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Feasibility Demonstration of Cryogenic Fluid Gauging for Space Vehicle Applications

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This article describes a gauging concept for determining the mass of liquid contained in a tank in a low-gravity environment. The concept, which is referred to herein as the "compressibility gauge," is based on the thermodynamic principle that the pressure of gas or vapor changes when its volume changes. In operation, the tank volume is changed slightly by an oscillating bellows (pulser) and the corresponding change in tank pressure is measured. The primary objective of the present investigation of this concept was to explore the effects specific to gauging cryogenic fluids, such as heat, mass, and momentum transport at the liquid-vapor-tank interfaces, on the accuracy of the gauge. Freon-11 was used as a convenient laboratory fluid to simulate liquid hydrogen and other cryogens. The test results and analyses indicate that cryogenic effects can have a significant effect on gauging accuracy. Nonetheless, it is concluded that the gauge has the potential of high accuracy in low gravity, to use simple hardware, and to be lightweight for space vehicle applications.

Nomenclature

C = boundary-layer coefficient, Eq. (4)
f = pulser frequency
$\dot{m}$ = evaporative mass flux
P = tank total pressure
P_{sat} = vapor pressure at temperature T
R = gas constant
T = temperature of liquid-vapor interface
V = gas or vapor volume
α = tank stiffness factor, Eq. (2)
β = constant in mass flux relation, Eq. (6)
ΔP = tank pressure change
ΔV = tank volume change
γ = polytropic constant, specific heat ratio of gas, or vapor for adiabatic process

Introduction

IN low gravity, the position of liquid in a container may be markedly different than it is on Earth where the liquid occupies the bottom of the container and forms a horizontal-free liquid-gas surface at the lowest possible level within the container. In low gravity, the liquid and gas are not dominated by the strong buoyancy force of Earth's gravity, the fluid may become a mixture of gas bubbles of many sizes interspersed within the liquid, and the liquid may not be either at the "bottom" or the "top" of the container. Consequently, the familiar gauging methods used on Earth are not generally applicable in space.

Since the available gauging methods do not work in low gravity, there is a pressing need for quantity gauging systems for future space missions in which subcritical liquid fluids, particularly cryogenic liquids, will be stored and handled. Typical gauging applications include liquids for life sustenance and engine propellants. Liquid mass gauging will also be required for fluid resupply to on-orbit systems for vehicles ranging from spacecraft to large space platforms. Future applications include propellants and life support fluids for the space station alpha,[1] on interplanetary propulsion systems, and manned lunar vehicles.

Many "low *g* quantity gauges" have been investigated in concept or tested in laboratory environments over the past 30 years. These systems have been based on the use of a variety of physical principles such as radio frequency microwaves,[2] gas bubble resonant frequency, liquid heat capacity, optical absorbency, ultrasonics, capacitance, acoustics,[3] gamma ray densitometry,[4] and flow meters for monitoring liquids leaving and entering the tank.[5] To this point, however, they have all proved to have significant limitations in gauging accuracy, complexity, or weight.

Compressibility Gauge Concept

The concept of compressing the ullage gas bubble as a means of gauging liquid volume has been investigated previously for ground applications,[6,7] and recently for space applications.[4,8] The physical basis of such a gauge is the relation between gas volume V and gas pressure P, when a small adiabatic volume change ΔV is used to produce a corresponding small change in pressure ΔP:

$$V = -\gamma P(\Delta V/\Delta P) \tag{1}$$

In principle, a compressibility gauge does not require knowledge of the way gas is distributed in the tank. In practice, however, several "nonideal" effects may limit the applicability of Eq. (1) and cause a need for elaborate gauging controls and data analyses. The effects are discussed in the following:

Liquid Compressibility

No liquid is completely incompressible, and some cryogens are significantly compressible. Thus, ΔV in Eq. (1) actually includes a liquid volume change as well as the desired gas volume change. This change can also be linearly related to ΔP, so that Eq. (1) is still applicable if it is modified appropriately.

