Journal of Fluids and Structures 80 (2018) 22–36

Contents lists available at ScienceDirect

Journal of Fluids and Structures

journal homepage: www.elsevier.com/locate/jfs

LNG-solid impacts with gas cushioning and phase change

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A R T I C L E I N F O

Article history:
Received 13 July 2017
Received in revised form 28 January 2018
Accepted 14 March 2018

Keywords:
LNG
Sloshing
Liquid–solid impact
Gas cushioning
Phase change

A B S T R A C T

LNG-solid impacts with gas cushioning and phase change are investigated theoretically in a coupled inviscid liquid and viscous gas regime. Condensation from the gas to the LNG is driven by local increases in the gas pressure above the saturation vapour pressure. This is modelled as a sink term on the kinematic boundary condition at the gas interface. To leading order, the bulk liquid motion is unaffected by condensation, with its evolution governed by the same boundary integral equation used in models of non-volatile gas-cushioned liquid–solid impacts. The proposed model extends the approach used to describe two-dimensional non-volatile gas-cushioned impacts by incorporating phase change and is applied to a range of physically relevant LNG-solid impacts associated with sloshing. As an LNG free-surface approaches touchdown with a solid wall, a gas pressure build-up occurs in the gap separating liquid from solid, which decelerates and deforms the liquid free-surface. This deformation of the free surface may result in gas entrapment. In non-volatile impacts, pockets of trapped gas are associated with oscillatory pressure signals, while previous experiments have shown that these oscillations may be damped by phase change in impacts involving volatile liquids. Compared to impacts with non-volatile liquids, gas condensation is shown to reduce both the impact pressures and the volume of gas trapped. Depending on the impact parameters, the proposed model differentiates between cases where a pocket of trapped gas may or may not be formed. A criterion on the critical normal impact velocity above which gas entrapment is not expected is obtained. This indicates that across a range of length scales that are physically relevant to LNG sloshing, gas entrapment is not expected for impact velocities greater than $0.05\,\mathrm{m\,s^{-1}}$. Impacts where gas compressibility is important are investigated, as well as impacts into corners of containment tanks with varying angles. The model developed is suitable for the analysis of small and medium-sized LNG-solid impacts, as well as larger-scale sloshing model tests involving impacts of water cushioned by water vapour. The importance of inertia in the gas is identified in larger scale impacts.

1. Introduction

The transport of liquefied natural gas (LNG) by ship occurs at atmospheric pressure, when the LNG is close to thermodynamic equilibrium with its gas phase. The resulting storage temperature of −163 °C poses many challenges for the structural containment of LNG, as the walls of the containment tank are constructed out of plywood (Arswendy and Moan, 2015), to improve the thermal insulation of the tank. Sloshing of LNG induced by global ship motions produces violent impacts between the LNG and the tank walls. During an inspection of the 138,000 $\mathrm{m^3}$ capacity LNG carrier Spirit of Catalunya in 2006, damage to the containment tank was observed (Gavory and de Seze, 2009). This has motivated further analysis of LNG sloshing impacts, to understand the induced loads and reduce the risk of a loss of containment.

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https://doi.org/10.1016/j.jfluidstructs.2018.03.005
0889-9746/

