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ScienceDirect
Cryogenics 48 (2008) 122–129
CRYOGENICS
www.elsevier.com/locate/cryogenics

Numerical and experimental comparisons of the self-pressurization behavior of an LH2 tank in normal gravity

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Received 23 August 2007; received in revised form 15 January 2008; accepted 25 January 2008

Abstract

In optimizing the design of cryogenic storage facilities for future in-orbit or on-surface applications the boil-off and the self-pressurization rates must be accurately predicted for different g-levels and for a variety of heat loads and distributions. In this paper, a two-phase CFD model is presented that describes the self-pressurization behavior of a flightweight partially full LH2 tank in normal gravity. Existing experimental data at different fill levels are used to assess the predictive capability of the model. The model's predictions indicate favorable agreement with the experimentally measured pressure histories. Small deviations are observed for the median fill level cases where it is suggested that a non-uniform heat load may be the source of this discrepancy.

Keywords: Space cryogenics (F); Hydrogen (B); Heat transfer (C)

1. Introduction

Future operations of many fluid, thermal, and power systems depend on the ability to store, transfer, and manage a variety of single or multiphase fluids in reduced gravity environments [1]. For many of these systems, especially the ones related to future missions to the Moon or Mars, cryogens will play an integral role.

Since cryogens are stored at very low temperatures, the storage tanks are quite sensitive to heat leaks while in Earth's atmosphere, loitering in LEO, in transit, or sitting on the surface of the Moon or Mars. The heat leaks can come from a variety of sources including incident solar radiation, planetary albedo, aerodynamic heating, or conduction loads from the tank's support structure. When heat leaks into the tank, it will be carried to the liquid–vapor interface by conduction and natural convection causing vaporization, which in a closed tank will result in a pressure rise. Accurate predictions of both the pressurization and the associated boil-off rates are critically important in defining design requirements corresponding to the tank's maximum operating pressure and expected cryogen losses.

Since the days of the Apollo program, several models with varying levels of sophistication have been developed to both interpret and predict experimental results. Historically, a homogeneous thermodynamic analysis was one of the earliest models developed to predict the self-pressurization rate in a cryogenic tank partially full of liquid. The homogeneous tank model assumes that the average energy of the liquid and vapor phases changes at the same rate as the energy of the two phase mixture defined at the saturation temperature. Because this assumption of homogeneity is typically not met during the initial phases of self-pressurization experiments, when thermal boundary layers are developing and temperature gradients in the liquid and vapor are not stationary, the agreement between thermodynamics and experiments has generally been poor especially in the initial transient regime [2–4].

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0011-2275/$ - see front matter
doi:10.1016/j.cryogenics.2008.01.003

In order to obtain better agreement with experimental data, transport effects must be included. A number of investigators have developed approximate models which account for energy and mass transport. Approximate integral methods [5], boundary layer related techniques [6], and zonal methods [7], for example, have provided better predictions of the tank pressure rise compared to the homogeneous model. However, these models are still severely limited in terms of their general predictive capability.

To obtain more meaningful predictions, these approximate techniques have given way to more sophisticated computational models. Lin and Hasan [8] developed a simple conduction model in the liquid and coupled it to the pressurization model of Brown [9] though rigorous coupling between the phases was lacking. They neglected gas-phase transport but allowed the interface to expand and contract radially. Hochstein et al. [10,11] also neglected the gas-phase transport and employed an effective conductivity model to account for transport in the liquid by performing a cell-by-cell mass balance along the interface to account for evaporation. Their comparisons with experiments [4,12] yielded reasonable agreement for when a tank was heated both uniformly and from the bottom in 1 g. Deviations however were noted for the top heating test case in 1 g and for low g uniform heating.

Grayson et al. [13] included transport in the ullage and, using the pressurization model of Hirt [14], attempted to simulate the AS-203 flight experiment [15,16]. While the results appear encouraging, a significant part of the experimental data was lost which makes it difficult to validate the numerical model over the entire experimental region of interest.

Merte et al. [17] also developed a pressurization model which included the effects of gas-phase transport. The interface was assumed flat and the pressure for the incompressible/incompressible system was updated using a first law energy balance. Merte et al. [18] later compared their predictions with data from the AS-203 flight but the agreement was not good. They attributed the errors to inadequately modeling the tank geometry, and thus the heat distribution along the wall. Val'tsiferov and Polezhaev [19], included the effects of transport in the ullage and used an integrated form of the ideal gas law to update the pressure but were not able to obtain agreement with Aydelott's self-pressurization experiments [4]. It is apparent from the above mentioned studies that validation and verification of two-phase storage tank models have proved to be quite elusive.

Given the difficulties associated with including transport effects in the ullage, it's no surprise that several investigators continue to couple lumped thermodynamic balances in the ullage to numerical solutions in the liquid. Amirkhanyan and Cherkasov [20] coupled an effective conductivity analysis in the liquid to a lumped model of the ullage. When comparing to experimental data, they obtained reasonable agreement for high liquid fill levels but overpredicted the pressure rise for lower fill levels. Panzarella and Kassemi [21] rigorously coupled a lumped energy and lumped mass model of the ullage to the transport equations in the liquid but no experimental comparisons were attempted. A version of this model has since been used to study the self-pressurization of large LH2 tanks in low g [22] and to numerically investigate subcooled jet mixing as a pressure control strategy [23].

In the present paper, the predictive capability of the Panzarella and Kassemi two-phase lumped vapor model [21] is assessed by comparing the model's predictions with pre-existing cryogenic self-pressurization data gathered during experiments in NASA Glenn's K-site facility [24–26].

2. Experimental description

The pressurization tests examined here were conducted using the flightweight LH2 tank in the K-site facility at NASA Glenn's Plum Brook Station [24–26]. The facility consisted of a vacuum chamber enclosing a cylindrical cryoshroud whose temperatures can be maintained with electrical resistance heaters. Within the shroud, an LH2 tank was suspended by twelve fiberglass composite struts. The tank was constructed from 2219 aluminum with a wall thickness varying between 1.9558×10^{-3} m and 2.2098×10^{-3} m. The tank was fabricated by joining two halves of a 1.2/1 oblate spheroid to a 0.0381 m cylindrical section. The major and minor diameters of the oblate spheroid were 2.22504 m and 1.8542 m, respectively. The internal tank volume was 4.955 m^3. The tank was covered by two MLI blankets to reduce radiative losses.

Before the self-pressurization experiments began, boil-off tests were performed to estimate the net heat leak into the LH2 tank. During these tests, the tank was 95% full of LH2 and the operating pressure was approximately 117×10^3 Pa. Heat leaking into the tank caused the liquid to evaporate and the resulting boil-off was directed through volume flow meters. For the lower heat flux cases considered in this paper, a steady boil-off rate of 2.7 SCMH was recorded. Redoing the calculations outlined in Stochl and Knoll [24], from this boil-off rate, we compute the net heat power into the system to be 30.01 W. It should be noted that this heat load is slightly different from the 28.08 W load reported by Stochl and Knoll. The approximately 2 W discrepancy is due to property differences in converting the boil-off rate (SCMH) to a heat leak rate (W). In our calculations, properties were evaluated from current NIST databases [27]. After the boil-off tests were performed, the tank was drained to the desired fill level, the operating pressure was reduced to 103×10^3 Pa, and venting occurred for another 4 h before tank lock-up. Finally lock-up occurred and the tank was allowed to self-pressurize for approximately 20 h.

3. Cryogenic tank model

In order to capture the K-site experiment, consider a closed tank partially full of LH2. As a result of heat