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Tank Elasticity

The tank itself can change volume when the liquid pressure changes. Equation (1) can be easily modified to account for this effect:

$$V = -\gamma P[(\Delta V/\Delta P) - \alpha] \tag{2}$$

where α can be experimentally estimated from Eq. (2) for tests at two different pressures (P_1 and P_2) and a constant f and ΔV:

$$\alpha = \Delta V \left(\frac{P_1/\Delta P_1 - P_2/\Delta P_2}{P_1 - P_2}\right) \tag{3}$$

Heat, Mass, and Momentum Effects

Gas and vapor near the walls and liquid interfaces do not respond to pressure pulsations the same way the bulk gas does because of the formation of boundary layers that transfer heat, mass, and momentum between the oscillating gas and the more nearly stationary liquid or wall. These boundary layers affect both the magnitude of the volume change near the interfaces and the phase lag between the volume change and the relevant physical process. That is, the entire gas volume does not respond adiabatically in-phase with the imposed volume change. These effects are more difficult to account for in Eq. (1) than the effects discussed previously.

Analysis and ground tests with noncryogens[5] indicate, however, that the gauge can still obtain acceptable accuracy by conducting the gauging process at two or more frequencies, from which an empirical parameter C can be determined that compensates for boundary-layer and diffusion effects. For this kind of empirical model, Eq. (2) must be modified as

$$V = -\gamma P[(\Delta V/\Delta P) - \alpha][1 + (C/2\sqrt{f})]^{-1} \tag{4}$$

The data from two separate gauging determinations can be used to eliminate C, by algebraically equating V from Eq. (4), for the two values of f:

$$V = \frac{\gamma P_1[(\Delta V/\Delta P_1 - \alpha)\sqrt{f_1 f_2} - (\Delta V/\Delta P_2 - \alpha)]}{\sqrt{f_1 f_2} - 1} \tag{5}$$

Thermodynamic Phase Change

Cyclic changes in the tank volume can cause a cryogenic fluid to change phase instead of causing a cyclic change of tank pressure, if the pulser frequency is sufficiently low to permit the fluid to come to near-thermodynamic equilibrium during each pulsation cycle. If this occurs, the gauge accuracy will be significantly degraded, unless the effects of the phase change are accounted for in the data analysis model, Eq. (4).

Mass transfer at the liquid-vapor interface can be modeled approximately as a flux $\dot{m}$ that depends on the difference between the actual vapor pressure and the equilibrium vapor pressure[7,9,10]:

$$\dot{m} = \beta(P - P_{sat})\sqrt{RT} \tag{6}$$

where β is an empirical constant; note that $P - P_{sat} \approx \Delta P$ in Eq. (4). Further development and demonstration of the model is needed to verify this analysis approach for cryogens. The effects of phase changes can be minimized by using a high pulser frequency, although this may conflict with the effect of multiple large bubbles in the ullage, as discussed below.

Multiple Large Ullage Bubbles

When the liquid contains several large bubbles, the total volume change will still equal the imposed ΔV, but there is the possibility that one of the bubbles may have a positive volume change that is much larger than the pulser ΔV if another bubble simultaneously has a correspondingly large negative volume change. If this were to happen, the pressure change ΔP would no longer be directly related to ΔV. These kinds of large volume excursions could occur when the pulser frequency is near the resonant frequency of the multiple bubble system. Since this resonant frequency cannot be predicted unless the volume and configuration of the bubbles are known, the best way to operate the gauge is to use pulser frequencies that are well below the lowest frequency of the worst case configuration.

Density Stratification

In low-gravity, there are no strong buoyancy forces to mix differentially heated liquids. For a cryogen, tank heat leaks can produce significant density variations, since the cooler (more dense) and warmer (less dense) parts of the liquid will not mix well naturally. The gas volume can still be gauged just as for a nonstratified liquid, but the liquid volume cannot be interpreted as a liquid mass unless the average density is known. To do so, the gauge must incorporate a temperature sensing array, from which the average density can be calculated. Furthermore, the instrumentation or software must discriminate reliably between liquid temperatures and vapor temperatures. In contrast, the effects of a thermally stratified vapor can be compensated relatively easily by operating the gauge at multiple frequencies to derive an average γ.

