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Unconventional Thermal Propellant Gauging System

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I. Abstract

Out of the most popular methods of propellant estimation, namely, book-keeping, PVT (Pressure, Volume, Temperature) and the thermal propellant gauging (PGS) methods, the latter is most accurate at End-Of-Life (EOL). The thermal method uses tank temperature respond to tank heating in order to infer propellant load of the tank. Propellant tanks are supposed to have attached heaters in order to have the thermal propellant gauging method successful. The paper discusses method of thermal propellant gauging when propellant tanks don't have installed heaters. It is shown that propellant gauging is possible even in this case. The biggest difference between conventional and unconventional thermal propellant gauging lies in role of tank environment in propellant gauging. Unconventional thermal propellant gauging requires development of a much more accurate spacecraft model than one used for the conventional propellant gauging. The paper discusses the difference between approaches.

II. Introduction

The Propellant Gauging System (PGS) method of propellant estimation 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[1,2]. Described in Ref. 1, 2 the PGS method employs a very sophisticated thermal model of the propellant tank which takes into account temperature gradients in the tank.

Non-uniform heat load on the tank and uneven propellant distribution inside of the tank cause a non-uniform temperature distribution on the tank surface. If the tank has heaters attached to the tank wall, non-uniformity of heat load comes from the fact that the heater strips typically cover only a fraction of the tank surface. If tank is heated by an external source, for example one of the bus or payload units, non-uniform temperature distribution stems from uneven heating of the tank from different directions.

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 is 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.

In absence of heaters installed on the propellant tanks, the tank temperature is typically controlled by internal satellite thermal control system. The BSS (former Hughes) 601 geosynchronous communication satellite is an example of such a thermal control scheme[3]. This design of tank temperature control presents a challenge for typical PGS methods because energy input into a propellant tank is done not by heaters installed on the propellant tanks but by rather by an external heat source like one of payload or bus units.

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Typically, the power dissipation of such unit is known. An example of a heat generating unit would be TWT or one of the bus units which generate enough heat to increase tank temperature. The key is the knowledge of heater power or/and surface temperature of the unit. If the unit in question has a temperature sensor, heat generation by the unit can be calculated and compared with heat dissipation of the unit (which is typically known). Conversely, knowledge of heat generation allows calculation of unit temperature which then can be compared with temperature sensor reading if the unit has temperature sensor installed. In both cases, the development of high fidelity models of payload and bus units is required. Unit models are incorporated into a spacecraft thermal model.

Heat transfer from the unit into a propellant tank is carried by radiation and conduction. Satellite components are involved in both mechanisms of heat transfer. For example, heat may be rejected via radiation from the unit into a satellite panel which in turn is radiativly coupled with a propellant tank. At the same time, heat is transferred from the unit to the tank via conduction through unit attachment to the panel, the panel itself and attachment of the tank to the satellite panel. In order to describe heat transfer from the unit into the tank correctly, a high fidelity model of the satellite is required.

Such a requirement constitutes the major difference for PGS method between satellites with and without heaters installed on the propellant tanks. If propellant tanks have heaters installed and the tanks are covered with a thick Multi Layer Insulation (MLI) blanket, the tanks do not have much thermal interaction with the satellite environment. Knowledge of the satellite thermal environment is not so important for correct propellant estimation by the PGS method. On other hand, if the payload or/and bus unit is a heat source which used for propellant estimation, the heat source is a part of the satellite environment. In this case, the tank temperature increase is determined by thermal interaction between the tank and the satellite environment. Therefore, knowledge of the satellite environment becomes very important for correct propellant estimation.

III. Thermal models

Regardless of the spacecraft type the PGS method employs the same steps:

- Develop a thermal model of the propellant tank
- Develop a thermal model of the satellite
- Simulate PGS operation for different propellant loads
- Prepare and conduct PGS operation
- Compare flight and simulation data
- Determine tank propellant load

The first step of the PGS method, namely, development of the tank thermal model, is mostly driven by the tank design and by the fact that heaters (if installed) create a large temperature gradient on tank walls in the heaters vicinity. Capturing temperature gradients and determining tank wall temperature at the temperature sensor location with high accuracy requires development of a high fidelity tank model. In the absence of the heaters on the tank surface, one can expect less temperature gradient and therefore, less stringent requirements for capturing temperature gradients.

