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PVT gauging with liquid nitrogen

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Abstract

Experimental results are presented for pressure–volume–temperature (PVT) liquid quantity gauging of a 0.17 m^3 liquid nitrogen tank pressured with ambient temperature helium in the normal gravity environment. A previously reported PVT measurement procedure has been improved to include helium solubility in liquid nitrogen. Gauging data was collected at nominal tank fill levels of 80%, 50% and 20% and at nominal tank pressures of 0.3, 1.0, and 1.7 MPa. The test tank was equipped with a liquid pump and spray manifold to circulate and mix the fluid contents and therefore create near-isothermal conditions throughout the tank. Silicon diode sensors were distributed throughout the tank to monitor temperatures. Close-spaced arrays of silicon diode point sensors were utilized to precisely detect the liquid level at the nominal 80%, 50%, and 20% fill levels. The tests simulated the cryogenic tank-side conditions only; helium mass added to the tank was measured by gas flowmeters rather than using pressure and temperature measurements from a dedicated helium supply bottle. Equilibrium data for cryogenic nitrogen and helium mixtures from numerous sources was correlated to predict soluble helium mole fractions. Results show that solubility should be accounted for in the PVT gauging calculations. Mole fractions predicted by Dalton's Law were found to be in good agreement with the compiled equilibrium data within the temperature–pressure range of interest. Therefore, Dalton's Law was deemed suitable for calculating ullage composition. Gauging results from the PVT method agreed with the reference liquid level measurements to within 3%.
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1. Introduction

Liquid propellant quantity gauging using the PVT method is an attractive option since it requires minimal, if any, additional hardware. A non-condensable gas pressurizes the propellant tank of known volume. The gas is supplied by a storage bottle, also of known volume. The hardware components and instrumentation for a PVT measurement are shown in Fig. 1. If the temperature and pressure are measured in both the supply bottle and the propellant tank, gas law relationships and mass conservation of the pressurant may be combined to determine the amount of propellant remaining in the tank. The method is an established technique used in communications satellites with storable propellants [1,2]. An uncertainty analysis for cryogenic propellants [3] has indicated that the accuracy of PVT measurement errors may exceed 10% for LH2, but that the method warrants further consideration for LO2, and by extension to LN2 and LCH4, since these liquids have similar thermodynamic properties. The primary drawback for use with LH2 is the much greater sensitivity of the propellant vapor pressure to small changes in temperature. The uncertainty analysis did not examine the effect of helium solubility in cryogenic liquids.

In the present study, the PVT method was experimentally investigated using a 170 L LN2 tank. Since concerns about the suitability of the PVT method to cryogenic systems pertain only to the propellant tank and do not involve the helium supply bottle, the experimental apparatus did not include a high pressure helium supply bottle. Helium was supplied at approximately constant pressure and ambient temperature from the test facility supply. The tests were not intended to be a full-up demonstration or exhaustive

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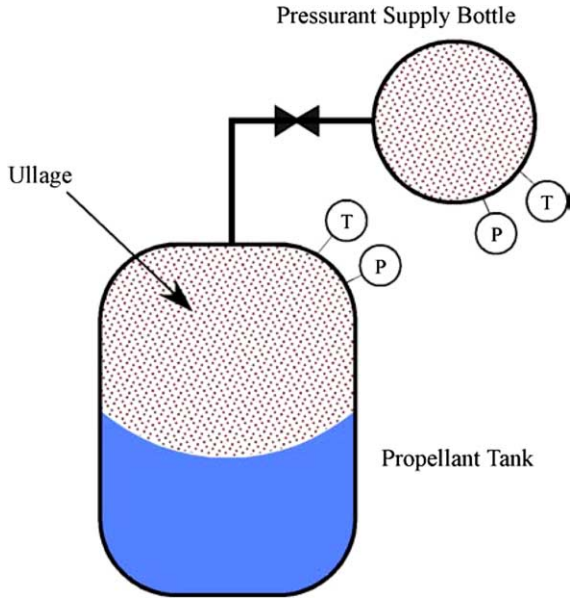

Fig. 1. Basic PVT gauging configuration with instrumentation.