Gas Mixtures

Cryogenic liquids can be stored at pressures greater than saturation by using a noncondensable pressurizing gas, such as helium. The ullage is then a mixture of cryogenic vapor and a foreign gas. During the pulsation imposed by the driver, the two gases can respond differently. For example, mass transfer of the pressurizing gas at liquid interfaces may be negligible. Also, the concentration of the pressurizing gas will change as the tank is emptied, leading to different values of γ at different fill levels. Furthermore, a noncondensable gas will contribute to temperature and density stratification in the liquid. Again, the effective γ can be determined by operating the gauge at multiple frequencies.

Liquid Motion

Large scale, unsteady motions of the liquid will affect pressure measurements and potentially degrade the accuracy of the gas volume estimation. Configuration-specific testing is required to determine if the gauge can be operated during tank draining and filling. Likewise, gauging accuracy may be poor during times when the liquid is sloshing.

Ground Test Calibration for Low-Gravity Use

Although in theory a compressibility gauge should work as well in low-gravity as it does in normal gravity, many of the effects that influence its accuracy, such as fluid phase changes and heating-induced convection, will be markedly different in low gravity. Consequently, the operation of the gauge must eventually be validated in low gravity. Some aspects of low-gravity can be simulated by ground tests. For example, a gas bubble embedded in the liquid, rather than at the top of the tank, can be simulated by the use of inflated, tethered balloons. Tethered balloons have also been used to investigate the effects of multiple ullage bubbles.[4] The ability of ground tests to represent all the effects that can occur in low gravity is, however, severely limited.

Experiment Apparatus

Based on previous work with the compressibility gauge,[5,6] and a preliminary error analysis of the applicable instrumentation, a simplified "breadboard" system was designed and constructed to investigate the nonideal effects discussed above. The main items of the breadboard system were: 1) tank, 2) liquid Freon-11, 3) pulser and driving motor assembly, 4) pressure transducers, 5) thermocouples, 6) heaters, 7) data acquisition system, and 8) equipment to calibrate the system and to verify gauging predictions.

The test tank was a 58.29-gal stainless steel drum stiffened structurally to reduce its flexibility. By use of Eq. (3) and test data, an α of 0.12 gal/psi was established for the tank. Since this stiffness value represents a tank that is about 50 times more flexible than that of a typical space vehicle tank, the present tests, from the standpoint of adverse effects induced by tank flexibility, are much more severe than would occur in space applications.

Freon-11, a nontoxic refrigerant, was used as a cryogenic simulant. The boiling point of Freon-11 is near room temperature at atmospheric pressure, and so it was convenient to use. When needed, two electrical heating elements in the tank were used to control the liquid and vapor temperature and to establish a specified level of thermal stratification.

A small metal bellows (2.25 in. diam, 1.44 in. long extended) driven by a cam shaft and rod arrangement connected to a dc motor was used to vary the tank volume. The swept volume of this pulser was 0.004473 gal, which represents 0.00768% of the tank volume. Depending on the liquid fill level, the bellows was submerged for some tests. Pulse frequencies from 1 to 10 Hz were investigated in the tests.

Two types of pressure transducers were initially evaluated to measure the oscillating pressure amplitude of the tank fluid. The first transducer required tubing and a manifold between the sensor and the tank, and thus a small pressure drop was induced between the tank and the sensor. The second transducer was a "spark plug"-type of piezoelectric transducer that mounted directly to the tank wall in contact with the tank contents. It was found that the piezoelectric transducer gave better accuracy, and so it was used for all the data tests. The magnitude of oscillating pressure amplitude that had to be sensed was on the order of 0.0002 atm. Arrays of fixed and adjustable thermocouples were used to measure liquid and vapor temperatures throughout the tank.

The data acquisition system consisted of 1) a digital multimeter to process pressure and frequency signals and 2) a personal computer-based microprocessor for acquiring data from the 20 thermocouples.

To establish the theoretical accuracy of the gauge, an error analysis of the gauging system was performed, based on an estimate of the maximum accuracy with which the fundamental parameters (pressures, temperatures, volumes, weights, and fluid properties) could be measured. This analysis indicated that the breadboard gauging system could obtain an accuracy of 0.5% of the total tank volume. The uncertainty analysis did not, however, account for the effects of liquid compressibility, tank elasticity, fluid phase changes, or boundary-layer formation. Therefore, for the gauging system to be accurate to within 1% of total tank volume, which was the desired goal, errors induced by these effects could not exceed a combined uncertainty of 0.5%.

