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Modeling of Impact Waves in LNG Ship Tanks

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This paper focuses on large sloshing waves that may impact the side walls or the ceiling of prismatic liquefied natural gas (LNG) ship tanks. Large pressure peaks may occur locally, which may damage the containment system. The physics involved prior to such impacts is complex and includes the development of free-surface instabilities due to the shearing gas flow, the gas compression just before and after entrapment, and the emission of pressure waves into the liquid at the impact points. Furthermore, as the LNG is in a state close to saturation, phase change phenomena might play an important role during the impact process, e.g., during the phase of gas compression driving condensation. This clearly poses a challenge to the software codes. This paper focuses on some of these aspects, especially gas compressibility and the influence of phase change. This paper concludes with an investigation of the possibilities concerning nonisothermal experiments with liquid methane or LNG.

INTRODUCTION

For any new project concerning a liquefied natural gas (LNG) membrane tank on a floating structure (an LNG carrier, a Floating Liquefied Natural Gas (FLNG), a Floating Storage Regasification Unit (FSRU), LNG fueled ships, LNG bunker ships, etc.), the sloshing assessment relies on sloshing model tests. For rather new applications such as offshore applications (FLNGs or FSRUs) or LNG as a fuel and related small-scale applications, as there is no feedback from the sea yet, the pressure measured at model scale (mostly at 1:40 scale) is directly upscaled as though there were a complete similarity between the model tests and the reality. This is obviously not the case as some phenomena involved at full scale are disregarded at model scale (e.g., the phase transition), and some others are biased due to unscaled properties of the fluids used at model scale (e.g., gas compressibility). Sloshing increases the boil-off rate of the cryogenic liquid. Clearly, it is of interest to reduce the boil-off as much as possible. Actually, only the gas-to-liquid density ratio (DR) is kept the same at both scales. This is achieved by the use of water and a heavy gas made of nitrogen and SF_6 in the model tank. Numerical simulations are not considered to be mature enough to replace tests. For the time being, they are not able to accurately simulate a single liquid impact including all the physics involved. Nevertheless, they are very useful for disentangling the different biases involved at model scale and analyzing their consequences for the scaling process.

Many tests or simulations have been performed in the last decade by different labs in order to better understand the influence of the different liquid and gas properties on the impact loads, often through the careful study of single impact waves.

Maillard and Brosset (2009) studied the influence of the gas-to-liquid density ratio through sloshing model tests with water and steam with a large range of pressures and temperatures. They showed the strong influence of this dimensionless number on the statistical pressures; the larger the density ratio, the smaller the pressures. Karimi et al. (2016) examined the influence of the DR on the wave shapes just before impact for single impact waves generated during sloshing model tests with a 2D tank. The same kind of single impact waves during 2D sloshing tests were simulated by Scolan and Brosset (2016) with a two-fluid potential code and by Hay et al. (2016) with a Finite Element (FE) incompressible two-fluid model and an Arbitrary Lagrangian Eulerian (ALE) approach. Their results matched Karimi's results, showing a delay in the breaking process for higher DRs. The influence of the density ratio is explained by a transfer of energy from the liquid to the gas. The higher the DR, the larger the transfer.

Among others, Bredmose et al. (2009), Bogaert et al. (2010), Kimmoun et al. (2010), and Lafeber et al. (2012a) described wave impact tests in flume tanks with water and air, looking especially at compressibility effects. Among others, Bredmose et al. (2015), Guilcher et al. (2013, 2014), Costes et al. (2014), and Rafiee et al. (2015) performed numerical simulations of single impact waves in flumes with different methods, but included two fluids and took into account their compressibility. They compared the behavior of entrapped gas pockets of different sizes at different scales, showing an analogy with the Bagnold piston model.

Lafeber et al. (2012b) showed that the impact loads can be considered to be the result of three different interacting influences that they named Elementary Loading Processes (ELPs): (1) the liquid compressibility involved during the direct impact when there is a discontinuity of normal velocity imposed by the rigid wall, which leads to the emission of a pressure wave through the liquid (ELP1); (2) the hydrodynamic load (Bernoulli) induced by the sharp turn of the liquid particles in front of the wall (ELP2); (3) the gas compression during the last stage of the escaping phase and when the gas is entrapped (ELP3). Guilcher et al. (2014) showed that these ELPs could be clearly discriminated in separated areas when a pressure map (a time history of the pressure profile) of the wall is examined.

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KEY WORDS: Wave impact, CFD, sloshing, LNG, phase change.