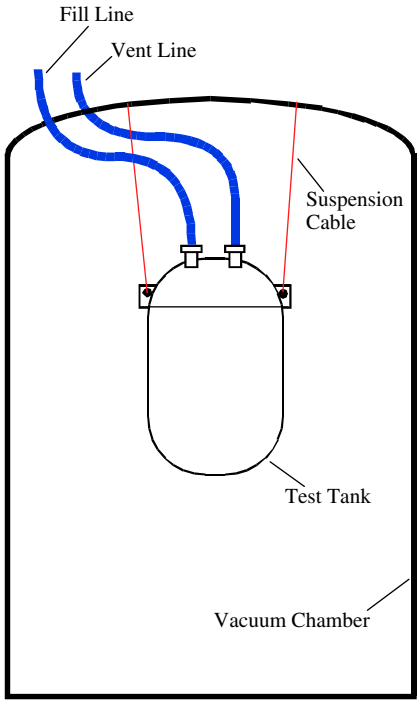

Fig. 2. Schematic of test tank suspended from vacuum chamber lid.

test of measurement accuracy. The test purpose was to examine the significance of helium solubility in the liquid, to study the composition of the binary ullage composition and compare it to the Dalton's Law prediction, to examine the uniformity of tank temperature, to investigate the repeatability of the PVT method, and to look for any unexpected results.

2. Experimental apparatus and instrumentation

Tests were conducted in a 1.8 m diameter by 3.0 m high vacuum chamber. The test tank was 0.5 m in diameter and 0.9 m in overall length and is suspended from the vacuum chamber lid as shown in Fig. 2. The test tank top and bottom are ASME flanged and dished ends. The tank lid separates from the rest of the tank and has four suspension points as well as internal cross-braces used to suspend internal tank hardware and instrumentation. The tank was plumbed with fill and vent lines. The fill line includes a dip tube within the tank that is used to expel liquid. Helium is injected into the tank through the vent line. Both the fill and vent lines were instrumented with three distributed internal temperature probes. A 380 Lpm pump positioned near the tank bottom pumped liquid through a vertical pipe to a cross-shaped spray bar positioned near the top of the tank as illustrated in Fig. 3. The discharge holes in the spray bar were oriented to spray liquid on the underside of the tank lid.

Fluid temperatures were measured by a vertical array of 10 silicon diode sensors with a reported accuracy of ±0.25 K. An in situ calibration of these sensors was conducted by filling the tank with LN2 at atmospheric pressure. A theoretical saturated temperature profile adjusted for the hydrostatic head effect was determined and offsets for each sensor were obtained. These individual offsets

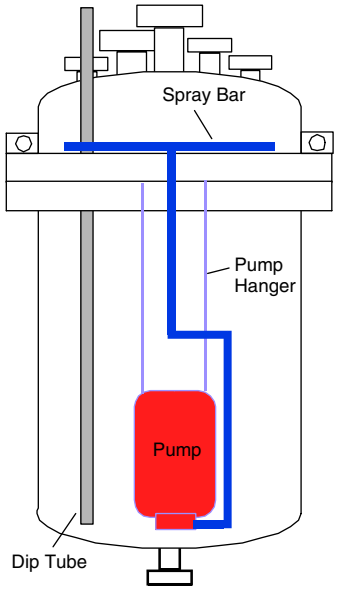

Fig. 3. Schematic of LN2 pump and spray bar, plus the fill line dip tube inside the test tank.

were within the manufacturer's specifications and were applied to all test data to reduce bias error. The offset corrections account for various systematic errors introduced by sensor variations, the data system, and other sources of electrical signal bias. The total uncertainty of the tank fluid temperature measurement is dominated by non-uniformity in the temperature readings from the 10 primary temperature sensors and is estimated from experimental results to be ±0.5 K.