A. High Fidelity Tank Model

If temperature gradients cannot be neglected, which is a common case, temperature distribution in the tank should be determined numerically with corresponding boundary and initial conditions. The previously developed a Finite Element (FE) model of the propellant tank[1,2] was based on grid provided by Surface Evolver[4]. The developed FEM model of the tank had several problems including difficulty of keeping the ratio of the maximum to minimum conductances of the links between nodes in the

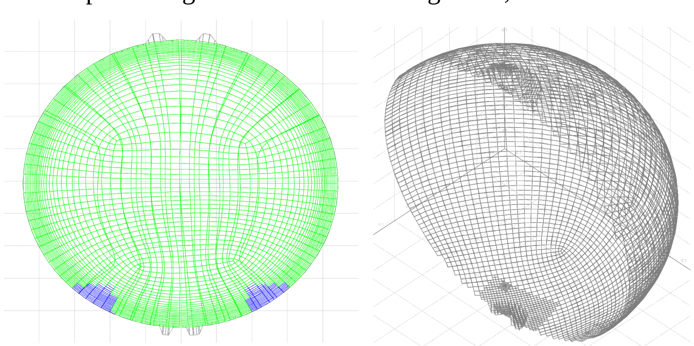

Figure 1 Cross section and shell of final tank grid

thermal model sufficiently small to avoid ill-conditioned matrices in the thermal modeling. Also, the previously developed grid which was based on Surface Evolver results_ had extremely small or large conductances, which are not generally necessary. Similarly, the minimum thermal capacitance of elements affects step size in time and thus overall computational time of the modeling.

In order to avoid such problems, a new FEM of the propellant tank was developed. Grid generation for such complex geometry like tank with gas and liquid volumes, tank wall, heaters, etc was not simple task. The grid should satisfy the following requirements: It should have high enough density to simulate temperature gradients, particular at the temperature sensor location; it should confirm to the primary geometry of model components like, tank wall; grids for propellant liquids and for pressurant gas should confirm grids at the interfaces; and grids should confirm to heater shape, etc.

GridPro[5] was selected as a primary tool for grid development. It is a powerful tool designed to create Computational Fluid Dynamics (CFD) grids. Use of the GridPro was not straightforward in our case. It is difficult to get a CFD style grid to converge and to model accurately the geometry when the geometry is complex. For example, GridPro has a problem with geometry like sharp edges or a zero-degree angle between two surfaces. The gas/fluid interface alone causes difficulty of converging for the GridPro. Add to this, satisfaction of different requirements for the grid like confirmation to tank heaters shape, variations in the tank wall profile, mounting lugs, etc. requires a lot of time in order to develop a grid that will converge. A suite of software tools was developed in order to overcome these limitations.

Figure 1 shows several cross-sections of the final grid. As one can see, the grid has higher density next to tank wall where large temperature gradients are expected.

B. High Fidelity Satellite Model

This paper discusses development PGS for BSS (former Hughes) 601 geosynchronous communication satellite. Reference 3 describes the satellite design. In particular, figures 4 through 6 of Ref.3 shows a general view of the satellite, its internal structure.

The satellite propulsion system has four spherical tanks (two fuel tanks and two oxidizer tanks). Tanks are covered with single layer MLI[3]. Figure 7 in Ref.3 shows two temperature sensors that are installed on the top and on the bottom of a propellant tank. The top temperature sensor approximates pressurant temperature. The bottom temperature sensor senses the temperature of the propellant contained inside of the trap (Fig.7 in Ref.3) at EOL.

As far as the PGS method concern, such design of the propellant tanks and the satellite requires development of a satellite thermal model which should describe: a). radiation heat transfer between tanks and satellite components such as panels and payload/bus electrical and electronic units; b). heat transfer by conduction between the units and satellite structure between satellite structure and propellant tanks. Due to the particular position of the temperature sensors on the propellant tank wall, heat transfer between bottom of the propellant tank and the satellite presents the greatest interest. The satellite thermal model should include also solar fluxes incident on the outer surfaces of the satellite.

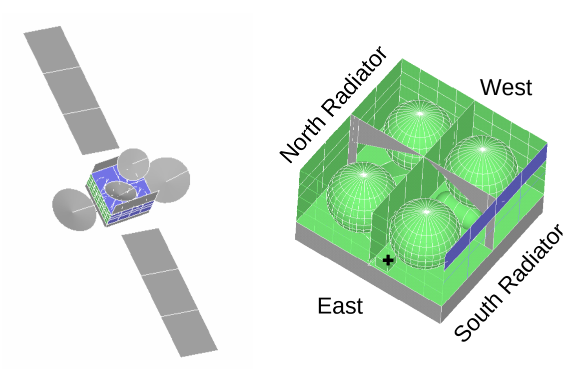

Figure 2 HS 601 satellite configuration.
Cross is a heat generating unit

The radiation interaction inside of the satellite and solar fluxes- which are incident on the outer surfaces of the satellite- were simulated by Thermal Synthesizer System (TSS) software tool. Typically, North and South panels of communication satellites house heat producing units, like a Traveling Wave Tube (TWT) which is usually instrumented with temperature sensors. Use of temperature sensor reading as a boundary condition simplifies the satellite thermal model because it circumvents the need to determine temperature of the North/South panels. Usually, East and West panels don't have any payload or bus units and temperatures of such panels should be calculated. All surfaces of the satellite internal panels are assumed painted black, which is common practice for communication satellites in order to increase heat rejection from the internal panels.

