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Review of Propellant Gauging Methods

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Nomenclature

C_p^i	=	specific heat of "i" component
m	=	mass of "i" component
$m_{MPL}{}^p$	=	propellant mass at Migration Point Load (MPL)
T	=	tank temperature
T_{env}	=	environment temperature
T_{rise}	=	tank temperature rise
$t_{heating}$	=	heating time
Q_{load}	=	heater power
Q_{cool}	=	heat exchange with environment
U	=	uncertainty of calculated or measured value
f	=	generic function\
ε^*	=	effective emissivity through Multi Layer Insulation (MLI)
σ	=	Stephane-Boltzman constant (5.68 10^{-8} W/K^4)
i	=	component index
p	=	propellant index
g	=	gas index
t	=	tank index

I. Abstract

Three of the most popular methods of propellant estimation, namely, book-keeping, PVT (Pressure, Volume, Temperature) and the thermal propellant gauging (PGS) methods are discussed in the current paper. Advantages and problems of each method are considered and compared. It is shown that the error of propellant estimation by the PGS method is inversely proportional to the heating time and proportional to the propellant fill level. The expression for the Migration Point Load was derived, after which the PGS method accuracy becomes superior to the bookkeeping and PVT methods.

II. Introduction

Several techniques are typically used to measure the amount of remaining propellant. The bookkeeping, PVT (Pressure, Volume, Temperature) and thermal Propellant Gauging System (PGS) are the most popular methods. Review of the propellant gauging techniques can be found in Ref. 1. Some of the methods, like the bookkeeping or PVT methods, have high accuracy at the beginning of spacecraft mission. The high accuracy of these methods is determined either by the fact that an error did not accumulate yet like in the bookkeeping method or due to a high propellant load as in the PVT method. On other hand, some methods which are not very accurate at the beginning of the mission life become very accurate at the end of the mission life. One such method is the thermal PGS method whose accuracy of propellant estimation increases as propellant load decreases due to increase of temperature rise sensitivity when the tank load decreases.

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Typically, if a gauging method is highly accurate at the beginning of the mission, when tank is full, then the accuracy deteriorates at the end of mission life, when the tank is depleting. The bookkeeping and the PVT methods exhibit such a behavior. The bookkeeping method accuracy is getting worse due to accumulation of the uncertainty throughout the mission life. The PVT method is loosing accuracy when pressure drops due to propellant drainage from the propellant tank.

A. Bookkeeping method

The bookkeeping method relies on the accuracy of the thruster flow rate prediction. Its uncertainty results directly from the uncertainty of the flow rate during LAE and thruster firings. It requires knowledge of all thruster on-times and pulse widths and exact thrust and flow rate through the engines. The flow rate depends on many parameters like duty-cycle, feed-pressure, thruster temperature, and its history of operation[2].

An error of estimation of the consumed propellant obtained by the bookkeeping method typically is in the range of ±2.5 % - 3.5 %, according to Ref. 1, 2, 3. Sources[1,3] did not give details how those numbers were obtained. A mathematical expression for uncertainty of propellant estimation by the bookkeeping method is given in Ref. 2, but the derived expression was not evaluated.

There are two concerns of using a constant value of fuel estimation error for the bookkeeping method. One of them is the fact that its thruster parameters, like an orifice diameter, do change with time which adds uncertainty with time. The second concern relates to the fact that thruster firing is executed many times, therefore, the efficiency of the firing in pulses should be different from firing continuously. A constant value of error estimation implies that an error of propellant estimation is the same if the thrusters fire continuously or in pulses. Such a conclusion is hard to believe.

The bookkeeping method does not allow determination of propellant load for each tank in a multi-tank configuration when tanks are connected. Several satellite buses have a propulsion system with multiple connected propellant tanks. Typically, the tanks form pairs of connected tanks. The bookkeeping method gives the total amount of the propellant in a pair but can't predict the propellant distribution between the tanks. It can lead to dire consequences, like unexpected tank depletion.

The bookkeeping method uncertainty increases in time which makes the method the least accurate at the End-of-Life (EOL) when fuel estimation should be the most accurate.

