Phase Change Equation of State for FSI Applications

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Abstract

To simulate fast transient phenomena, one must consider 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 the work on Homogeneous Equilibrium Model (HEM) phase change model implemented in the LS-DYNA® that is compatible its legacy ALE and FSI capabilities. Validation against experimental data is shown through previously published test case of cavitation in elastic water pipe.

Introduction

Under certain configurations, compressible liquids the local pressure may fall below the saturated pressure that gives rise to cavitation. This situation can be encountered in industrial applications such as Water Hammers and Under Water Explosion in nuclear and marine industries, respectively. The different transition regimes that occur in cavitation phenomena (phase change, shock waves creation due to the collapse and its propagation) must be modelled in order to lead to reliable and accurate results. From the existing approaches, we can distinguish two major categories: The “Two-Fluid Models” [1, 2, 3] and the “One-fluid Models”.

In this paper, we present the Saurel et al.[4] HEM one-fluid models that has been recently implemented in LS-DYNA due to their simplicity, easy implementation within existing codes (ALE and Lagrangian SPH), and finally, their ability to model phase changes in many industrial applications, in particular for water applications. The solved density and energy variables are mixture quantities expressed in function of the saturated vapor fraction. In order to close the system, the appropriate EOS based on the mixture quantities is used such that the kinematic and the thermodynamic equilibrium are satisfied; and also the continuous phase change transitions. 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 [5, 6, 7], it is thus mandatory to consider FSI.

In this paper, we present the work presented in detail in [6], on the implementation of HEM phase change model in LS-DYNA and its validation using ALE and FSI capabilities of the software.

Phase Change Models

This section presents the model by Saurel et al. [4] that has been implemented for modeling model complex industrial problem including phase change in compressible flows, shock waves. The method is based on the following three main assumptions in the mixture region:

1- Mixture density and mixture internal energy are mean quantities of both liquid and vapor phases. They are functions of vapor fraction, saturated liquid and vapor liquid densities:

$$\rho = \alpha_v . \rho_v^{sat}(T) + (1-\alpha_v) . \alpha_v . \rho_l^{sat}(T) \tag{1}$$

$$e = Y_v . e_v^{sat}(T) + (1-Y_v) . e_l^{sat}(T) \tag{2}$$

Where α_v is the vapour fraction defined by:

$$\alpha_v = \frac{V_v}{V} = \left(\begin{array}{l} 0 \ if \ \rho \geq \rho_l^{sat}(T) \\ \frac{\rho - \rho_l^{sat}(T)}{\rho_v^{sat}(T) - \rho_l^{sat}(T)} \ if \ \rho \leq \rho_l^{sat}(T) \\ 1 if \ \rho \leq \rho_v^{sat}(T) \end{array} \right) \tag{3}$$

Y_v, the vapor mass fraction defined by

$$Y_v = \frac{\rho_v^{sat}(T) . \alpha_v}{\rho} \tag{4}$$

T the temperature.

2- Liquid and vapor phases are in kinematic equilibrium

3- The liquid and vapor phases are in thermodynamic equilibrium

$$\rho_l^{sat}(T) = \rho_v^{sat}(T) = \rho^{sat}(T) \quad \text{and} \quad T_l^{sat} = T_v^{sat} = T^{sat} \tag{5}$$

Pressure, liquid density and vapor density at saturation state can be either provided by tables obtained from experimental database or derived analytical equations. The latest one is selected in the LS-DYNA implemented version. For further details on the specific case of water material, the reader can refer to Messahel et al. [6]

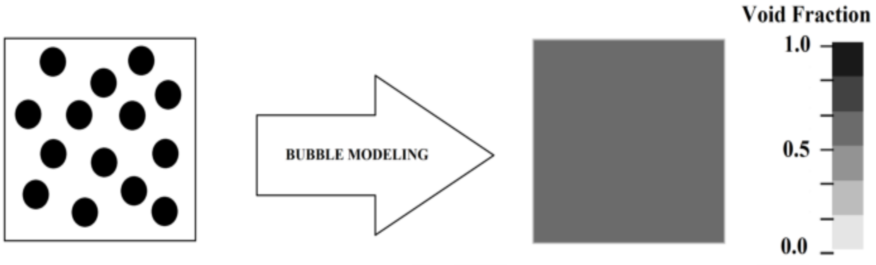

Figure 1 Discrete vapor bubbles and Fringe levels of the vapor fraction homogeneous model representation (Eq.3).