Simulated Cryogen Test Results

Analytical Models

Two analytical models for estimating the quantity measurement accuracy of the compression gauging system were evaluated. The first model, Eq. (2), will be referred to as the "single frequency model" and the second, Eq. (4), as the "dual frequency model." For the dual frequency model the coefficient C in Eq. (4) was computed by equating estimates of V at two frequencies f to yield:

$$C = [(A - 1)\sqrt{f_2}/(\sqrt{f_1 f_2} - A)] \tag{7}$$

where

$$A = \frac{\Delta P_2}{\Delta P_1}\left(1 - \alpha\frac{\Delta P_1}{\Delta V}\right)\left(1 - \alpha\frac{\Delta P_2}{\Delta V}\right)^{-1} \tag{8}$$

The computed values of C from tests using Freon in thermodynamic equilibrium are shown in Fig. 1 as a function of fill level (i.e., for tests without heating, stratification, or liquid motion). Except for low fill levels, the value of C was nearly constant at 0.098. Using these values of C, the computed maximum gauging error for equilibrium Freon for any fill level was found to be less than 1.5%. The value of C for a given fill level varied somewhat depending on the two frequencies used to compute it; the results shown in Fig. 1 represent averages of those values.

All the values of C were negative for cases where water was the tank liquid and a mixture of air and water vapor was the ullage; furthermore, the values decreased uniformly from −0.00214 to −0.155 as the fill level was increased from almost empty to nearly full.[8] This difference in sign with respect to the Freon tests is an indication of the difference in physical phenomena for a fluid that is capable of changing phase when subjected to a pulsating pressure, compared to one that does not change phase.

Total Tank Pressure Effect

It was found that the total pressure of the vapor in the tank appeared to have an adverse effect on gauging accuracy. Figure 2 shows this effect clearly for the water tests (for which air and water vapor is the "vapor"). The gauging error increased (negatively) as the tank pressure was increased and

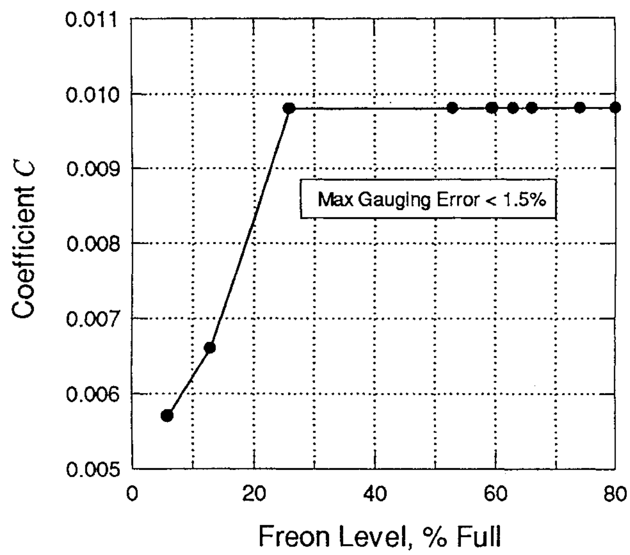

Fig. 1 Empirical coefficent C for Freon.

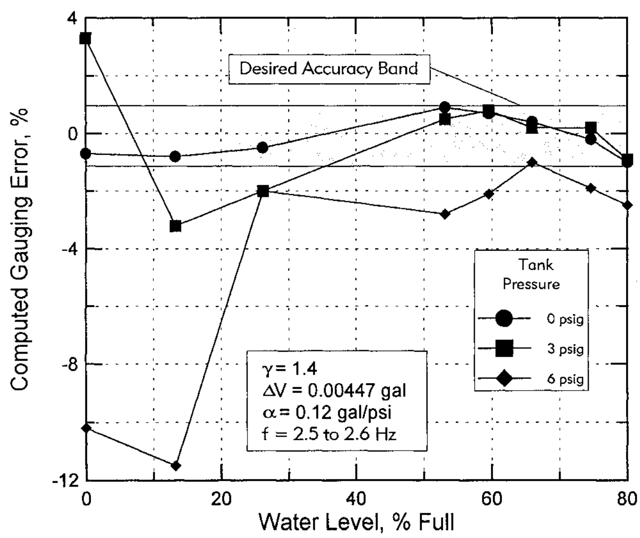

Fig. 2 Gauging error vs tank pressure.

