Numerical Modelling of Dissolved Gas in Compressible Two-phase Mixture

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Abstract

Cavitation posses great challenges in the engineering industries as they leads to performance loss and material damage. Cavitation flows entail phase change and hence very large and steep density variations in the low pressure regions. The cavitation inception and the corresponding erosion are very sensitive to the magnitude of non-condensible gases, which are dissolved or ingested in the operating liquid. The overall goal of this study is to develop a mathematical model that accounts for the effect of dissolved gas in the two-phase flow and apply it in industrial applications.

As an initial attempt a homogeneous model based on barotropic equation of state is being developed. The model is fully compressible. The numerical code will be implemented in finite volume based open source code called OpenFOAM

Methods and Materials

The aim is to develop a homogeneous barotropic model for a two-phase mixture with NCG.

The density of the pure liquid, vapor and gas is defined as

$\rho_l = \rho_{lsat} + \psi_l (p - psat);\ \rho_v = \psi_v p;\ \rho_g = \psi_g p$

Where, ψ is the compressibility of the corresponding phases

The mixture density is defined as

$$\rho_m = \alpha_l \rho_{lsat} + \alpha_v \rho_{vsat} + \alpha_g \rho_g$$

where,

$\alpha_v = (1-\alpha_g)\frac{(\rho_{lsat}-\rho_m)}{(\rho_{lsat}-\rho_{vsat})}$ and $\alpha_l + \alpha_v + \alpha_g = 1$

From the above relations the three-phase mixture density can be derived as

$$\rho = \alpha_l \rho_{lo} + (\alpha_l \psi_l + \alpha_v \psi_v + \alpha_g \psi_g - \psi) p_{sat} + p\psi$$

The compressibility is modeled using either (Wallis or linear). This can be selected during the run time.

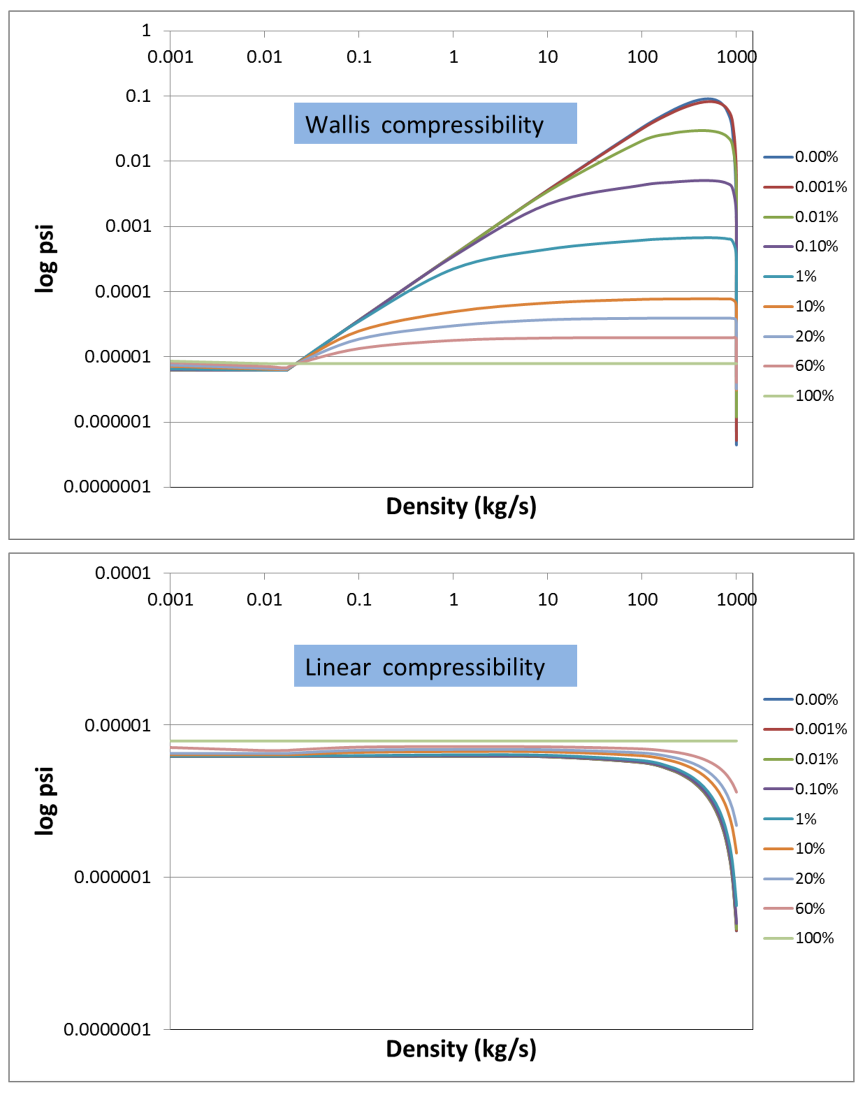

Figure 2. compressibility vs density relation with Wallis and linear compressibility model

Introduction

The capability for simulating multi-dimensional cavitation flow is of critical importance for efficient designing of engineering devices. In most of the engineering devices cavitation is an undesirable phenomena which leads to loss of efficiency.

