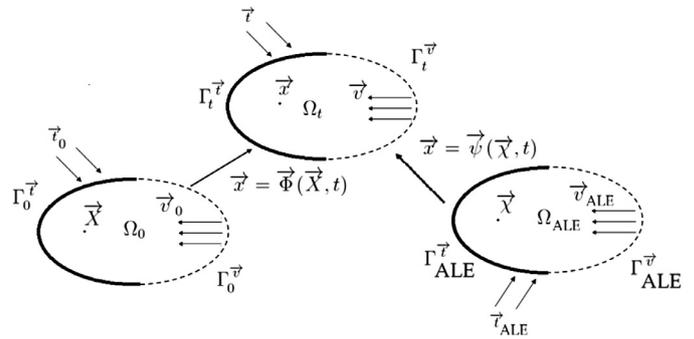


Fig. 1. Description of a material continuum body in the reference domain Ω_0 , the current domain Ω_t and the arbitrary domain Ω_{ALE} .

2.1. ALE Multi-material formulation

Let Ω_t^{ALE} be an arbitrary domain of boundary Γ_t^{ALE} , we define the injective function $\vec{\psi}(\vec{\chi}, t)$ that associates the ALE coordinates $\vec{\chi}$ in Ω_t^{ALE} at time t to the Eulerian coordinates \vec{x} in Ω_t by

$$\vec{x} = \vec{\psi}(\vec{\chi}, t). \tag{1}$$

A description of the transformation of a material continuum body from the reference domain Ω_0 to the current domain Ω_t and ALE domain Ω_{ALE} is shown in Fig. 1.

Let $f(\vec{x}, t)$ be a function of the Eulerian coordinates \vec{x} and the time t . The expression of $f(\vec{x}, t)$ in the ALE referential is given by

$$f(\vec{x}, t) = f(\vec{\psi}(\vec{\chi}, t), t) = f^{ALE}(\vec{\chi}, t). \tag{2}$$

The partial time derivative of the function $f^{ALE}(\vec{\chi}, t)$ in the ALE referential is given by

$$\frac{\partial f^{ALE}(\vec{\chi}, t)}{\partial t} = \frac{\partial f(\vec{x}, t)}{\partial t} + \frac{\partial \vec{\psi}(\vec{\chi}, t)}{\partial t} \cdot \nabla_{\vec{x}} f(\vec{x}, t), \tag{3}$$

where $\vec{v}_{ALE} = \frac{\partial \vec{\psi}(\vec{\chi}, t)}{\partial t}$ is the ALE velocity.

Now considering material time derivative is related to the partial time derivative by

$$\frac{df(\vec{x}, t)}{dt} = \frac{\partial f(\vec{x}, t)}{\partial t} + \vec{v} \cdot \nabla_{\vec{x}} f(\vec{x}, t). \tag{4}$$

And subtracting Eqs. 3 to 4, we finally obtain the relation between the material time derivative and the partial time derivative in the ALE referential

$$\frac{df}{dt} = \frac{\partial f^{ALE}}{\partial t} + (\vec{v} - \vec{v}_{ALE}) \cdot \nabla_{\vec{x}} f. \tag{5}$$

We denote by $\vec{w} = (\vec{v} - \vec{v}_{ALE})$ the convective velocity (the difference between the fluid's velocity and the ALE domain velocity).

2.2. Conservation equations

The ALE formulation for the conservation equations are obtained by substituting the function $f(\vec{x}, t)$ Eq. 5 by the density, the velocity vector and the internal energy in the equations of the conservation of mass, conservation of linear momentum and conservation of the energy, respectively. Thus, the ALE conservation equations in its nonconservative form are given by:

$$\frac{\partial \rho}{\partial t} = -\rho \frac{\partial v_i}{\partial x_i} - w_i \frac{\partial \rho}{\partial x_i} \tag{6}$$

$$\rho \frac{\partial v_i}{\partial t} = \sigma_{ij,j} - \rho w_i \frac{\partial v_i}{\partial x_j} \tag{7}$$

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