Thermal Analysis of Spacecraft Propulsion System and its Validation

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Heaters for the spacecraft propulsion system are sized to prevent propellant from catastrophic freezing. For this purpose, thermal mathematical model (TMM) of the propulsion system is developed. Calculation output is compared with the results obtained from thermal vacuum test in order to check the validity of TMM. Despite a little discrepancy between the two types of results, both of them are qualitatively compatible. It is concluded that the propulsion system heaters are correctly sized and TMM can be used as a thermal design tool for the spacecraft propulsion system.

Key Words : Spacecraft, Propulsion System, Thermal Analysis, Heater Sizing, Thermal Vacuum Test

Nomenclature

A : Surface area [m^2]
B : Absorption factor
C : Thermal capacitance [J/K]
E : Emissive power [W/m^2]
F : Form (view) factor
F' : Exchange quantity
G : Thermal conductance, 1/R [W/K]
$\hat{G}$: Radiation conductance, $1/\hat{R}$ [W/K^4]
k : Thermal conductivity [W/mK]
L : Length between the two nodes [m]
q : Radiant heat [W]
Q : Heat source/sink in Eq. (1) [W]
R : Thermal resistance [K/W]
$\hat{R}$: Linearized radiation resistance [K/W]
T : Temperature [K]

Greek Symbols

ε : Emissivity
σ : Stefan-Boltzmann constant [$=5.67\times10^{-8}$ W/m^{2}K^4]

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1. Introduction

A spacecraft propulsion system commonly uses hydrazine as its liquid propellant. Physical properties of the hydrazine are similar to those of water. The freezing point could be one of them since hydrazine freezes at 2℃. If the propellant freezes in propulsion system, the spacecraft encounters a catastrophic situation, which could ends up with a mission failure. For this reason, thermal control system must be dedicated to protect the propellant from freezing and heaters are commonly selected as thermal control hardware due to their reliability and low cost.

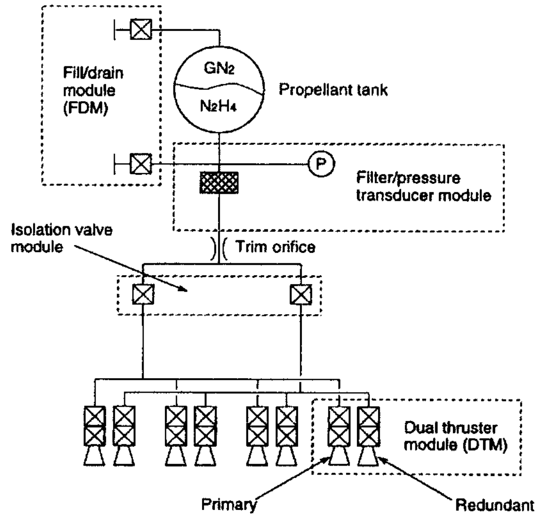
'Heater sizing' is a first step to design an effective thermal control system. It estimates the heater power using a thermal mathematical model (TMM). Once the valid TMM is developed, the thermal information, which couldn't be obtained from other expensive tests, can be achieved. This study contains the comparison between the results from numerical analysis and the thermal vacuum test. For the thermal vacuum test, Structural and Thermal Model (STM) is developed, which is equivalent to the flight model in terms of structural and thermal point of view. STM consists of dummy masses and simulation heaters to simulate the spacecraft electrical components.

2. KOMPSAT Propulsion System

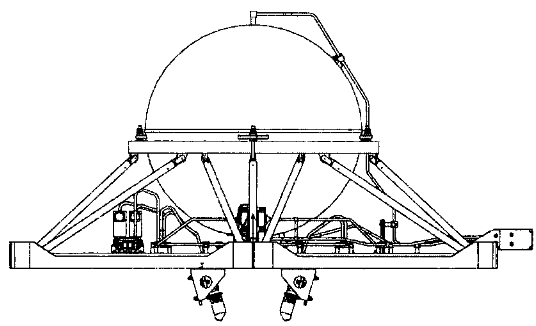
Since 1994, Korea Aerospace Research Institute (KARI) has developed a series of Low-Earth-Orbit (LEO) observation satellites such as KOMPSAT (KOrea Multi Purpose SATellite; Kim et at., 2000a) series. The KOMPSAT-2 propulsion system contains 4.45 N MRE-1 (Monopropellant Rocket Engine-1, NASA standard component). The propellant is supplied by Pressure Feeding System (PFS) with high operational reliability. A spherical Titanium tank with 56 cm diameter contains hydrazine of 72.6 kg and the gaseous nitrogen pressurant of 27.6 bar. They are mechanically separated by a diaphragm inside the propellant tank. The elastomeric polymer diaphragm with an active expulsion type operates in a blowdown mode. This type of tank is able to supply the propellant to the propulsion components effectively under any acceleration vector. At the operating pressure, 3.4~27.6 bars, the expulsion efficiency over 99% is achieved (Han and Kim, 2003; Kim et al., 2000b).

