Experimental Investigation of Pressure-Volume-Temperature Mass Gauging Method under Microgravity Condition by Parabolic Flight

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Introduction
Motivation of our research

Cryogenic Propellant Storage and Transfer (CPST):
the development of cryogenic storage systems,
low-gravity propellant management systems, cryogenic transfer and handling technologies

- Technology for susceptibility to environmental heat, complex thermodynamic and fluid dynamic behavior in low gravity and the uncertainty of the position of the liquid–vapor interface

- Important technology for lunar exploration and deep space mission for Korea space plan

- Propellant gauging: the interface of liquid propellant under microgravity in space becoming uneven and globular unlike that on the ground and this fact making the usual gauging liquid amount under microgravity impossible

S.M. Motil, et al., 2007, NASA/TM
PVT (Pressure-volume-temperature) mass gauging method

1. Minimal hardware
2. Simple measurement process

=> one of the most attractive gauging methods for transition period of self-development of Korea space rocket vehicle

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

by Dalton’s law
Calculating the ullage volume from the gas state equation using the measured mass, temperature, and the partial pressure of the injected non-condensable pressurant gas.

\[ V_u = \left. \frac{m_f - m_i}{\rho_f - \rho_i} \right|_{He} \]

\[ m_{He,f} = m_{He,i} + \Delta m_{He,sup} \]

\[ \rho_f - \rho_i \bigg|_{He} = f(P_{He,f}, T_f) - f(P_{He,i}, T_i) \]
Experimental set-up
Experimental apparatus for microgravity flight

- Experimental set-up consisting 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.
- Operating all control of fluid injection or venting solenoid valves for convenience during the short parabolic flight experiment (~ 20 sec).
The geometric dimensions of the tank with 227 mm in height, 250 mm in diameter, and 9.2 L in internal volume

Installation of a liquid nitrogen level meter, a liquid nitrogen injection pipe, a helium gas injection and vent line, and a guide rod for temperature sensor in the tank

Vertical installation of six silicon diode cryogenic temperature sensors (Lakeshore DT-670-SD, ±0.25 K accuracy) to measure the temperature gradient in the tank
Experimental apparatus for microgravity flight

Photos

Liquid nitrogen storage tank
Main experiment part (Cryostat and liquid nitrogen storage tank)
Helium supply tank
Electric devices
Water visualization
Background of microgravity parabolic flight
- One minute before entering microgravity, the aircraft performing rapid descent and ascent to reach its maximum velocity at the point where microgravity begins
- Achieving microgravity condition under $3 \times 10^{-2} \text{ G}$ for 20 seconds with a parabolic flight
- Japan Space Forum (JSF) coordinating a parabolic flight experimental program for foreign scientists and Diamond Air Service (DAS) in Nagoya, Japan
On-board equipment

- Photo of installation in the airplane
Experiment and results
Water configuration under microgravity

Video clip

Microgravity

FL2PF3
Liquid volume fraction: 30.81%, Injected helium mass: 0.67 g

Z axis acceleration (g)

Time (s)

Microgravity
## Experimental condition for microgravity flight

<table>
<thead>
<tr>
<th>Experimental conditions</th>
<th>#1 flight (10th, Oct., 2013)</th>
<th>#2 flight (14th, Oct., 2013)</th>
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<tbody>
<tr>
<td>Liquid filling fraction (%)</td>
<td></td>
<td>Low fraction, 30~32</td>
</tr>
<tr>
<td>He supply tank pressure (kPa)</td>
<td>300</td>
<td>350</td>
</tr>
<tr>
<td>He mass flow rate (slpm)</td>
<td>15 ~ 3</td>
<td>50 ~ 13</td>
</tr>
<tr>
<td></td>
<td>(80 with needle valve)</td>
<td>(150 with needle valve)</td>
</tr>
<tr>
<td>The number of experiment (times)</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Initial pressure (kPa)</td>
<td>106 ~ 107 (after self-pressurization)</td>
<td></td>
</tr>
<tr>
<td>Preparation period before helium</td>
<td>~3</td>
<td>~10 - 12</td>
</tr>
<tr>
<td>pressurization at 0G (sec)</td>
<td>(~10 for last 3 exp.)</td>
<td></td>
</tr>
<tr>
<td>Pressurization period at 0G (sec)</td>
<td>~5</td>
<td></td>
</tr>
<tr>
<td>After pressurization period (sec)</td>
<td>~30 - 40</td>
<td></td>
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Characteristics under closed condition

- Self-pressurization experiments without helium gas injection to observe the thermodynamic characteristics of liquid nitrogen in the tank during microgravity condition
- T1 ~ T4, the superheated temperature which is varied between 81 and 115 K before microgravity (they are invisible due to the graph scale), quickly becoming saturation temperature and move along the saturation temperature curve several seconds after the microgravity condition begins => thermal equilibrium state under microgravity
1. Initial He partial pressure before injection

- Assigning the preparation period about 10 seconds to ensure adequate stabilization period for saturated condition
- To obtain the quantity of the initial helium partial pressure, comparing the total tank pressure and the saturation pressure from the measured temperature data during microgravity condition before helium injection
2. Final He partial pressure after injection

- Obtaining thermal equilibrium and saturated condition after enough stabilization period longer than 60 seconds after helium pressurization despite of the condition under normal gravity

=> calculating the final helium partial pressure by the same procedure as for the initial one
Microgravity experimental results

- The average error and the standard deviation => 10.9% and 11.9, respectively
- Two experimental limits in the parabolic flight: the charged mass limitation of helium gas due to pressure safety and short helium injection duration for approximately 5 seconds

\[ V_u = \frac{\Delta m_{He,sup}}{\rho_f - \rho_i} \]

\[ \rho_f - \rho_i \bigg|_{He} = f(P_{He,f}, T_f) - f(P_{He,i}, T_i) \]

\[ e_i = \left| \frac{V_{l,PVT} - V_{l,true}}{V_{tank}} \right| \times 100(\%) \]
Conclusion

- Accurate 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 saturated condition.

- Thermal equilibrium condition is very important to measure the initial and the final helium partial pressures in a storage tank.

- Temperature variation due to non-fully homogeneous condition with the limitation of short duration of parabolic flight experiment results in the experimental uncertainty.

- 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.