B. PVT method

The PVT method uses the Ideal gas law to estimate a propellant volume based on telemetry temperature and pressure reading[1,4,5]. The gas law is applied to the pressurizing gas (Helium). The accuracy of the estimated propellant volume depends on the precision of several parameters, including propellant tank volume and its stretch, and the pressure and temperature sensors mounted on a propellant tank, Helium mass, etc. Typically, the tank is considered isothermal and any temperature gradient is neglected. The accuracy analysis of PVT method is reported in Ref. 5. It is shown that PVT accuracy greatly depends on the accuracy of the pressure transducer. The accuracy of the PVT method decreases when the amount of propellant in the tank decreases[5]. It means that the PVT and book keeping methods are less accurate at the end of the spacecraft mission.

III. Accuracy of the Thermal Propellant Gauging method

A Thermal Propellant Gauging method is based on a concept of measuring the thermal capacitance of a tank containing liquid fuel and pressurant gas by measuring the thermal response of the propellant tank to heating and comparing the observed temperature rise to simulation results obtained from a tank thermal model[3,6,7]. Developed in Ref. 3 the Thermal Propellant Gauging Technique (TPGT) is based on a simple thermal model of the propellant tank which consists of two nodes, for the gas and liquid portions of a propellant tank. Described in Ref. 6, 7 the thermal Propellant Gauging System (PGS) employs a very sophisticated thermal model of the propellant tank which takes into account temperature gradients in the tank.

Non-uniform heater power distribution and uneven propellant distribution inside of the tank cause a non-uniform temperature distribution on the tank surface. Non-uniformity of heater power distribution stems from the fact that heater strips typically cover only a fraction of the tank surface. If propellant position in the tank is controlled by a vane-type Propellant Management Device (PMD) in microgravity, then at EOL the propellant is located in the sump and in the corners formed by PMD vanes and the tank wall. A significant portion of the internal tank wall is not in contact with propellant and therefore dry. All these factors lead to the formation of significant temperature gradients on the tank wall. Therefore, the temperature, which is measured by the temperature sensors on the external side of the tank wall, depends on the sensor locations. The temperature distribution on the tank surface must be determined to successfully compare the test flight data with calculated temperatures.

C. Simple Tank Model

The purpose of this work is to estimate an accuracy of the thermal PGS. No papers were found in open literature where the thermal PGS accuracy was obtained. We will start from consideration of a simple tank model and will use obtained results to analyze a real propellant tank. Let's consider a tank which contains liquid propellant and gas at the same temperature. The tank is covered by MLI and radiation is the major mechanism of heat exchange between the tank and the environment. The tank temperature is governed by the energy conservation law:

$$\sum_{i=p,g,t}(m^i C_p^i)\frac{dT}{dt} = Q_{load} - Q_{cool}$$

$$Q_{cool} = \varepsilon^* \sigma A(T_t^4 - T_{env}^4) \tag{1}$$

$$\sum_{i=p,g,t}(m^i C_P^i) = m^p C_p^p + m^g C_p^g + m^t C_p^t$$

where m^i is the mass of ***i*** component, C_p^i is the heat capacity of ***i*** component, Q_{load} is the heater power, ε* is the effective MLI emissivity through, σ=5.68 10^{-8} Stephane-Boltzman constant, A is the tank wall area, T_{env} is the tank environment temperature, superscript: *p* - propellant, *g*- pressurizing gas, *t*- tank

Following the usual approach of uncertainty analysis, the mass uncertainty is defined as:

$$m_p = f(T, Q_{load}, \varepsilon^*, m_g, m_t, T_{env}, C_P, ...)$$

$$U^2(m_p) = \left(\frac{\partial m_p}{\partial T}U(T)\right)^2 + \left(\frac{\partial m_p}{\partial Q_{load}}U(Q_{load})\right)^2 + \left(\frac{\partial m_p}{\partial \varepsilon^*}U(\varepsilon^*)\right)^2 + ... \tag{2}$$

