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Research Paper

Influence of filling methods on the cool down performance and induced thermal stress distribution in cryogenic tank

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HIGHLIGHTS

- Liquid nitrogen filling tests using three different filling methods were performed on a vertical aluminum tank.
- The cool down characteristics and thermal stress distribution of the tank under different filling methods were compared.
- A method for quickly and conveniently assessing the thermal stress level of a cryogenic tank was proposed.

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ABSTRACT

Experiments were performed to investigate the cool down performance and thermal stress in an aluminum tank versus filling elapsed time with different liquid nitrogen filling methods, i.e., the bottom axial filling, top axial filling and top lateral sprayer filling. Among three filling methods, the top lateral sprayer filling obtained the fastest cool down of the entire tank, however accompanied with the greatest temperature gradient and the most serious thermal stress. Comparatively, axial filling methods led to more uniform temperature distributions and lower thermal stress levels. The peak value of thermal stress for a top axial filling was about 75% of that for a bottom axial filling under the same feeding rate, although the thermal stress distribution patterns were similar. The thermal stress for a top lateral sprayer filling had descending values in the lower part of the tank, while kept at a much higher level in the central and upper part. The peak value reached up to 50% higher than that of a bottom axial filling. This work could be beneficial to the selection and design of filling methods, which are significant to cryogenic tanks in consideration of filling efficiency and safety.

1. Introduction

With the broad application of liquid hydrogen (LH2), liquid oxygen (LO2) and liquified natural gas (LNG) in the aerospace industry as well as in civil industries, the safe production, delivery and storage of such cryogenic fluids become important issues. The most significant concern on cryogenic fluids is their huge temperature differences from the ambient, which could lead to a series of problems during fillings and storage, including the transient chill-down of the whole system, the emergence of thermal stress within transmission pipes and containing tanks, and continuous vaporization and pressurization.

The chill-down processes of cryogenic transmission pipes have been experimentally studied by many researchers [1–5]. The flow regimes and heat transfer characteristics within the pipes have been figured out, and the chill-down time and cooling efficiency of the pipes have been evaluated, based on which different chill-down strategies such as pulse flows and continuous flows have been proposed. Effects of various influencing factors including the flow rates, flow directions, inlet subcoolings and fluid species on the chill-down performance of cryogenic pipes have been investigated comprehensively. Kashani et al. [6] reported modeling and optimization of non-equilibrium two-phase cryogenic flow in the transfer line of a cryogenic propellant loading system using SINDA/FLUNIT. They established a one-dimension model based on the two-phase flow conservation equations, and took into account the changes of flow patterns and heat transfer in the pipes and valves. Through the model, they analyzed effects of tank pressure and openings of the control and dump valves on the consumed time and amount of cryogenic liquid during chilldown of the system.

The cool down and filling processes of cryogenic tanks have also been surveyed extensively in the literature, with both numerical and experimental methods. Stephens et al. [7] developed a 2D finite-difference thermal-fluid numerical model to predict the transient behavior

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Nomenclature

E	elasticity modulus, MPa
e	real strain
e_n	nominal strain
e_T	thermal output of strain sensor
K	strain sensitivity coefficient
R	electric resistance of strain sensor
T	temperature, K

Greek symbols

α_R	temperature coefficient of resistance of strain sensor
α_T	thermal expansion coefficient of strain sensor
ε	strain
μ	Poisson’s ratio
σ	stress, MPa

Subscripts

c	circumferential direction
ga	gauge
l	longitudinal direction
w	wall
0	initial state

of a horizontal cryogenic tank during LN2 fill and drain operations. They predicted fill times and profiles, wall-temperature gradients and boiloff rates of LN2 during fill processes, and analyzed effects of the circumferential thermal conduction and the vapor free convection heat transfer coefficient on the cool down of the tank wall. They claimed that vapor convection heat transfer was the primary mechanism of wall cooling until the liquid level was within 20.3 cm of a monitoring node, after which the circumferential thermal conduction began to have influence on the wall temperature. Keefer and Hartwig [8] presented a transient analytical model to study the thermodynamic and heat transfer behaviors within a cryogenic tank during the chill down process using the charge-hold-vent procedure. They considered different heat transfer patterns including natural convection and jet impingement during different chill down stages, and obtained accurate predictions of consumed propellant mass for each cycle.

