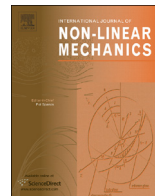




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Modeling gaseous and vaporous cavitation in liquid flows within the context of the thermodynamics of irreversible processes

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ABSTRACT

This paper deals with the modeling of gaseous and vaporous cavitation in homogeneous and isothermal flows of compressible Newtonian liquids. The constitutive equations are derived within the framework of the thermodynamics of irreversible processes. The rate mass transfer related to the cavitation phenomena are consistently described as irreversible processes, being each of these mechanisms associated with a specific rate of energy dissipation. By means of a simple numerical simulation, which describes an expansion motion of water at room temperature confined in a piston-cylinder system, the influence of each type of cavitation on the mechanical response of the fluid is investigated, when they act isolatedly and simultaneously. The obtained results show that quite distinct physical behaviors are observed. The vaporous cavitation significantly inhibits the mass transfer process associated with the gaseous cavitation, but the reciprocal is not true.

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1. Introduction

Cavitation is the formation of a gaseous phase in a liquid as a result of pressure reduction. There are two types of cavitation, the vaporous cavitation (V-cavitation) and the gaseous cavitation (G-cavitation), both of them taking place at almost constant temperature. The V-cavitation is the well-known formation of a vapor phase and the G-cavitation is the release of gas that was dissolved in the liquid. While the former process takes place whenever the pressure falls below the saturated vapor pressure, the latter is activated when the pressure drops below the saturation pressure of the dissolved gas in the liquid.

Internal and external liquid flows may be subjected to V and G-cavitation under not only steady but also unsteady regimes. The cavitation phenomena may be induced by different aspects related to the fluid flow such as boundary curvature of solid surfaces in contact with the liquids, vortices, turbulence and transient expansion waves [1–3]. They appear in many engineering problems, more specifically in turbomachinery, hydrofoils, marine propellers and hydraulic pipelines and their appurtenances such as valves and nozzles. Since the cavitation is associated with loss on performance and damage to system components, the prediction and characterization of cavitating flows have been the subject of intense research in past decades [4–18]. For a broad and updated

review on the subject the reader is referred to the articles of [2,3,17] and references therein.

Since in many practical applications the liquid has a dissolved gas in solution, these phenomena should be analyzed simultaneously in spite of having quite distinct time scales, as long as the pressure reduction is capable to induce both cavitation mechanisms. The acknowledgment of the need to take both cavitation phenomena into account in the analysis of engineering problems is not new [5] and the continuing effort in pursuing non-equilibrium models capable to describe non-linear effects, such as hysteresis, is still a subject of current research [17,18].

However, in the great majority of these problems the cavitation phenomena are either approached separately or mass transfer effects are not accounted for. Moreover, several mechanical models used to describe these physical phenomena are derived without appealing to any thermodynamic theory [4–7,15,9,18]. For instance, in V-cavitation the pressure is assumed to remain constant at the saturated vapor pressure during the cavitation, what is equivalent to admit a non-dissipative process [10]. In G-cavitation, the rate mass transfer of gas either is not accounted for [7,8] or is derived by extending Henry's law to non-equilibrium states [4–6,14]. For both cavitation phenomena no explicit rate of energy dissipation has been proposed and associated with the mass transfer processes.

Aiming to advance the knowledge in the area by unifying these non-linear phenomena within the same framework, it is proposed in this paper a new logically consistent thermodynamic model to describe simultaneously both the V and G-cavitation as truly dissipative mechanisms. To properly account for the irreversible

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character of the cavitation phenomena, the constitutive equations for the rate mass transfer of vapor and gas are derived within the framework of the thermodynamics of irreversible processes. The proposed model unifies some recent works [10,17] within the same context and allows the assessment and quantification of the rate of energy dissipation for each one of these mass transfer mechanisms. By means of a simple numerical simulation, the influence of the gaseous and vaporous cavitation (acting together or isolatedly) on the mechanical response of the fluid is investigated, when the mixture is subjected to a single expansion motion.

2. Balance equations and the second law of the thermodynamics

Because vaporous and gaseous cavitation are localized phenomena, which take place at discrete and small regions of the fluid flow domain, it is reasonable to assume that the homogeneous two-phase fluid flow assumption holds (the liquid and gaseous phases share the same velocity and temperature). Thus, by restricting the analysis to isothermal transformations ($\dot{\theta} = 0$ and $\nabla\theta = 0$; θ being the absolute temperature), it suffices to consider the balance equations of mass, momentum along with a local version of the second law of thermodynamics (SLT) for the mixture as a whole, instead of doing it for each phase separately as it occurs for two-fluid models and theories of mixture [19,20]. Under suitable regularity assumptions, these equations in Eulerian coordinates become [21]

$$\dot{\rho} + \rho \nabla \cdot \mathbf{v} = 0, \quad (1)$$

$$\rho \dot{\mathbf{v}} = -\nabla p + \nabla \cdot \mathbf{S} + \rho \mathbf{g}, \quad (2)$$

$$d = -(p + \Psi) \nabla \cdot \mathbf{v} + \mathbf{S} : \mathbf{D} - \dot{\Psi} \geq 0. \quad (3)$$

As usual, the superimposed dot stands for the material time derivative, ρ is the mass density of the mixture, \mathbf{v} is the mixture spatial velocity field, $\mathbf{S} = \mathbf{S}^T$ is the extra stress tensor due to motion, \mathbf{g} is the external body force per unit mass and \mathbf{D} is the rate of deformation tensor. The mixture pressure is represented by p , whereas Ψ stands for the Helmholtz free energy of the mixture per total unit volume. Eq. (3) is the well-known Clausius–Duhem inequality and requires that the rate of energy dissipation d be non-negative.