Most of the numerical studies related to cavitation flow assumes that the liquid is pure, i.e. absolutely no gas (NCG). There are few numerical and experimental studies which reports about the effect of NCG in the performance of hydraulic and fuel pumps [5, 6]. One primary effect of NCG could be due to the expansion of the gas at lower pressure leading to significant gas volume fraction and thus impacting the density, velocity and pressure distribution of the mixture. Another impact could be on the threshold pressure for the phase-change. In spite of these , there have been very few attempts to model the effect of dissolved gas in cavitation phenomena. Few noticeable works are from Singhal et al.(2002) and Örley et al.(2015).

The 'Full cavitation model' developed by Singhal et al.(2002) is being widely used in most of the commercial solvers. In this model a transport equation for the vapor mass fraction with proper source terms to incorporates condensation and evaporation is solved in order to track the vapor.

Örley et al.(2015) employ a barotropic two-phase/two-fluid model to study primary breakup of liquid jets in nozzle. They used a homogeneous mixture approach for modelling liquid vapor and NCG. They assume constant speed of sound (c) for the liquid and liquid-vapor region in order to derive a relation between the density and pressure.

The model used for the current study is described in the following sections. The major assumptions involved are described below

Assumptions

- The mixture is in thermodynamic equilibrium
- Surface tension is neglected
- Slip between the phases is neglected
- The mass fraction of the gas is known a priori

Procedure and Results

1. A transport equation for the gas mass fraction is solved
$$\frac{\partial f_g \rho}{\partial t} + \nabla\left(f_g \rho \mathrm{U}\right) = 0$$
2. Volume fractions are calculated
3. The compressibility is calculated (Linear/Wallis)
$$\psi = \alpha_l \psi_l + \alpha_v \psi_v + \alpha_g \psi_g$$
$$\psi = (\alpha_l \rho_{lsat} + \alpha_v \rho_{vsat} + \alpha_g \rho_g)\left(\frac{\alpha_l \psi_l}{\rho_{lsat}} + \frac{\alpha_v \psi_v}{\rho_{vsat}} + \frac{\alpha_g \psi_g}{\rho_g}\right)$$
4. Momentum equation is solved
$$\frac{\partial \rho U}{\partial t} + \nabla \bullet (\rho U U) = -\nabla p + \nabla \bullet [\eta_{eff}(\nabla U + (\nabla U)^T)]$$
5. Iterative pimple algorithm is used for solving pressure
$$\frac{\partial \rho}{\partial t} = \frac{\partial (p\psi)}{\partial t} - p_{sat}\frac{\partial \psi}{\partial t} - \frac{\partial \alpha_v}{\partial t}\left(\rho_{l,0} + (\psi_l - \psi_v)p_{sat}\right) - \frac{\partial \alpha_g}{\partial t}\left(\rho_{l,0} + (\psi_l - \psi_g)p_{sat}\right)$$