as the water level was reduced. It is suspected that at least part of this increased error is a result of the increase in α with pressure, which was not accounted for in the data reduction. If this is the case, then the effect will not be as evident for space vehicle tankage since such tankage is estimated to be stiffer than the breadboard test tank by a factor of at least 50. It was also concluded from these results that the values of C used in the model should be computed as a function of tank pressure, as well as of liquid level. Note that for a tank pressure of 0 psig the gauge error computed from the dual frequency model remained within the desired goal of $\pm 1\%$. The effect of tank pressure in the Freon tests was different than the results shown in Fig. 2; these results will be discussed later.

Pulser Frequency and Freon Quantity Effects

An extensive series of tests was conducted over a range of pulse frequencies to 1) examine gauging accuracy over a range of Freon liquid levels and 2) establish the effects of submerging the gauge bellows in the Freon. The bellows centerline was located at approximately the 63% fill level for these tests.

The effects of varying the pulser frequency and Freon level are illustrated in Figs. 3 and 4, for cases when the data results were analyzed by the single frequency and dual frequency models, respectively. Comparing Fig. 3 to Fig. 4 shows conclusively the improvement in accuracy that can be obtained by the proper choice of an analytical model. With the exception of pulser frequencies that excited a tank structural resonance (which will be discussed below), the predicted accuracy of the gauge was quite good, and the accuracy tended to improve with an increase in pulse frequency up to the point at which the tank resonance was excited at about 9–10 Hz. It is believed that an analytical model that incorporated phase change effects explicitly would improve the accuracy even more. Even so, the tests show that the compression gauge provides accurate results throughout the liquid depth range regardless of whether the bellows device is submerged or not.

The effect of a harmonic response of the tank structure that occurred at pulse frequencies between 9–10 Hz is readily apparent in Figs. 3 and 4. This structural resonance greatly reduced the predicted accuracy of the gauge.

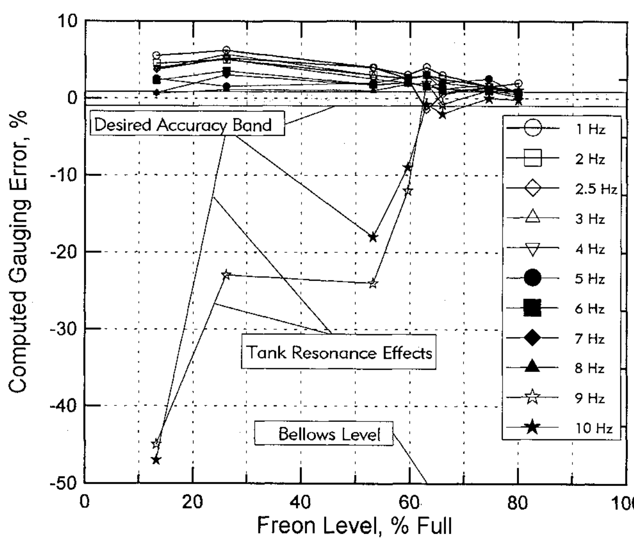

Fig. 3 Pulser frequency vs Freon quantity, single-frequency model.

Effects of Unsteady Heat Transfer

Another series of tests was conducted with the objectives of investigating the effects of 1) creating a thermally stratified layer in the liquid Freon near its free surface, 2) subcooling the heated liquid near the free surface by venting vapor for a short time, 3) effectively subcooling the heated liquid by introducing a noncondensable gas in the ullage space, and 4) heating the Freon ullage vapor.

A stratified layer was created in the liquid Freon by an electrical heating element located 2 in. below the liquid surface. Heating was terminated when the vapor pressure increased to 16.33 psia, which represented a tank pressure of 2 psig. The gauging results for this condition are shown in Fig. 5. As can be seen, the gauging error was initially about 38%, presumably because of both an increased rate of phase change compared to an equilibrium fluid and the heating-induced buoyancy currents that impinged on the pressure sensor. It should be noted, however, that the heating rate used in these tests (about 700 Btu/h) was more than 100 times that which would be expected for a LH_2 tank of comparable size in a space environment and thermally protected with 2 in. thickness of high-performance insulation. Had the heating rate been less severe, it is suspected that the 38% gauging error would have been substantially less. Furthermore, any errors caused by the buoyancy currents would be greatly reduced in low gravity.