where U is the uncertainty of calculated or measured value

Let's estimate an accuracy of PGS propellant estimation for the case when a temperature derivative with respect to time is proportional to the ratio of temperature rise $\boldsymbol{T_{rise}}$ over the heating time $\boldsymbol{t_{heating}}$, that is, $\frac{\partial T}{\partial t} \approx \frac{T_{rise}}{t_{heating}}$. The derivatives in Eq. (2) can be expressed as:

$$\frac{\partial m_p}{\partial T} = -\frac{\left[\sum_{i=p,g,t}(mC_p^i)_i\right]^2}{C_p^p}\frac{1}{(Q_{load} - Q_{cool})t_{heating}} - \frac{4\varepsilon^* \sigma A t_{heating} T_{rise}^2}{C_p^p}$$

$$\frac{\partial m_p}{\partial Q} = \frac{t_{heating}}{C_p^p T_{rise}} \tag{3}$$

Only terms which make the greatest contribution in propellant mass uncertainty Eq. (2) are retained in Eq. (3), that is, the temperature measurement uncertainty U(T) and heater power uncertainty $U(Q_{load})$. Figure 1 shows results of uncertainty calculation at temperature measurement uncertainty U(T) of 0.5 C and the heater power uncertainty $U(Q_{load})$ of 5%. Easy to see, that the error of propellant estimation by the PGS method is inversely proportional to the heating time. Data in Fig. 1 allows an estimation of an absolute value of the accuracy of propellant estimation by the PGS method. For example, the PGS method has accuracy of 1 kg at 10 kg fill level after 8 hr. of heating. This estimation pertains to one node model of the propellant tank.

It is convenient to express uncertainties of all parameters in terms of the temperature uncertainty. For example, the second term in Eq. (2), which shows the mass uncertainty related to the heater power uncertainty, can be expressed as

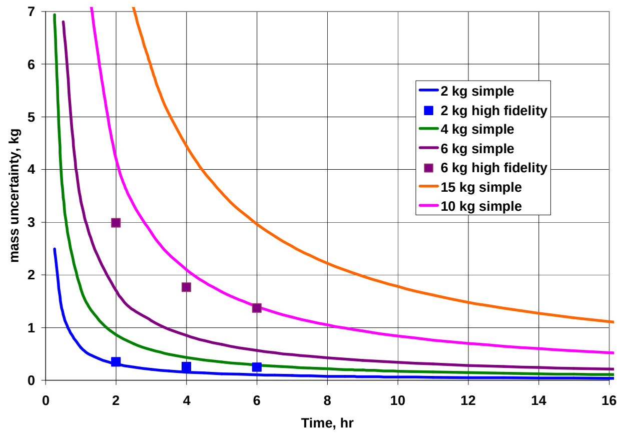


Figure 1. Uncertainty of PGS propellant estimation vs. heating time. Curves – simple tank model; markers – high fidelity tank model
The long heating time leads to an increase of the PGS propellant estimation accuracy

$$\frac{\partial m_t}{\partial Q} U(Q) = \frac{\partial m_t}{\partial T} U(T_Q) \; ; \quad where \qquad U(T_{Q)}) = \frac{\partial T}{\partial Q} U(Q) \tag{4}$$

Using this manipulation, it is easy to present Eq. (2) in the form

$$U^2(m_p) = \left[\frac{\partial m_p}{\partial T} \right]^2 \delta^2(T)^2$$

Where δ (T) is the total temperature uncertainty, defined as

$$\delta^2(T) = \left[U^2(T) + U^2(T_{Q_{load}}) + U^2(T_{\varepsilon^*}) + ... \right] \tag{5}$$

D. High Fidelity Tank Model

If temperature gradients can not be neglected, which is a common case, a simple thermal model does not provide high enough accuracy and temperature distribution in the tank should be determined numerically with corresponding boundary and initial conditions. A Finite Element (FE) model of the propellant tank was developed in Ref. 6, 7 and used for the propellant estimation. In this case, an accuracy of the PGS method can not be derived in close form similar to Eq. (3). In order to calculate the derivatives in Eq. (2), the terms in mass uncertainty Eq. (2) are expressed in Eq. (4) form. Essentially, the derivative of tank temperature with respect to a parameter is calculated instead of finding the derivative of mass with respect to the parameter. The derivative of the temperature with respect to the model parameters, like, heater power ($\frac{\partial T}{\partial Q}$) , effective emissivite ($\frac{\partial T}{\partial \varepsilon^*}$), etc is obtained by solving the FE tank thermal model with varied parameters.