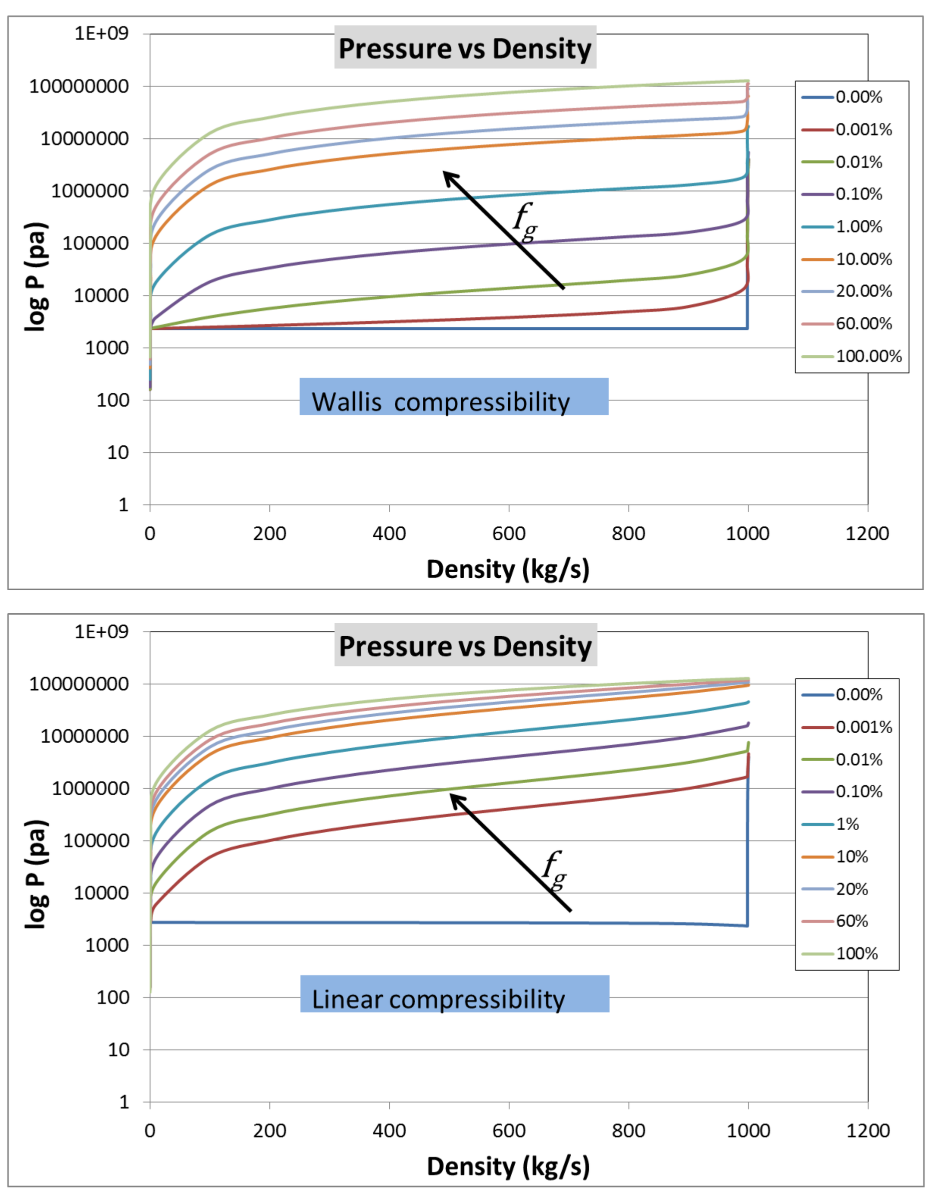

Figure 1. Pressure vs density relation with Wallis and linear compressibility model

Discussion

The three phase is being tested for simple 2D nozzle flows. Below shown is the contours of NCG distribution and the vapor generated after 6.7ms and the simulation result

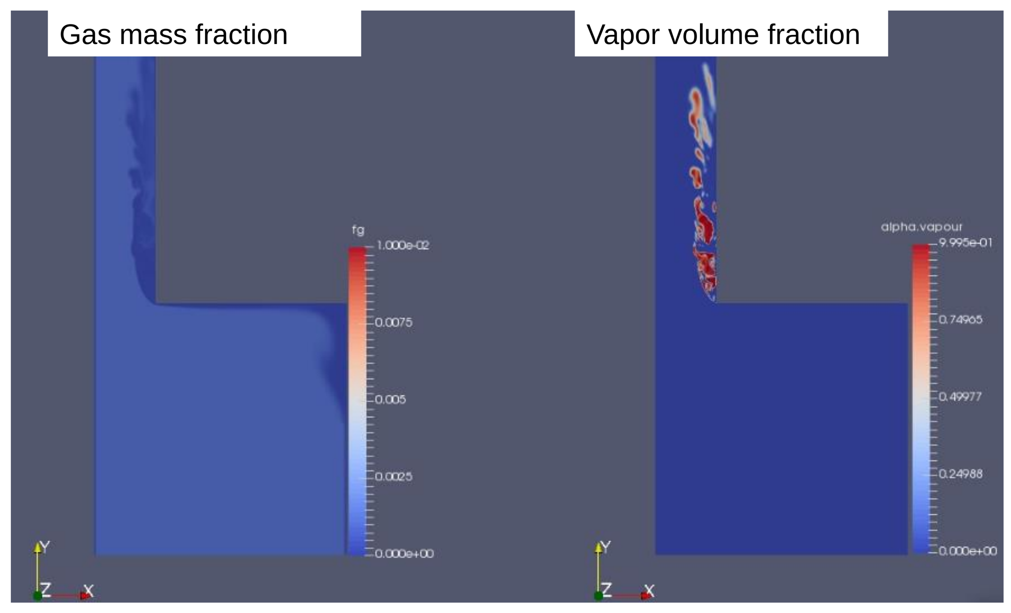

Figure 3. distribution of gas mass fraction and vapor volume fraction after 6.ms

From the analysis performed it was found that the model over predicts vapor fraction in the presence of gas.

Conclusions

The above equations of state for three-phase cavitation have two major drawbacks inherent to the equations.

1. It over predicts the vapor fraction
2. It has multiple solutions for density for the same pressure near saturation.

In order to overcome these difficulties an alternate two-phase model is being considered, which is a piecewise model. With proper tuning of parameters this model gives continuous variation for speed of sound from pure liquid to pure vapor phase.

The model uses modified Tait equation for pure liquid, Wallis equation for liquid-vapor mixture and isentropic gas equation for pure vapor phase to relate density and pressure.

This model is now implemented in OpenFOAM and is being tested for two-phase flows. Further it will be expanded to accommodate effect of NCG.

Contact

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