
Experimental investigation of pressure-volume-temperature mass gauging method under microgravity condition by parabolic flight

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Abstract

Gauging the volume or mass of liquid propellant of a rocket vehicle in space is an important issue for its economic feasibility and optimized design of loading mass. Pressure-volume-temperature (PVT) gauging method is one of the most suitable measuring techniques in space due to its simplicity and reliability. This paper presents unique experimental results and analyses of PVT gauging method using liquid nitrogen under microgravity condition by parabolic flight. A vacuum-insulated and cylindrical-shaped liquid nitrogen storage tank with 9.2 L volume is manufactured by observing regulation of parabolic flight. PVT gauging experiments are conducted under low liquid fraction condition from 26% to 32%. Pressure, temperature, and the injected helium mass into the storage tank are measured to obtain the ullage volume by gas state equation. Liquid volume is finally derived by the measured ullage volume and the known total tank volume. Two sets of parabolic flights are conducted and each set is composed of approximately 10 parabolic flights. In the first set of flights, the short initial waiting time (3 ~ 5 seconds) cannot achieve sufficient thermal equilibrium condition at the beginning. It causes inaccurate gauging results due to insufficient information of the initial helium partial pressure in the tank. The helium injection after 12 second waiting time at microgravity condition with high mass flow rate in the second set of flights achieves successful initial thermal equilibrium states and accurate measurement results of initial helium partial pressure. Liquid volume measurement errors in the second set are within 11%.

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1. Introduction

About ninety percent of the total mass of liquid propellant rocket is occupied with liquid propellant, like liquid oxygen for an oxidizer and liquid hydrogen or kerosene for fuel. It is important to predict accurately the quantity of consumed propellant in a space mission for economical propellant fuelling and efficient rocket design. Optimization of the charging mass of liquid propellant makes it possible to load a rocket with additional satellite payload. It is, however, extremely difficult to predict the exact amount of consumed propellant before launching rocket. Consequently, it is necessary to measure the remaining propellant in space to obtain the actually consumed mass of propellant and this information shall be very useful data for next rocket design.

Various gauging methods for liquid propellant under microgravity have been studied so far and well summarized by Dodge (2008). Pressure-volume-temperature (PVT) gauging method is one of the most attractive gauging methods due to its simplicity and minimal hardware addition as mentioned by Van Dresar (2004, 2006). The effect of mass flow rate of pressurant gas injection was also studied and the low mass flow injection turned out to be suitable to minimize the disturbance effect of thermally equilibrium condition in a tank by Seo et al. (2012). Transient effect of PVT gauging method was investigated and the improved PVT concept which reduced the measuring period remarkably was suggested by Seo et al. (2012). It applies the discretized analysis considering the instantaneous increment of the pressure and the injected mass of pressurant gas.

This paper reports on the experimental results and discussion of PVT gauging method under actual microgravity condition in a parabolic flight. This is the first and unique experiment of testing the PVT gauging method under microgravity situation in a parabolic flight. The experiment was carried out using liquid nitrogen to simulate the behavior of cryogenic liquid propellant. The exceptional experimental set-up and the process for a parabolic flight are also presented for discussion.

2. PVT gauging method

Liquid volume can be obtained by subtracting the gas ullage volume from the total volume of a storage tank.

\[ V_t = V_{tank} - V_u \]  

The ullage volume is determined when the total gas mass is divided by the density of total ullage gas as (2). In a
propellant storage tank, the ullage volume is composed of pressurant gas, usually helium, and boil-off gas of liquid propellant. Assuming that these gases are homogeneously mixed and follow Dalton’s Law, the mass and density of helium gas can substitute for those of total gas as (2). Density of helium is calculated by the measured ullage temperature and the partial pressure of helium.

### Nomenclature

<table>
<thead>
<tr>
<th>f</th>
<th>Defined function</th>
<th>Subscript</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>mass</td>
<td>BOG Boil-off gas</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>f Final state</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
<td>He Helium gas</td>
</tr>
<tr>
<td>V</td>
<td>Volume</td>
<td>i Initial state</td>
</tr>
<tr>
<td>(\rho)</td>
<td>Density</td>
<td>l Liquid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>sup Supplied gas</td>
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<tr>
<td></td>
<td></td>
<td>sat Saturation state</td>
</tr>
<tr>
<td></td>
<td></td>
<td>tank Storage tank</td>
</tr>
<tr>
<td></td>
<td></td>
<td>total Total vapor and liquid</td>
</tr>
<tr>
<td></td>
<td></td>
<td>u Ullage</td>
</tr>
<tr>
<td></td>
<td></td>
<td>v Propellant vapor</td>
</tr>
</tbody>
</table>

