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Modeling of release and absorption of gas in liquid–gas flows within a consistent thermodynamic framework

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ABSTRACT

This work presents a consistent thermodynamic model to describe the gas release and gas absorption phenomena in homogeneous liquid–gas flows undergoing isothermal transformations. The liquid–gas mixture is regarded as a pseudo-fluid whose constitutive behavior is obtained from two thermodynamic potentials: the Helmholtz free energy and a pseudo-potential of dissipation. Thanks to the inclusion of the concentration of dissolved gas in the liquid in the list of state variables, along with the gas volume fraction and the mass densities of the liquid and gas constituents, a suitable and simple expression for the rate of mass transfer of gas is derived. Besides of unconditionally satisfying the Second Law of the Thermodynamics, the proposed expression is capable to properly describe experimental data available in the literature with great accuracy for a relatively wide range of saturation pressures. Numerical simulations carried out for an water–air mixture, subjected to a single expansion and cyclic expansion–contraction loadings, illustrate the influence of the gas release on the mechanical response of the fluid, which exhibits dispersion and attenuation and also hysteresis.

1. Introduction

Liquids are known to be able to absorb certain amount of gas in contact with their free surfaces. Through a diffusive process, the gas dissolves in the liquid and stays there, unless its temperature is raised beyond the boiling point or its pressure is lowered below the saturation pressure of the dissolved gas. In this last process, usually referred to as gas release or, alternatively, gaseous cavitation, the gas comes out of solution as small bubbles that either are carried by the fluid flow stream as free gas or migrate towards the free surface or the upper parts of the systems where the liquid is confined, forming small and discrete cavities. Internal as well as external flows may be subjected to gaseous cavitation under steady and unsteady regimes. Boundary curvature of solid surfaces in contact with the liquids, vortices, turbulence and transient expansion waves are some typical examples of sources responsible for triggering the gas release phenomenon.

When wave propagation phenomena are involved in, the presence of free (also called entrained) gas in suspension in the liquid, even in tiny quantities, is responsible for reducing the wavefront speed in the medium and for attenuating the pressure peaks due to the added compressibility of the gas. Making use of distinct approaches, several investigators (Capriz & Cohen, 1983; Drew & Passman, 1999; Drumheller, Kipp, & Bedford, 1982; Henry et al., 1971; Marchal, 1962; Semenov & Kosterin, 1964; Temkin, 1992; Wood, 1930; Wylie & Streeter, 1993) have shown that the wavefront speed becomes highly dependent on the fluid pressure in a non-linear fashion. Depending on the amount of free gas and the pressure levels, the

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wave speed can reach values comparable with the fluid velocity, giving rise to the occurrence of shock waves. In addition, whenever the fluid pressure falls below the gas saturation pressure, dissolved gas evolves increasing even further the amount of free gas in the mixture and introducing additional and relevant effects of dispersion and attenuation (Baasiri & Tullis, 1983; Chaudhry, Bhallamudi, Martins, & Naghash, 1990; Wiggert & Sundquist, 1979; Wylie & Streeter, 1993).

By focusing on practical engineering applications, the most relevant problems in which gaseous cavitation plays an important role are those associated with transient fluid flows in piping systems. Typical examples include water distribution systems, sewage networks, nuclear reactor piping systems and aviation fuel pipelines (Bergant, Simpson, & Tijsseling, 2006; Swaffiled, 1972; Wylie & Streeter, 1993). The relevance of these applications seems to be responsible for concentrating the great majority of the scientific works related to free gas and gaseous cavitation on this specific context (Baasiri & Tullis, 1983; Cannizzaro & Pezzinga, 2005; Chaudhry et al., 1990; Hadj-Taieb & Lili, 1998; Kessal & Bennacer, 2005; Kranenburg, 1974; Swaffiled, 1972; Wiggert & Sundquist, 1979; Wylie, 1984). Since the gaseous cavitation in general precedes and influences the vaporous cavitation (the phenomenon in which the liquid is transformed into vapor whenever the pressure falls below the saturated vapor pressure of the liquid) many of the studies address both issues simultaneously (Baasiri & Tullis, 1983; Kranenburg, 1974; Wiggert & Sundquist, 1979; Wylie, 1984), in spite of having quite distinct time scales. Whereas the gas release takes place in a scale of the order of seconds, the vaporous cavitation is a faster process, occurring on a few micro-seconds. Like free gas and gaseous cavitation there are also other phenomena responsible for wave attenuation in transients in fluids (Bergant et al., 2008a, 2008b).