Hedayat et al. [9] developed a comprehensive thermal-fluid model to evaluate the thermodynamic behavior of a cryogenic LH2 storage tank during chill and fill processes. They considered the LH2 supply source, the feed system, the charged tank and the vent system in the model, and modeled the vaporization and accumulation of LH2 in the tank based on the heat transfer between the tank wall and interior fluids. In the solving process of temperature evolutions of the tank wall, they ignored the thermal conduction along the tank wall. The predicted accumulated LH2 mass curve and the maximum ullage pressure were in close agreement with measured values, while obvious discrepancies existed between the predicted tank wall temperatures and chilldown rates with test data. The ignorance of the axial thermal conduction within the tank wall may be a major reason for the discrepancies. Leclair and Majumdar [10] proposed a computational model for predicting the chilldown and propellant loading processes of the LO2 and LH2 tanks of the Space Shuttle External tank. They included the ground system transfer line, the propellant tanks with insulation and the vent valves in the model, and considered relevant transient behaviors including unsteady flow, phase change and solid to fluid heat transfer. They adopted the model to predict filling times of LO2 and LH2 tanks as well as ullage pressures and temperatures, vent flowrates and wall heat leaks, and the predictions were validated to have reasonable accuracies.

Due to its potential application in micro gravity situations, the non-vented cryogenic filling procedure has been studied [11–15] to demonstrate the feasibility of the rapid chill and fill concept and the operating performance of the non-vented fill procedure in cryogenic propellant filling processes. The tank pressure and the ultimate fill level were the main concerns during non-vented cryogenic fillings.

Besides the filling time, the filling level, and the internal pressure during cryogenic filling processes, the thermal stress distribution within the tank wall should also be considered, owing to its potential impact on the safety of the tank. Thermal stress is commonly caused by the existing local temperature gradient within a continuous solid, or by the combined actions of temperature variations, differences between the thermal expansion coefficients of different materials (if there exist two or more kinds of materials) and existing mechanical constraints. For example, in the multilayered thermoelectric material in [16], a N-type layer, an insulating layer and a P-type layer are bonded together at each contact surface, meaning that a mechanical constraint exists between two adjacent layers, and the local deformation at the contact surface must be consistent. Therefore, when temperature changes, thermal stress arises at the contact surface due to the difference between thermal expansion coefficients of adjacent layers.

During filling a tank with cryogenic liquids, the tank suffers from a fast cool down process from normal temperature to cryogenic temperatures, resulting in remarkable temperature gradients and thermal stresses within the solid wall. The thermal stress issue during a cryogenic filling process is a typical fluid–solid coupled matter, which means that the flow field in the fluid region directly dominates the temperature distribution within the solid region, which further governs the thermal deformation and stress field in the solid region. Moreover, remarkable deformations in the solid region will in turn influence the flow field in the fluid region. It was pointed out in [7] that during a cryogenic filling process, the actual filling rates would be limited either by boiloff flow from rapid vaporization or by thermal stress limits within the tank wall. Fedorov and Luk'yanova [17] presented a discussion on different filling procedures of cryogenic tank filling processes, and stated that in a top filling, the temperature distribution within the tank was more uniform than that in a bottom filling, resulting in a lower thermal stress level. While no quantitative thermal stress data was provided in their paper. Therefore, a comprehensive study is needed to establish the explicit connection between the flow-temperature field and the thermal stress field in cryogenic storage systems during filling processes.

Due to the complexity of practical solid components or structures and the difficulty in measuring the internal thermal strains within solids, the numerical simulation method is most commonly used in evaluating thermal stress distributions in various objects with working temperatures far from the normal temperature, e.g., automobile engines, steam generators and fuel cells [18–20]. The analytical and experimental methods can only be applied to simple structures such as tubes, planar plates and circular plates or rings [16,21]. Kang et al. [22,23] presented a thermo-structure numerical analysis on a cryogenic propellant tank with a metal liner and overwrapped composite layers, and evaluated the thermal stress distribution in circular ring specimens which are made of the same composite/metal materials at cryogenic temperature using both experimental and numerical methods. They found that the composite layers suffered from compressive stress, while the metal liner was subject to tensile stress, due to the difference between the thermal expansion coefficients of the two materials.

Recently, Zhu et al. [24] performed an experimental study on the cool down characteristics and transient thermal stress distributions of an aluminum tank during LN2 fillings using the bottom axial filling procedure. An alternating tension–compression thermal stress evolution at each measure point on the outer surface of the tank wall was