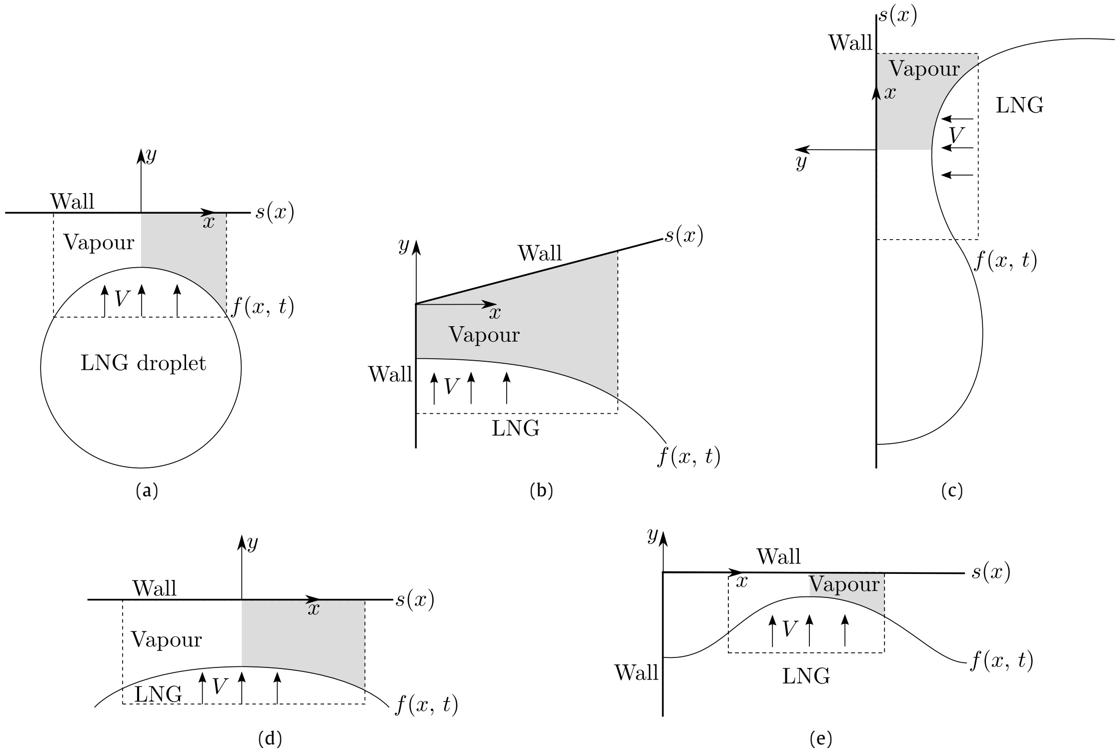

Fig. 1. A sketch of different types of gas-cushioned liquid–solid impacts associated with LNG sloshing, presented in approximate order of increasing size, showing (a) an LNG droplet approaching the roof of a tank, (b) a tip of a liquid jet running up the side of a tank wall and approaching a corner of a tank, (c) a tip of a breaking wave as it approaches impact with a wall, (d) LNG rising up to hit the roof of a tank and (e) LNG trapping a gas pocket in the corner of a tank. In each case the region enclosing the initial vapour cushioning is bounded by a dotted line, while the grey shaded areas indicate the spatial domain illustrated in subsequent plots of the free-surface evolution.

The behaviour of LNG during sloshing has been investigated, both experimentally and theoretically, to accurately predict the pressures and loads on the containment tank walls (see e.g. Dias et al., 2007; Faltinsen and Timokha, 2009). A feature of many liquid–solid impacts, including those associated with liquid sloshing, is the entrapment and entrainment of gas. This occurs due to interactions between the liquid, the wall and the gas separating the liquid from the wall prior to impact. Such phenomena occur across a wide range of impact length scales and momenta, ranging from sea wave impacts with coastal defences (Peregrine, 2003), to impacts of individual droplets on solid substrates (Li and Thoroddsen, 2015). Pockets of trapped gas or regions of aerated liquid, which expand and contract during impact, give rise to oscillatory pressures signals (Topliss et al., 1992; Abrahamsen and Faltinsen, 2012, 2013). Oscillatory pressures have been measured experimentally in a pocket of gas trapped in the corner of a tank by a free-surface wave (Abrahamsen and Faltinsen, 2011) and in wave impacts with vertical walls (Lugni et al., 2010b). In wave impacts with vertical walls, flip-through events that result in vertical jets running up the wall, may or may not involve gas entrainment (Lugni et al., 2006). Three different flip-through modes have been identified, which are referred to as: mode (a) *flip-through events without gas entrainment*, mode (b) *flip-through events with a single well define gas cavity* and mode (c) *flip-through events involving a region of small scale gas and liquid mixing* (Lugni et al., 2010a,b). The importance of gas entrainment to sloshing has led to further numerical investigation of this phenomena using smooth particle hydrodynamics (Delorme et al., 2009; Colagrossi et al., 2010; Yan et al., 2015; Gong et al., 2016), and boundary element methods (Abrahamsen and Faltinsen, 2009).

A sketch of a gas pocket trapped in the corner of a tank is shown in Fig. 1, alongside other flows associated with LNG sloshing that involve gas entrapment and entrainment. Ordered by an increasing typical characteristic length scale, these include 1(a) a droplet of LNG approaching a wall, 1(b) a jet of LNG running up the tank wall and approaching a corner of the tank, 1(c) a free surface wave hitting the roof of the tank, 1(d) the tip of a breaking wave as it approaches impact with a wall and 1(e) a pocket of gas trapped in the corner of a tank. In each case the approximate initial region of impact cushioning by the gas is bounded by a dashed line. The flow associated with the impact of an individual droplet is not usually considered when investigating LNG sloshing, as the pressure induced by droplet impacts are not appreciable in the context of the forces and loads associated with larger sloshing impacts. However, droplet impact cushioning is briefly described herein to highlight the analogies that exist with existing gas cushioning models, which are more frequently applied to smaller scale phenomena.