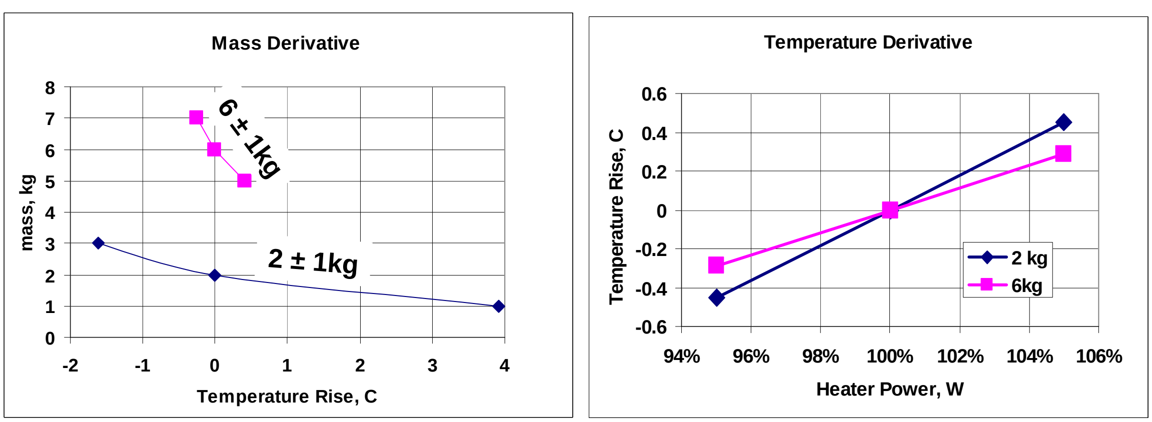
Data in Table 1 shows the effect of a parameter variation on the tank temperature rise for two loads of 2 kg and of 6 kg of fuel after 4 hr of heating. For an illustration purpose, let's consider a case of 2 kg load. The temperature rise for 2kg load and 100% of heater power is considered as nominal. If the tank load is increased by 1 kg, that is, the tank load is equal to 3 kg, the temperature rise will be 1.61°C lower than at the load of 2 kg. Similar, consideration is applied to the heater power variation. As Table 1 shows, an increase heater power of 5% leads to an increase of temperature rise of 0.45 °C at 2 kg load. Derivative calculations are shown in Fig. 2.

Table 1. Effect of parameters variation on tank temperature at sensor location.

		2kg	6kg	2kg	6kg
Parameter	**Variation**	**Delta T**		**Delta kg**	
-Base Line---	<none>	0.00	0.00	0.00	0.00
-Lower Bound -	-1kg	3.91	0.41	-1.00	-1.00
-Upper Bound-	+1kg	-1.61	-0.26	1.00	1.00
Heater Power	5%	0.45	0.29	-0.16	-0.86
	-5%	-0.44	-0.29	0.16	0.86

The derivative sought $\left[\dfrac{\partial m_p}{\partial T}\right]_{m=2kg}$ is approximated by a slope of the curve (2± 1kg) mass vs. temperature rise at m=2 kg (see Fig. 2a). It is easy to see that the slope is about -0.5 kg/°C at the temperature rise corresponding to m=2 kg. The derivative for a 6 kg load is obtained in similar way. The slope is about -2.9 kg/°C at the temperature rise corresponding to m=6 kg. The derivative $\left[\dfrac{\partial T}{\partial Q_{load}}\right]_{m=2kg}$ is assumed to be equal to a slope of the curve temperature rise vs. heater power for a 2 kg fuel load at 100% of Q_{load} (see Fig. 2b). Similar derivative is obtained for 6 kg load. The slopes are 1.45°C/W and 0.94°C/W for loads of 2 kg and of 6 kg, respectively.

