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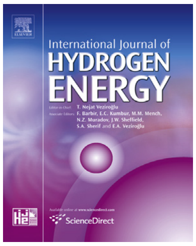

Design and analysis of a multi-cell subscale tank for liquid hydrogen storage

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ABSTRACT

This paper outlines the structural performance of a conformable pressurizable tank consisting of intersecting spherical shells (multi-cell tank). Multi-cell tanks outrival conventional multiple cylindrical tanks in volumetric efficiency when required to fit in a rectangular envelope in the automotive industry. When pressurized, the multi-cell (or multi-bubble) tank experiences high stress concentrations at the vicinity of the junctions, and thus the concept of effectively reinforcing those regions without adding significant excess weight becomes crucial. Furthermore, when applied for cryogenic medium storage, the heat transfer between different bodies and the generation of respective thermal stresses in such vessels makes the solution more complicated. In this paper the effect of the i) fiber-reinforced materials at the membrane and ii) unidimensional carbon tows at the intersections on the structural integrity of the tank is analysed for different loading scenarios. An operating window for the proposed tank configuration under the given loading scenario is established indicating the safe zone where the tank can operate.

Introduction

In the aerospace hydrogen containment field, tanks are required to have a high internal volume-in a pre-defined allowable space. The EU CHATT (Cryogenic Hypersonic Advanced Tank Technologies) project deals with investigating the use of carbon-fibre reinforced plastics (CFRP) for type IV liquid hydrogen (LH_2) tanks in the two-stage hypersonic reusable launch system (RLV) Space-Liner [1]. Throughout operation the tank is subjected to various combined loading cases that involve inner pressure and temperature changes as well as gravitational accelerations induced by the RLV.

Multi-cell pressure vessels have shown the potential of higher volumetric efficiency -within a rectangular envelope-compared to conventional cylindrical tanks [2,3]. They consist of rows of spherical cells joined together at appropriate intersections. Spherical membrane cells enable the structure to be loaded in uniform equal biaxial tension, which enables structural efficiency maximization [4]. Additionally spheres are the most favorable shapes for pressure vessels stress-wise, as well as having the maximum volume and

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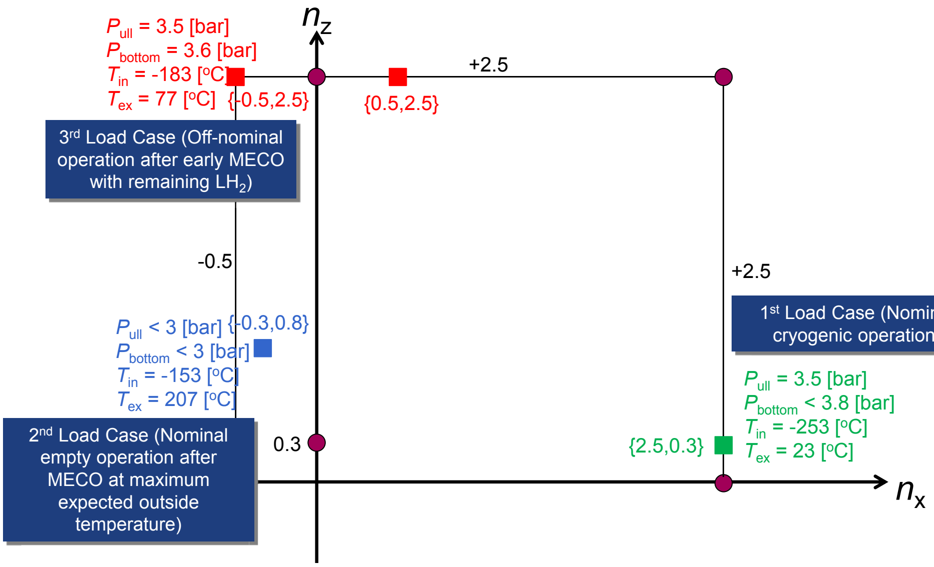

Fig. 1 – Simplified flight load cases of the Space Liner LH_2 tank.

minimum surface area, thus lowest material requirement. The use of intersecting pressure tanks has been reported in several published works, ranging from automotive fuel tanks [3] to deep-submerged pressure hulls [5,6]. The only reported application multi-cell vessels with fiber-reinforced materials for cryogenic fuel storage was the X–33 LH_2 tank, consisting of a multi-lobed and linerless configuration with integrally bonded, woven composite joints [7].

For the case of cryogenic tanks, thermal insulation systems are employed-in order to minimize the liquid fuel boil-off rate [8,9]. T.C. Nast et al. studied the sensitivity of boil-off to multi-layer insulation (MLI) thermal conductivity [10]. However, the main focus of most published works has been to estimate the temperature gradient through-the-thickness of the shell and determine respective fuel loss, rather than isolating the effect of different insulation configurations on thermal stresses and thus tank performance [11].

Additionally, a plastic liner is generally employed in a composite overwrapped vessel (a Type IV vessel), in order to prevent boiled-off gas leaking through the wall, and to reduce weight compared to Type III vessels that utilize a metal liner. However, differences in the values of the coefficient of thermal expansion (CTE)-between the liner and the tank wall can lead to thermal stresses and even separation under a particular temperature gradient. Therefore, besides permeability resistance, the two driving properties for liner material selection are i) the CTE compatibility with the composite tank wall and ii) the modulus of elasticity, since the liner must be flexible enough to be pressed against the tank wall surface in order to transfer the pressure load. However, a safe operating window for plastic-lined tanks of such geometry has not yet been established and is hereby present in the current work.

In the present work, a trade-off design study of plastic-lined multi-cell tank concepts has been performed in terms of evaluating their structural performance-under a given loading scenario, both analytically and with the use of Finite Element Analysis (FEA). The effect of the reinforcement of the intersections on the tank behavior was evaluated. Furthermore, a coupled temperature-displacement FE analysis was employed to investigate heat transfer phenomena between the liner and the tank wall, as well as to evaluate respective thermal stresses. Different insulation systems were analysed based on their effect on the arising shell stresses and strains. Finally, an operating window for the case of thermo-mechanical loading was established for the proposed tank design indicating the safe zone where the tank can operate.

Tank operation requirements

To ensure safety and acceptance, pressurized fuel tanks are always subject to strict design and verification requirements. Throughout operation in the Space-Liner, the LH_2 tank will be subjected to various combined loading cases such as inner pressure and temperature change -due to the stored medium being at cryogenic temperatures-as well as gravitational accelerations induced by the RLV [12].

Fig. 1 depicts the different LH_2 tank loading scenarios induced at the tank throughout the RLV flight, which were considered as load reference scenario in this study. These load cases are associated with i) nominal cryogenic operation at maximum expected temperature or ii) nominal empty operation after main-engine-cut-off (MECO) and iii) off-nominal operation after early MECO with remaining LH_2 inside. The service pressure of 0.38 [MPa] (in the first case) which together with a safety factor of 1.5 are the most significant tank design constraints. An integral part of the design is to reinforce the LH_2 tank, in order to be able to withstand service loads. The application of CFRP at the tank wall will provide support to the structure, due to its high specific strength and stiffness. Symbols P_{ull} and P_{bottom} refer to the pressures of the unfilled (ullage) and filled -with liquid-tank areas respectively, while T_{in} and T_{ext} represent the tank internal and external