The two-phase fluid flow is assumed to be a two-constituent mixture. The gaseous phase is formed by the vapor of a liquid and an inert free gas, whereas the liquid phase is constituted of pure liquid along with dissolved gas. The vapor and the free gas are assumed to occupy the same volume in the gaseous phase. The same assumption is admitted to hold with respect to the liquid and the dissolved gas in the liquid phase. The concentration of dissolved gas in the liquid c is defined as being the quantity of mass of dissolved gas per unit volume of liquid phase. To account for the coexistence of the liquid and gaseous phases at every material point and time instant, we consider an internal variable α , $\alpha \in (0, 1)$, which denotes the void fraction. It is defined as being the ratio of the volume occupied by the vapor along with the inert gas in suspension and the total volume of the mixture. As a result, the mass density of the mixture can be expressed as

$$\rho := (1 - \alpha)(\rho_l + c) + \alpha(\rho_v + \rho_g), \quad (4)$$

in which ρ_v and ρ_g stand for the mass densities of vapor and the free gas per unit volume of the gaseous phase, respectively and ρ_l the mass density of the liquid per unit volume of the liquid phase, all of them assumed as being compressible fluids.

By taking into account the interchange of mass of gas as well as vapor between the liquid and gaseous phases along with Eq. (4),

Eq. (1) can be split as follows:

$$(1 - \alpha)\dot{\rho}_l - \rho_l \dot{\alpha} + (1 - \alpha)\rho_l \nabla \cdot \mathbf{v} = -\Gamma_v, \quad (5)$$

$$(1 - \alpha)\dot{c} - c\dot{\alpha} + (1 - \alpha)c \nabla \cdot \mathbf{v} = -\Gamma_g, \quad (6)$$

$$\alpha\dot{\rho}_v + \rho_v \dot{\alpha} + \alpha\rho_v \nabla \cdot \mathbf{v} = \Gamma_v, \quad (7)$$

$$\alpha\dot{\rho}_g + \rho_g \dot{\alpha} + \alpha\rho_g \nabla \cdot \mathbf{v} = \Gamma_g, \quad (8)$$

in which Γ_g and Γ_v are associated with the G and V-cavitation phenomena and represent the rate mass transfer of gas and vapor per total unit volume, respectively.

When $\Gamma_g > 0$, the gas dissolved in the liquid evolves in the fluid as free gas in suspension. On the other hand, if $\Gamma_g < 0$, then the free gas dissolves in the liquid. Analogously, when $\Gamma_v > 0$, the liquid transforms into vapor. On the other hand, if $\Gamma_v < 0$, then vapor is converted into liquid. Finally, if $\Gamma_g = 0$ and $\Gamma_v = 0$, then there is no interchange of mass between the phases.

Eqs. (2)–(3) and (5)–(8) form the fundamental balance equations to describe the G and V-cavitation problem in homogeneous flows under isothermal transformations. To complete the problem description, we must add the constitutive relationships for p , \mathbf{S} as well as for Γ_g and Γ_v , which must satisfy Eq. (3).

3. Constitutive theory

The constitutive equations describing the macroscopic mechanical behavior of the mixture are derived in the framework of the thermodynamics of irreversible processes. In this theory, once the local state of the material has been characterized by means of an appropriate choice of a set of state variables, two thermodynamic potentials – the Helmholtz free energy and a pseudo-potential of dissipation – are sufficient to derive a complete set of constitutive equations. As we shall see, the restriction associated with α is treated in this work as a physical property in the constitutive equations. This approach has already been used in the modeling of the sorption–desorption problem in saturated porous media [22] and more recently in the modeling of vaporous [10] and gaseous [17] cavitation in flows of compressible fluids and of surface tension effects in homogeneous liquid–gas flows [23].

3.1. Helmholtz free energy

By restricting the analysis to Newtonian fluids, we choose as state variables the set $(\rho_l, c, \rho_v, \rho_g, \alpha, \theta)$ and assume that the free energy per total unit volume Ψ is supposed to be a function of this set, i.e., $\Psi = \Psi(\rho_l, c, \rho_v, \rho_g, \alpha, \theta)$. Since the fluid is regarded as a mixture, its behavior is supposed to comprise a combination of the thermo-mechanical properties of their constituents. Thus, the following form is proposed:

$$\Psi := (1 - \alpha)(\rho_l \Psi_l + c \Psi_c) + \alpha(\rho_v \Psi_v + \rho_g \Psi_g) + \bar{I}(\alpha), \quad (9)$$

in which

$$\Psi_l = \Psi_l(\rho_l, \theta) := -C_l \theta \log \theta + a_l^2 (\log \rho_l + \rho_l^0 / \rho_l), \quad (10)$$

$$\Psi_c = \Psi_c(\theta) := -C_g \theta \log \theta + a_g^2 \log(p_s / a_g^2) + a_g^2, \quad (11)$$

$$\Psi_v = \Psi_v(\rho_v, \theta) := -C_v \theta \log \theta + a_v^2 \log \rho_v + L, \quad (12)$$

$$\Psi_g = \Psi_g(\rho_g, \theta) := -C_g \theta \log \theta + a_g^2 \log \rho_g, \quad (13)$$

$$\bar{I}(\alpha) := \begin{cases} 0 & \text{if } \alpha \in (0, 1) \\ +\infty & \text{otherwise.} \end{cases} \quad (14)$$

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