IV. Results and Discussion

In order to study an effect of heat generation by a unit on tank temperature, we assume that such a unit is located on the bus panel next to a panel that goes East/West direction (Fig. 5 in Ref.3). The temperature of the unit is assumed of 60 C when the heater is turned ON. Figure 3 shows the tank temperature trend when the unit is turned ON and OFF. As one can see, it takes about 48 hr. to reach equilibrium with satellite environment. The cooling period also lasts about 48 hr.

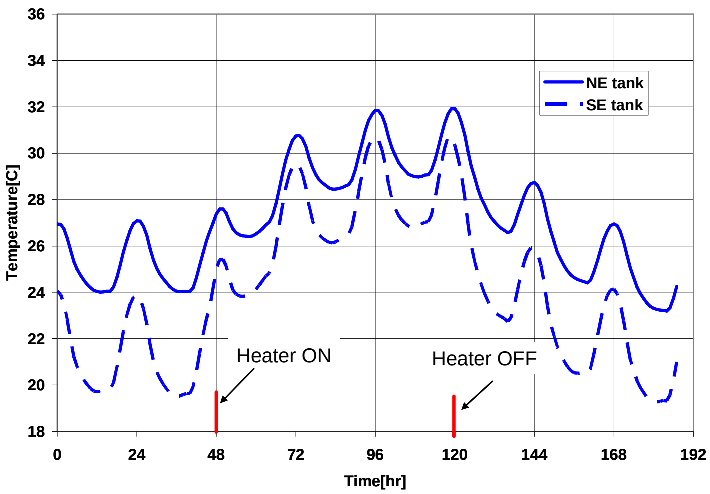

Figure 3 Tank Temperature at the bottom;

When the heat generation unit is turned ON temperature of both tanks, NE and SE, increase. Heat transfer to the SE tank is conducted mostly via radiation. Heat transfers from the unit to the NE tank via conduction through the base panel and via radiation across the middle wall. As expected, temperature rise of NE tank is less than temperature rise of SE tank.

Tank temperature increase due to heat input from the heat generating unit presents the most interest, as far as the PGS method is concerned. Such a temperature increase has the same magnitude as tank temperature change due to daily temperature variation. This obscures temperature increase, which is coming from the unit. A normalization procedure was developed in order to extract tank temperature change coming from the unit. Figure 4 shows behavior of the normalized temperature. Daily temperature fluctuations are removed and only temperature rise due to heat injection remains.

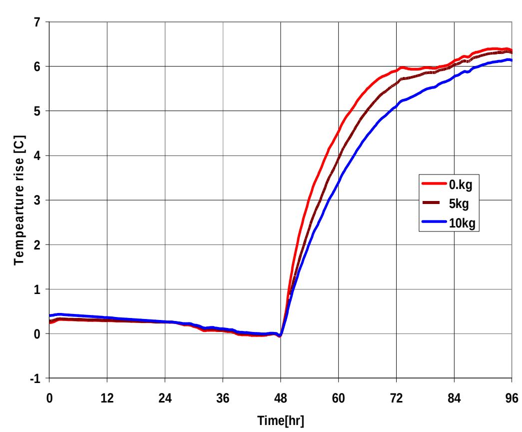

Figure 4 Normalized Tank Temperature

The plot also shows an effect of tank propellant load on the temperature increase, which is the most interest to the PGS method. The data clearly demonstrates that temperature increase depends on the propellant load and can be used for propellant estimation by the PGS method.

This paper does not address an accuracy of the PGS method in the case under consideration, namely, when tank heating is provided by external to tank heat source like a payload or bus unit. Accuracy of propellant estimation will be the subject for the next paper.

V. Conclusion

This paper discusses a feasibility of applying the PGS method for propellant estimation of a satellite which does not have heaters installed on the propellant tanks, like BSS (former Hughes) 601 geosynchronous communication satellite. It is shown that the PGS propellant estimation is feasible if a payload or a bus unit is used as an external heat source. However, use of the PGS method for propellant estimation requires development of a satellite thermal model of higher fidelity compared to the case when the propellant tanks have heaters installed and tanks are insulated from the satellite environment.

VI. Reference

[1]J. Ambrose, B. Yendler, and S. H. Collicott, "Modeling to Evaluate a Spacecraft Propellant Gauging System", *Journal of Spacecraft and Rockets*, vol. 37, Nov-Dec 2000, pp. 833--835

[2]A. Yip, B. Yendler, T. A. Martin, S. H. Collicott, "Anik E Spacecraft Life Extension", proceeding of Eighth International Conference on Space Operations, Montreal, Quebec, Canada. May 17-21, 2004

[3]Purohit, G.P., et al. " Transient Lumped Capacity Thermodynamics Model of Satellite Propellant Tanks in Microgravity", Proceedings of the 37th AIAA conference, 11-14 January 1999, Reno, NV, USA

[4]K.A. Brakke, The Surface Evolver, Experimental Mathematics, 1(2):141-165, 1992

[5]K. Rajagopalan, P. R. Eiseman: Automatic nested refinement: a technique for the generation of high quality multi-block structured grids for multi-scale problems using GridPro, Engineering with Computers, Vol. 21(1): 2005, pp. 29-35