Equation (2) can be further expressed with the properties of helium mass and density in a storage tank during helium injection process as described in Fig. 1 and (3).

\[
V_u = \frac{m_{\text{total}}}{\rho_{\text{total}}} = \frac{m_{\text{He}}}{\rho_{\text{He}}(T_u, P_{\text{He}})}
\]

The amount of helium mass change is equal to the supplied mass from a helium supply tank. It is determined from the measured pressure and temperature change and a known volume of the helium supply tank. Each initial and final state of helium density is obtained by using helium partial pressure and ullage temperature at each state as (5). Helium density is calculated by Refprop fluid property database by NIST (National Institute of Standards and Technology).

\[
\rho_f - \rho_{l_u} = \frac{m_f - m_i}{\rho_f - \rho_{l_u}}
\]

The components of each partial pressure are conceptually illustrated in Fig. 1. It is assumed that the liquid propellant and the ullage vapor in the storage tank become well-mixed and the vaporized propellant is in saturated state. Saturation pressure of vapor propellant is then obtained by measuring the ullage temperature which is supposed to be the saturation temperature when the tank is in thermal equilibrium. Saturation pressure is equal to the partial pressure of vapor propellant consisting of initial partial pressure and the boiled-off partial pressure. Therefore, the partial pressure of helium at each state is determined by subtracting the saturation pressure from the total tank pressure as followings:

\[
P_f - P_{sat}(T_u) = P_{l_u} + P_{\text{He}} + P_{\text{He,sup}} - P_{sat}(T_u) = P_{l_u} + P_{\text{He}}
\]

\[
P_f - P_{sat}(T_{u,f}) = P_{l_u} + P_{\text{He}} + P_{\text{He,sup}} - P_{sat}(T_{u,f})
\]

\[
P_f - P_{l_u} = P_{\text{He,sup}} = P_{\text{He,f}}
\]
3. Experimental set-up and results

3.1. Experimental set-up

Liquid nitrogen is chosen to be a representative liquid in this flight experiment to simulate the behavior of cryogenic liquid propellant. Practical cryogenic liquid propellant for Korea space launch vehicle (KSLV) series is liquid oxygen for an oxidizer. Since the density and temperature of liquid nitrogen, 806 kg/m³ and 77.2 K, are similar to those of liquid oxygen, 1141 kg/m³ and 90.0 K at 0.1 MPa, liquid nitrogen is an appropriate substitute for liquid oxygen. Also, oxygen gas is dangerous because it supports to burning of other substances. The experimental preparation process needs to pass the additional safety procedure and it requires the more complicated and validated experimental set-up because the experiment is conducted in an airplane with parabolic flight. The experimental set-up consists of a liquid nitrogen storage tank, an outer vessel for safety, a helium gas supply tank, a liquid nitrogen supply tank, and an exhaust system as shown in Fig. 2(a). The liquid nitrogen supply tank is detached before taking off of the airplane. The liquid nitrogen storage tank is a cylindrical-shaped stainless steel tank with dome cover at the upper and lower sides. The geometric dimensions of the tank are 227 mm in height, 250 mm in diameter, and 9.2 L in internal volume. A liquid nitrogen level meter, a liquid nitrogen injection pipe, a helium gas injection and vent line, and a guide rod for temperature sensor installation are located in the tank. The liquid level meter is a capacitance-type one (AMI, model 185) with 0.1% accuracy of the total measuring length, 190 mm. Two pressure transducers for measuring high and low range pressure (Delta Metrics, SPA-030P, 35 and 2.1 bara range with 0.25% accuracy) are installed on the top of the tank. Six silicon diode cryogenic temperature sensors (Lakeshore DT-670-SD, ± 0.25 K accuracy) are installed vertically to measure the temperature gradient in the tank as shown in Fig. 2(b). All control of fluid injection or venting operation is conducted with solenoid valves for convenience during a parabolic flight. Relief valves and parallel exhaust system for venting to outside atmosphere are connected to the storage tank with the outer vessel for safety in the aircraft.

![Fig. 2. Schematic diagram of (a) PVT gauging experimental set-up and (b) installation of temperature sensors in the liquid nitrogen storage tank](image)

3.2. Experimental results

Parabolic flights achieve successful microgravity condition under $3 \times 10^{-2}$ G. Although liquid nitrogen in the metal storage tank is not visible, uneven and globular interface of liquid nitrogen under microgravity is indirectly deduced by water configuration in the glass bottle as shown in Fig. 3.

