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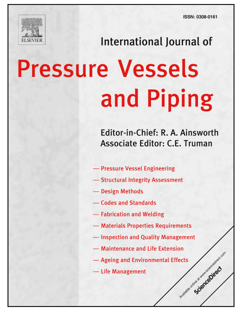

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WATER HAMMER WITH NON-EQUILIBRIUM GAS RELEASE

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Abstract
Water hammer transient with gaseous cavitation in a pipe shows that the amplitude of the first pressure surge, caused by the closure of the fast valve, is approximate to the Joukowsky pressure rise in liquid, while subsequent pressure surges are strongly influenced by the presence of air in the mixture with liquid water. These conditions are described and numerically simulated with the homogeneous two-phase flow model and a non-equilibrium model of air mass transfer between dispersed air bubbles and continuous liquid water. It is found that the generation of air bubbles is intensive when the rarefaction wave decreases pressure below the pressure of gas saturation in water for the first time after the Joukowsky pressure peak, while, later on, the mass transfer rate, due to air degassing and absorption, is much smaller. A numerically predicted pressure transient is validated by the comparison with available measured data, and an excellent agreement is achieved.

Keywords: water hammer, gaseous cavitation, numerical simulation.

1. Introduction

In natural and technical systems, water comes into contact with air, which dissolves in the water mass or is entrained in the form of microbubbles. If the water surface is, for a sufficiently long time, in contact with air, dissolved air will reach its saturation in water. Practically, there is no water without dissolved air. Brennen [1] reported that it takes weeks of deaeration to reduce the concentration of air in the water of a tunnel below 3 ppm (saturation at atmospheric pressure and related cold water temperature is about 15 ppm). According to Hammitt [2], untreated tap water contains about $n_b=1.13\times10^9$ microbubbles per m³ with the most probable size being about $d_b=6$ μm, while in degassed water, they are reduced to 0.911×10^9 microbubbles per m³ with the same most probable diameter of about 6 μm (a review of data on air and other gases' solubility in water was presented by Kolev [3]). The microbubbles encountered in degassed water have a negligible influence on water hydrodynamics in the initial states of water hammer experiments. These small microbubbles have the same velocity as a continuous water volume, while their influence on the air-water mixture's thermophysical parameters and sonic velocity is negligible. On the contrary, if the air dissolved in water is degassed during a pressure transient, it has a noticeable influence on the water-air mixture hydrodynamics. The obvious example is the water hammer test performed by Bergant and Simpson [4], with fast closing of the valve at the end of the 37.23-m long pipeline and with the relatively low velocity of 0.3 m/s prior to the valve closure (Fig. 1). The pressure change in front of the closed valve is shown in Fig. 2. After the valve closure, a compression wave is generated in front of the valve, which propagates towards the pipeline inlet connected to the upstream reservoir. The compression wave is reflected as the rarefaction wave at the upstream reservoir (the sign of the wave is changed by the reflection concerning the water mass in the reservoir). The rarefaction wave travels from the reservoir towards the closed valve and, at its arrival at the closed valve at 0.066 s (Fig. 2), the rarefaction wave reflects from the solid of the closed valve as the wave of the same sign and the pressure drops below the pressure of non-condensable air saturation in liquid, which results in air release from liquid. This phenomenon is known as gaseous cavitation and the appearance of discontinuity in the liquid phase, due to the presence of the gas phase, is called liquid column separation. It should be noted that, according to the measured pressure values reported by Bergant and Simpson [4], the minimum pressure during the column separation in front of the closed valve in the presented test case is still higher than the pressure of water thermodynamic saturation, which means that the conditions of water evaporation are not reached and only the air-water mixture exists. Further, the expansion wave travels towards the reservoir, reflects and changes its sign. The arrival of the compression wave at the closed

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