In contrast to the problem related to the free gas influence on the wave propagation in liquid–gas mixtures for which there exists a significant amount of theoretical and experimental studies (Capriz & Cohen, 1983; Chaudhry et al., 1990; Drumheller et al., 1982; Marchal, 1962; Freitas Rachid, 2006; Semenov & Kosterin, 1964; Swaffiled, 1972; Wood, 1930 ; Wylie & Streeter, 1993), only a few works are devoted to the gaseous cavitation phenomenon. With respect to experimental works concerned with measuring the gas released, those attributed to Schweitzer and Szebehely (1950), Wiggert and Sundquist (1979), Baasiri and Tullis (1983) and Zielke et al. (1990) are the most relevant. While in the first three works the gas release is monitored fundamentally during the vaporous cavitation, in the last one the authors are concerned only with the gas release process, by avoiding pressures as low as the saturated vapor pressure of the liquid in their experiments.

Theoretical works dealing with gas release in the context of fluid transients in piping systems are also restricted to a few number of works (Cannizzaro & Pezzinga, 2005; Kessal & Bennacer, 2005; Kranenburg, 1974; Wiggert & Sundquist, 1979; Wylie & Streeter, 1993). To cope with the effects of free gas on the wave propagation, most of these works consider as a basic premise the existence of small contents of free gas distributed throughout the flow by admitting homogeneous and isothermal liquid–gas mixtures. Since the liquid and the free gas share the same velocity and temperature, only balance equations for momentum and mass for the mixture as a whole are needed, along with one balance equation of mass for the free gas. Complemented with constitutive equations for the liquid and the free gas (which are assumed to be barotropic fluids and to share the same pressure), these equations form a set of three non-linear hyperbolic partial differential equations for the unknown fields of pressure, velocity and gas volume fraction.

The gaseous cavitation is commonly taken into account as a non-negative source term in the balance equation of mass for the free gas. It is equivalent to assume a one-way process of gas release, inasmuch as the reverse process (i. e., the gas absorption phenomenon) takes place in a time scale greater than the one associated with the gas release (Baasiri & Tullis, 1983; Wylie & Streeter, 1993). This assumption implies that the released gas stays as free gas or in cavities and does not re-dissolves in a subsequent rise in pressure. Since only a small portion of dissolved gas actually evolves during the life of most practical systems transients, it is generally assumed that the mass of dissolved gas remains constant at the initial value during a transient event.

One of the first attempts of deriving an expression for the rate of gas release is due to Van Wijngaarden (1967). Admitting that gas release is governed by convective diffusion of gas dissolved in the liquid to within the bubble, the author has appealed to the dynamics equation of a single spherical bubble, along with the large Péclet number assumption, to express the rate of gas release in terms of three parameters: the difference in dissolved gas concentration far from the bubble (saturation concentration of dissolved gas in the liquid) and at the bubble surface, the relative velocity between the bubble and the fluid and, finally, the bubble radius.

Seven years latter, by extending implicitly the Henry's law to states of non-equilibrium, Kranenburg (1974) rewrote the expression for the rate of gas release proposed by Van Wijngaarden (1967). The author has replaced the difference in dissolved gas concentration by the difference between the saturation pressure and the instantaneous fluid pressure. As a consequence, the Henry's proportionality constant appeared in the proposed expression. Making use of suitable values for the number of bubbles per unit volume of fluid and the relative velocity between the bubble and the fluid, Kranenburg (1974) has carried out numerical simulations involving pressure transients in the presence of gaseous and vaporous cavitation to investigate the influence of the former on the last phenomenon.

By recognizing the uncertainties involved in Kranenburg's model and also the need of more precise and physically based formulations, Wiggert and Sundquist (1979) have simplified the expression proposed by Kranenburg (1974) by admitting that the rate of gas release depends exclusively on the aforementioned pressure difference, seen as as a measure of the degree of supersaturation. To closure their proposal of a more simpler rate of gas evolution, Wiggert and Sundquist (1979) have introduced a coefficient of proportionality, which has been adjusted by using experimental data generated in their work.