In addition to the propellant tank, thrusters, latching valve, fill/drain valve, pressure transducer, and propellant filter are classified as major components of propulsion system. Also, the propulsion system includes propellant lines, interface components, brackets, and the thermal control components such as heaters, thermostats, and the temperature sensors.

In ease of manufacturing, assembly, and design change, the KOMPSAT-2 propulsion system is modularized, such as Dual Thruster Module (DTM), Filter/Pressure transducer Module (FPM), Latching Isolation Valve Module (LIVM), Fill/Drain valve Module (FDM), and the Propellant Tank Module, etc. To avoid single-fault failure, all on-orbit operational components are designed to have the redundant circuit (Kim et al., 2000c). The design schematic and actual configuration of KOMPSAT-2 propulsion system are shown in Fig. 1. All the modules and components except FPM are insulated



(a)



(b)

Fig. 1 KOMPSAT-2 propulsion system : (a) Design schematic, (b) System configuration

with Multi-Layer Insulation (MLI) to be thermally isolated from the outer environment.

3. Thermal Requirements and Approaches

Table 1 (Han et al., 2003) shows the thermal management criteria of KOMPSAT-2 propulsion system. To avoid single-fault failure, two separate heater circuits are designed to protect the hydrazine-wetted components from propellant freezing: the primary and redundant heater circuits with two thermostats in series. The temperature set-points of primary thermostats are 11℃ (turn-on) and 18℃ (turn-off) while the redundant thermostats are 7℃ (turn-on) and 17℃

Table 1 Thermal management criteria

Relevant component	Thermal management criteria
All wetted components	≥7℃
At any point (except propellant valves and tank)	≤49℃
Propellant valves resulting from thruster firing	≤116℃
Propellant tank	≤38℃
Catalyst bed	≥177℃

* Heater sizing with maximum duty cycle of 70%.
* Single-fault tolerance to propellant freezing and over-temperature.

Table 2 Boundary conditions used in thermal analysis

Worst cold case	Thruster valves	Propellant lines, modules, and propellant tank	Parts of components exposed to deep space
Conduction	−13℃	−10℃	N/A
Radiation	−13℃	−10℃	−273℃

(turn-off).

The worst cold condition is applied to the thermal analysis, which confirms whether the thermal design can meet the thermal requirements in all cases. With conservatism in the thermal design, the worst cold condition is defined as follows :

- All the heat generating components of the spacecraft do not operate.
- Spacecraft is in eclipse.

A detailed solid model and its related nodes of each module are shown in Fig. 2, 3, and 6. The interface temperatures to which the heaters accommodate are described in Table 2. The temperature of −13℃ is assumed as a boundary value for the Dual Thruster Module (DTM) bracket, because it is the worst cold temperature for the propulsion platform, which came from thermal prediction of spacecraft system level.

The lowest voltage of the battery cell is estimated as 1.31 volts. And 21 out of 22 battery cells are expected to operate at the worst condition. The worst voltage drop of harness is estimated as 1.51 volts. Under this condition, the lowest voltage at the spacecraft component input terminal is calculated as 26 volts. In this reason, 26 volts is recommended as the worst case input voltage of the spacecraft bus heater design. However, the lowest expected voltage of the propulsion heaters is set up at 25 volts for conservatism in heater sizing.

4. Method of Thermal Analysis

To determine an appropriate heater size, i.e., heating power, it is necessary to conduct the thermal analysis by using dedicated software, which characterized as a solver for conduction and radiation heat transfers. Among many available commercial solvers, TAS (Thermal Analysis System, by Harvard Thermal, 1999) is selected for the numerical simulation. TAS is a general-purpose tool used for a computer-simulation on thermal problems. It was evolved from a previous programmable tool, i.e. SINDA (Analytic Corporation, 1996a), which takes advantage of a lumped parameter approach (Choi, 1996). It provides an integrated, three-dimensional graphical and interactive environment to users. It performs the electrical network analogy that takes account of the resistance (R) and the capacitance (C). Finite element solution is then used to calculate those resistors. It also contains the finite difference solver of iterative nature.

4.1 Conduction resistance

The heat balance equation on an arbitrary node is expressed as follows :

$$\frac{C_i}{\Delta t}(T_i^{n+1}-T_i^n) = Q_i+\sum_{j=1}^{n}[G_{ji}(T_j-T_i)+\hat{G}_{ji}(T_j^4-T_i^4)] \quad (1)$$

The linear conductor G_{ij} (or conduction resistance R_{ij}) is related to the conduction heat transfer as in Eq. (1). It can be expressed as a function of conductive shape factor S.

$$G_{ji}=\frac{1}{R_{ji}}=\frac{kA}{L}=kS \quad (2)$$

4.2 Radiation resistance

The calculations of the radiation resistances are solved by the absorption factor method suggested by Gebhart (1971). When an n-surface enclosure is considered where A_i and A_j are the areas of any two surfaces, if all of the surfaces are black, the rate q_j of radiant energy loss from surface A_j is given as follows:

$$q_j = E_j A_j - \sum_i^n F_{ij} F_i A_i \tag{3}$$

where F_{ij} is the view factor defined as the fraction of radiation that leaves A_i and is intercepted by A_j; E_j is the emissive power of j-th surface.