Vapor Phase $\alpha_v = 1$

Pressure in the liquid region is computed using the modified Tait EOS

$$P(T) = \rho(T).R.T \qquad (6)$$

R is the specific gas constant for vapour (for water R= 461.5. J.Kg^{-1}.K^{-1}**)**

Mixture Phase $0 < \alpha_v < 1$

In the mixture region, pressure and temperature of both liquid and vapor phases are assumed to be in equilibrium.

$$\rho = \rho_l = \rho_v = \rho^{sat}(T) \text{ and } T = T_l = T_v = T^{sat}$$

Using equations (1-4), the internal energy in the mixture, $e(T)$ is given by (6)

$$e(T) = (\alpha_v.\rho_v^{sat}(T).e_v(T) + (1.-\alpha_v).\rho^{sat}{}_l(T).e_l(T)) / \rho(T) \qquad (7)$$

and the speed of sound in c the mixture by Wallis equation [14]

$$\frac{1}{\rho.c^2} = \frac{\alpha_v}{\rho_v^{sat}(T).c_v^2} + \frac{1.-\alpha_V}{\rho_L^{sat}(T).c_L^2} \qquad (8)$$

A nonlinear procedure is developed to solve for the mixture temperature and the vapour fraction to satisfy equilibrium equation for the internal energy equation (7).

For mixture region the pressure is given by:

$$P(T) = P^{sat}(T) \qquad (9)$$

Numerical Simulation

In this section we present validation against an experimental study of cavitation in elastic water pipes. This test case is complex is a sense that it includes non-linear and complex multi-physics effects such as FSI, phase change and solid-solid contacts. Thus, it represents an ideal case to validate the implemented phase change model and its conjugate application with the legacy capabilities of LS-DYNA.

Some researchers tried to simplify the problem and treated it in a two steps decoupled manner: first, by assuming that the structure is rigid and solving the fluid problem to obtain fluid pressure; then secondly, by applying the resulting fluid pressure load on the deformable structure. This strategy led to an over-estimation of the pressure wave velocity that will be compared to experimental data by Tijsseling et al., 1996 [8]. In figures 2 and 3 we show a description and a sketch of the numerical setup, respectively.

The model is composed of 217,920 ALE hexahedra solid elements (Hallquist [15]) for the water, 5160 Lagrangian hexahedra solid elements for both the rigid steel rod, the impact end plug and the remote end cap and 44,0 0 0 Belytschko–Lin–Tsay shell elements for the full single elbow pipe system, Half of the model is simulated by considering the X–Y plane symmetry. A sketch of the model is shown in Fig. 3. The numerical pressure at location PT6 is plotted and compared to experimental data, which shows good correlation.

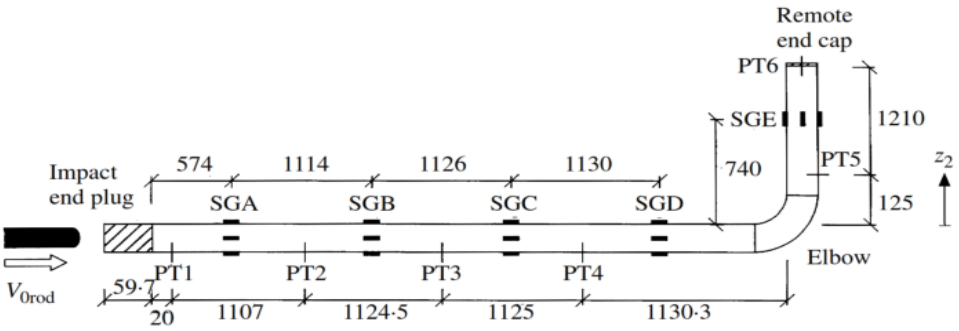

Figure 2: One-elbow pipe system (numerical values in mm are not to scale)[8]

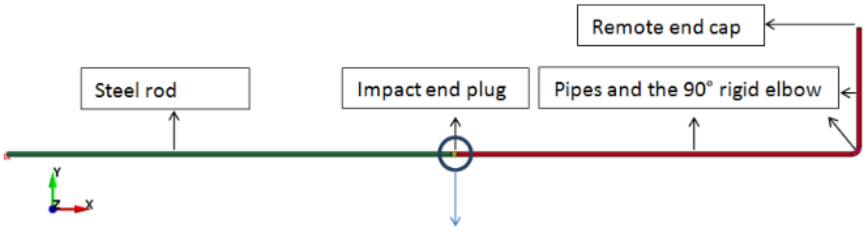

Figure 3: Sketch of the numerical model [6]