In order to investigate methods of diminishing the adverse effects of heating the tank liquid, a series of tests was conducted in which, after heating the liquid, the tank was vented to the atmosphere for 15 s immediately before starting the gauging process. Figure 5 shows that this venting promptly

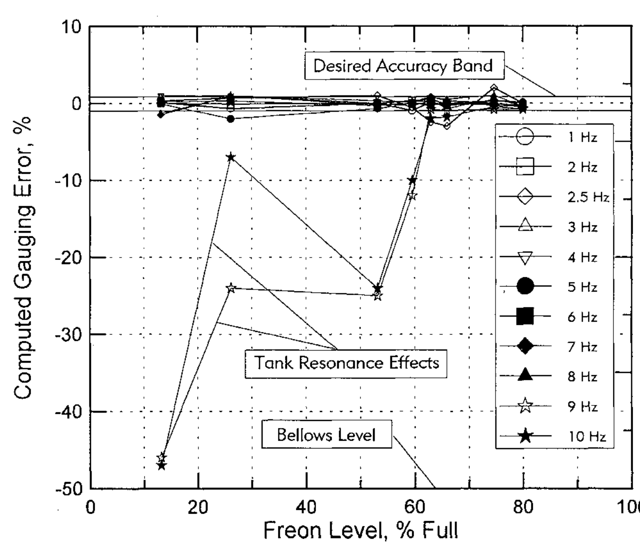

Fig. 4 Pulser frequency vs Freon quantity, dual-frequency model.

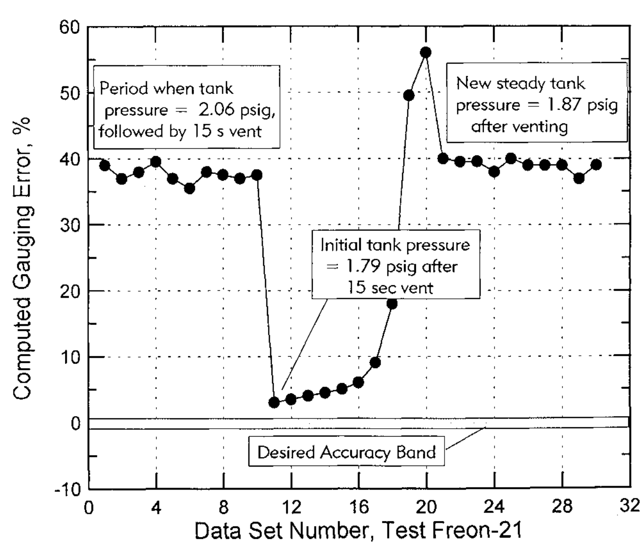

Fig. 5 Gauging error with liquid Freon heating.

reduced the gauging error to less than 3%. The error then began to increase with time and approached 5% within 10 min. Eventually, the error returned about to its initial high value and then remained steady. It was concluded from these results that, even in the absence of an analytical model that can be used to interpret pressure data with strong thermal effects, reasonably good gauging accuracy can be obtained during periods of liquid heating by momentarily subcooling the gauged liquid by tank venting to suppress the phase changes.

Another series of tests was conducted to investigate the effects of introducing a noncondensable gas on gauging a heated liquid, with the idea that such a gas would also suppress phase changes. The results of these tests are also shown in Fig. 6 (along with a baseline test with no heating shown by the open circle data that indicates the accuracy limit of the gauge). The introduction of air in the vapor did immediately reduce the gauging error (the inverted triangle data), although the improvement seemed to depend on the pulser frequency. Furthermore, just as with venting, the error eventually (after about 20 min) returned to its initially high value of 25%. When the heating rate was increased, the noncondensable gas had a less pronounced effect (the upright triangle data points), although, had additional air been introduced, the error would perhaps have been reduced further.