The last two columns in Table 1 show a mass uncertainty that corresponds to different factors. For example, 5% of heater power uncertainty corresponds to the uncertainty of 0.16 kg of fuel mass at 2 kg fill level and to the uncertainty of 0.86 kg at 6 kg fuel load.



2a **2b**

Figure 2. Temperature rise as a function of parameters variation for 2 kg and 6 kg loads. 2a- temperature rise vs. fuel load. 2b – temperature rise vs. heater power.

Results for a high fidelity model are shown in Fig. 1. Qualitatively, results for simple and high fidelity models look similar. However, the results of the simple and high fidelity models can not be compared quantitatively because different assumptions were used for the error analysis. For example, the simple model assumes $\frac{\partial T}{\partial t} \approx \frac{T_{rise}}{t_{heating}}$ which corresponds to a small heat rejection to the environment. No such assumption was made for the high fidelity model. The simple model does not take into account temperature distribution in the tank which reduces the number of parameters for which uncertainty should be taken into account.

E. Migration point load

A "One Size Fits All" approach is difficult to implement, because one method of propellant estimation can not cover the entire range of loads with a high accuracy. In order to keep an accuracy of mass gauging at a high level, it makes sense to use a hybrid method which consists of two independent methods. The first method is used from beginning of the mission life, when propellant tanks are at the highest load. The second method will be used when the propellant load drops below a predetermined propellant load, a Migration Point Load (MPL). The migration point load is defined as a tank load above which accuracy provided by the 1st method is better than the accuracy of the 2nd method. Such a hybrid method will provide the highest possible accuracy in the entire range of propellant loads. The similar idea was discussed in Ref. 3.

Figure 3 shows a comparison of the propellant estimation errors for the bookkeeping and for the PGS methods assuming a 3% error of propellant used by the bookkeeping method. Data in Fig. 3 demonstrates that the PGS method accuracy becomes superior to the bookkeeping method when the propellant load drops below 20% of the initial load.

As soon as the level of propellant load drops below the MPL, the PGS method becomes a method of choice because from this point on the accuracy of the PGS method becomes superior to the accuracy of the 1st method, what ever the 1st method is.

For the case when heat loss to the environment is insignificant compared to the heat load from the tank heaters, one can derive an estimation of MPL ($m_{MPL}{}^{p}$) from Eq. (3) – (5):

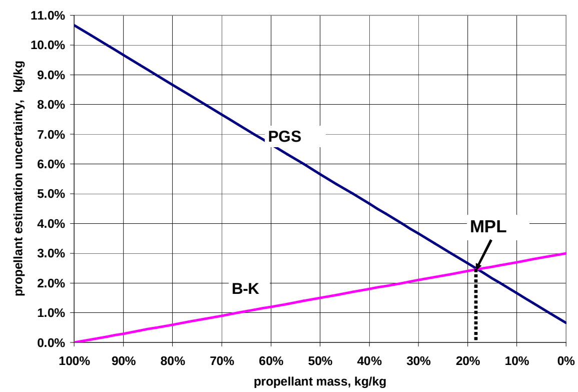


Figure 3. Comparison of bookkeeping and PGS methods. MPL – Migration Point Load

$$m_{MPL}{}^{p} = \frac{T_{rise}\,U(m_p)}{\delta T} - \frac{m^g C_p^g + m^t C_p^t}{C_p^p}\,\delta T \qquad (6)$$

The PGS method should be used when the propellant estimation error provided by the PGS method is less than the error of propellant estimation of the first mass gauging method used from the BOL to the MPL. Equation (6) allows estimation of a break point when PGS accuracy exceeds the accuracy of the first method.

IV. Conclusion

Three of the most popular methods of propellant estimation, namely, the book-keeping, the PVT (Pressure, Volume, Temperature) and the thermal propellant gauging (PGS) methods are discussed in the current paper. Advantages and problems of each method are considered and compared. It is shown that the error of propellant estimation by the PGS method is inversely proportional to the heating time and proportional to the propellant fill level. The expression for the Migration Point Load was derived, after which the PGS method accuracy becomes superior to other methods, like the bookkeeping and PVT methods.

V. Reference

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