Fig. 4(a) shows a typical example of PVT gauging experiment with helium gas injection during flight. $T_2 \sim T_4$
representing ullage temperatures become saturated condition when microgravity begins. The tendency of curves of T2 ~ T4 is similar to the tendency of the saturation temperature curve calculated by ullage pressure. T1 is originally in a superheated condition because T1 sensor is the nearest sensor to the hot upper wall of the storage tank and becomes dramatically cooled. T6 keeps stable subcooled condition before helium injection. T5 is not used due to a hardware problem in this experiment. Helium gas injection for 5 seconds is performed 9 seconds after the start of microgravity condition. Entire temperature data after helium injection seems to be unrelated to the saturation temperature curve due to sudden pressurization by hot helium gas injection. After helium gas injection, temperatures except T1 move along the pressure and the saturation temperature curves to converge as shown in Fig. 4(a). It implies that the thermal situation in the tank becomes equilibrium condition qualitatively due to the similar tendency between the measured temperature curves and the saturation temperature curve. Since there is helium partial pressure contribution in the measured total tank pressure after helium injection, temperature discrepancy about 1 K exists between the measured temperatures and the saturation temperature that is calculated by the total pressure. T1 stands for clearly subcooled condition because there can be an evaporation cooling effect. T1 submerges in the saturated liquid and emerge to ullage during parabolic flight and it is the nearest temperature sensor to the hottest wall of the tank. This phenomenon was also occasionally observed in the preliminary experiment when the storage tank was shaken to simulate saturation condition with uneven liquid interface shape on the ground.

To obtain the initial helium partial pressure, the total tank pressure and the saturation pressure from the measured temperature data during microgravity condition before helium injection are compared. There is slight discrepancy between the saturation pressure from the measured temperature and the measured total tank pressure due to the injected helium of the previous experiment set. The pressure discrepancy indicates the initial helium partial pressure and it can be calculated by Equation (5). The final helium partial pressure is also calculated by the same procedure with Equation (6). The saturated pressure of liquid nitrogen in the tank which is deduced from the measured temperature varies approximately 5 ~ 10 kPa because it is still unstable, transient, and not completely homogeneous condition due to the limitation of short duration of parabolic flight experiment. This saturated pressure variation is considered as the experimental uncertainty.

Fig. 4(b) shows liquid volume measurement errors of the PVT gauging experiments performed during the parabolic flight. The liquid volume measurement error is calculated as \( e = \left| \frac{V_{\text{PVT}} - V_{\text{true}}}{V_{\text{tank}}} \right| \times 100(\%) \). The true volume of liquid nitrogen is measured just before take-off. The #1 parabolic flight is a self-pressurization experiment for cooling hot tank wall and the PVT gauging experiment starts from the #2 parabolic flight. Although we can allow approximately 10 seconds to achieve stable saturation condition in the tank before helium injection, it
is extremely difficult to get complete thermal equilibrium condition due to the limitation of short duration of parabolic flight. The average error and the standard deviation are 10.9% and 11.9, respectively. These results seem inadequate for real measurement. There are two experimental limits in the parabolic flight: the mass limitation of helium gas due to pressure safety and short helium injection time which is approximately only 5 seconds. The more the injected helium mass for PVT method is, the more accurate the PVT measurement results become. This fact has been confirmed by Seo et al. (2012). It is believed that the improved PVT measurement is possible for practical situation in space, because there can be enough injected helium mass and injection duration in a space vehicle.

Fig. 4. (a) Pressure and temperature variation with helium gas injection and (b) liquid volume measurement error of PVT gauging method using liquid nitrogen under microgravity condition by parabolic flight experiment

4. Conclusions

PVT gauging experiments have been performed with a 9.2 L cylindrical shaped liquid nitrogen storage tank under 0.03 G microgravity condition by parabolic flights. Successful PVT measurement is achieved within 11% average at 30% liquid filling fraction when a sufficient stabilization period longer than 10 seconds is assigned before helium gas injection to guarantee thermal equilibrium condition. Saturated equilibrium condition is very important to measure the initial and the final helium partial pressures in a storage tank. The applicability of PVT gauging method in a space mission is verified by the experimental results under microgravity condition of parabolic flight. PVT gauging method is suitable for lunar or deep space exploration program with long microgravity duration in that thermal equilibrium condition is easily obtained in a storage tank.

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