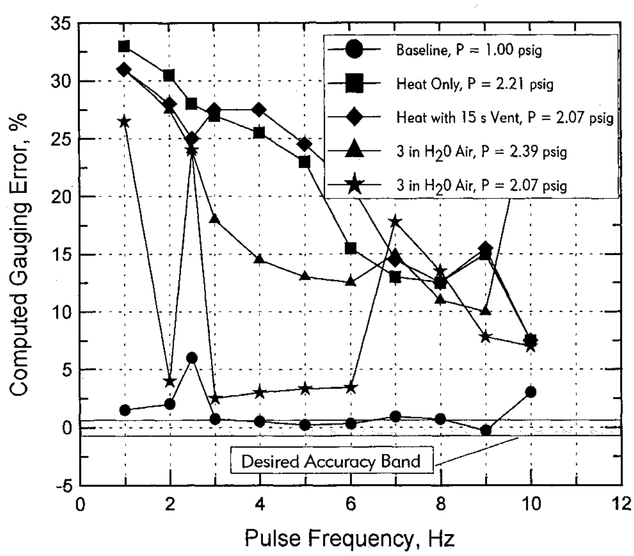

Fig. 6 Freon gauging with air pressurization and tank venting.

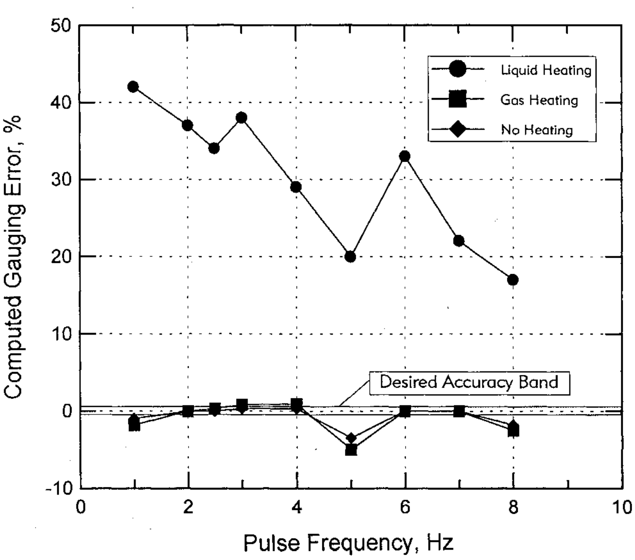

Fig. 7 Freon liquid and ullage heating effects on gauging.

Figure 6 also indicates that, regardless of whether air pressurization or vapor venting was used with the heated liquid, the gauging error was progressively reduced as the pulser frequency was increased. This trend is interpreted to mean that less time was available during each pulse cycle for phase changes to occur. Heating the Freon vapor in the ullage, as contrasted with heating the liquid, had almost no effect on gauging accuracy, as shown in Fig. 7.

Conclusions

Based on results of this work, it is concluded that the compression gauge is a feasible method for gauging liquid quantity, including cryogenic fluids, in low gravity. A summary of the test results follows:

1) Gauging accuracy of ±1% has been repeatedly demonstrated with a simulated cryogenic liquid (Freon-11) for conditions when the fluid is in thermodynamic equilibrium or is only slowly heated to self-pressurize the tank by less than 1.5 psig.

2) Predicted gauging errors exceed 25% during high heating rates of the cryogenic simulant. Although the test heating rates were over 100 times that expected in a space application, it was demonstrated that the gauging error can be reduced to less than 3% by conducting a short venting operation on the tank or by injecting a small amount of noncondensable gas into the tank.

3) Since there was no significant difference in gauging accuracy when the volume-pulser was submerged, the compression gauging system may perform as well in a microgravity environment as it did in these laboratory tests.

4) Gauging accuracy increased with increased pulser frequency during the liquid Freon heating tests, thus indicating that phase changes were probably the cause of the increased gauging error during heating. It is therefore possible that an acceptable accuracy can be achieved for a suitably rigid tank by operating the gauge at a high enough frequency to minimize phase changes during any one pulse cycle. On the other hand, if multiple large ullage bubbles exist in the liquid, the use of high-frequency pulses may excite the bubble system into resonance, thereby decreasing the gauging accuracy.

5) The analytical data-reduction models need to be extended to include the effects of thermodynamic phase-change phenomena.

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