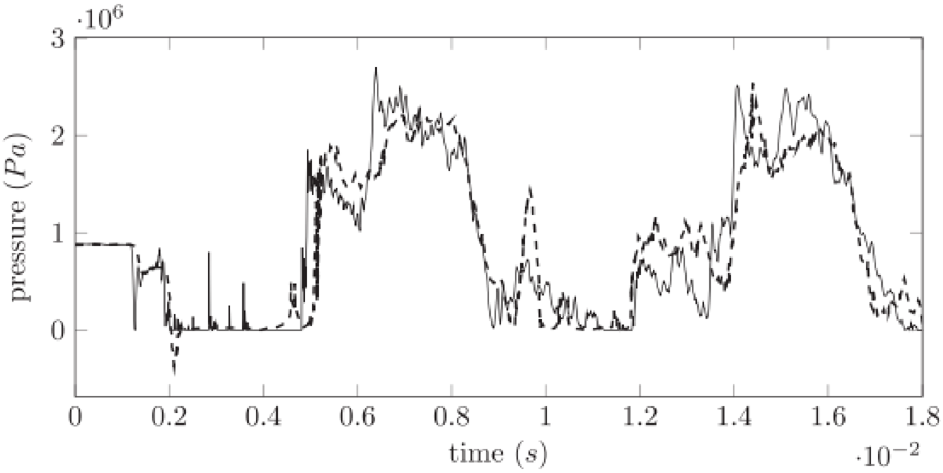

Figure 4: Absolute pressure at sensor PT6: Experimental results Tijsseling et al., [8], (--), numerical results with elastic pipes (—).

Conclusion

In this paper, HEM phase change model implemented model is presented and its validation shows good agreement between strongly coupled simulations and experimental results. It shows that combination of HEM phase change model and ALE formulation and FSI capabilities of LS-DYNA used for modeling multiphase flows in interaction with structures including phase change and shock wave due to the collapse of the cavitation can be modeled accurately. This last point is of crucial interest in industrial engineering for the design and the conception of safer pipe systems and the improvement of its performance. Indeed, once numerical simulations are validated with experimental test results, complex systems including FSI phenomenon with phase change can be numerically simulated.

References

[1] V. Ahuja, V. Hosangadi, S. Arunajatesan, Simulation of cavitation flows using hybrid unstructured meshes,
Journal of Fluids Engineering 40 (2001) 123–331. doi:10.1115/1.1362671.
[2] I. Senocak, W. Shyy, A pressure-based method for turbulent cavitating flow computations, Journal of Computational Physics 176 (2002) 363–383.
[3] S. Venkateswaran, J. W. Lindau, R. F. Kunz, C. L. Merkle,
Computation of multiphase mixture flows with compressible effects,
Journal of Computational Physics 180 (2002) 54–77.
[4] R. Saurel, J. P. Cocchi, P. B. Butler, Numerical study of cavitation in the wake of a hyper-velocity underwater projectile,
Computer Methods in Applied Mechanics and Engineering 15 (4) (1999) 513–522.
[5] A. R. Simpson, Large water hammer pressures due to column separation in sloping pipes,
Ph.D. Thesis, University of Michigan, USA (1986).
[6] R. Messahel, B. Cohen, M. Souli, M. Moatamedi, Fluid-structure inter- action for water hammers effects in petroleum and nuclear plants,
The International Journal of Multiphysics 5 (2011) 377–386.
[7] Messahel, R., Regan, C., Souli, M., Ruiu, C.
Numerical investigation of homogeneous equilibrium model and fluid-structure interaction
for multiphase water flows in pipes,
International Journal of Multiphase Flow, vol. 98, pp. 56–66, Year 2018.
[8] A. S. Tijsseling, A. E. Vardy, D. Fan, Fluid-structure interaction and cavitation in a single-elbow pipe system,
Journal of Fluids and Structures 10 (1996) 395–420.
[9] G. B. Wallis, One-dimensional two-phase flow
McGraw-Hill, 1969.
[10] J. O. Hallquist, LS-DYNA Theory Manual,
LSTC, Livermore Software Technology Corporation CA 94551 (USA) (8 2015).