For gray surfaces, the fraction of the emission of the i-th surface which is absorbed by A_j is not the same as F_{ij}. Thus an absorption factor B_{ij} is defined as the total fraction of the emission rate of A_i, i.e., $E_i A_i$, which is absorbed by A_j, taking into account all paths whereby this radiant energy may reach A_j for absorption, as represented in the following.

$$q_j = E_j A_j - \sum_i^n B_{ij} E_i A_i \tag{4}$$

The network method by Hottel and Sarofim (1967) is introduced to calculate the radiation conductors incorporating with the absorption factor B_{ij}. An energy exchange quantity between the diffuse-gray surfaces A_i and A_j, q_{ij}, is defined in terms of an exchange quantity F'_{ij} as:

$$q_{ij} = F'_{ij} A_i \sigma (T_i^4 - T_j^4) \tag{5}$$

By comparing the above equation with the absorption factor method, F'_{ij} can be related to B_{ij} as $F'_{ij} = \varepsilon_i B_{ij}$ (Gebhart, 1971). As a consequence, the following general relation can be represented in terms of the matrix form:

$$\begin{aligned} &[SF] = [E][B] \\ &[\boldsymbol{B}] = \{[I] - [F] + [F][E]\}^{-1} [F][E] \end{aligned} \tag{6}$$

In the above equation, $[SF]$, $[E]$, $[I]$, and $[F]$ represent the exchange quantity (F'_{ij}), surface emissivity (ε_i), unit, and view factor matrices, respectively.

Due to the significant complexity from Eq. (6), TAS incorporates with TRASYS (Analytix Corporation, 1996b) to acquire the exchange quantity, F'_{ij}, from the three-dimensional model provided by user. Hence the final radiation conductor in Eq. (1) is expressed as $\hat{G}_{ji} = F'_{ji} A_j \sigma$. In computation, the radiation resistance $\hat{R}_{ji}$ from Eq. (7) is utilized according to the linearization of the radiation exchange term in Eq. (1).

$$\hat{R}_{ji} = \frac{1}{\hat{G}_{ji} (T_j^2 + T_i^2)(T_j + T_i)} \tag{7}$$

5. Results and Discussion

During the design stage of the satellite propulsion system, the thermal analysis of each module is carried out with full three-dimensional model, which will be used to predict the thermal behavior and the total heater power. The average power (total power × duty, see Table 3) must be in the range of its power budget assigned from the system. Among the modules, the Fill/Drain valve Module (FDM) and the Filter/Pressure transducer Module (FPM) are exemplified in this paper.

After the thermal analysis of each module, the whole propulsion system including all the modules should be analyzed in turn. It is not efficient to establish the thermal analysis model of the whole propulsion system with full three-dimensional nature. For this reason, a lumped parameter approach is introduced in propulsion system level modeling. This approach is very effective not only for system level thermal modeling but also for systematical thermal model validation. In this approach, all of the pertinent parameters, such as thermal resistors between each modules and the propulsion platform, are the same as those incorporated in the full three-dimensional thermal modeling of each module.

All physical properties adopted in the thermal analysis refer to the satellite design handbook (Gilmore, 1994) and component specifications from the vendors. The general properties of contact conduction, such as the contact conductivity and the conduction path etc., are hardly found. Therefore the design heritage (KARI, 1996) from the precedent, i.e., KOMPSAT-1 (known as Arirang Satellite) is referenced as required. All

Table 3 Estimation of heater power for worst cold case

Components	Unit Heater Power at 25 Volts of Bus Voltage [Watts]			Total Power [Watts]	Duty [%]		Total Average Power [Watts]
Thruster Valves	2.71		per DTM	10.85	1R ON	70	7.59
					3P+1R ON	38.8	4.21
Cat. (Catalyst) Beds	1R ON	0.61	pre DTM	2.43	N/A		2.43
	3P+1R ON	2.43		9.73			9.73
Propellant Tank	1.54		per Heater	6.17	59.3		3.66
Filter and Pressure Transducer Module	2.17		Total	2.17	15.3		0.33
Latching Isolation Valve Module	2.17		Total	2.17	52.6		1.14
Fill and Drain Valve Module	2.17		Total	2.17	39.7		0.86
Propellant Lines #1	5.06		per Circuit	12.96	52.9		2.68
#2	5.06				54.3		2.75
#3	2.84				20.3		0.58
Overall Values	1 Red. Cat. Bed Heater ON			38.92	56.6		22.02
	3 Pri.+1 Red. Cat. Bed Heaters ON			46.21	56.1		25.93

* Pri. (or P): Primary, Red. (or R): Redundant

of the results from thermal analysis have transient nature, caused by the thermostat behavior. Consequently, the initial temperature is needed and it is set at 10℃ for computation.

5.1 Thermal analysis of each module

Fill and drain valve module in Fig. 2(a) shows all nodes considered in thermal analysis and its three-dimensional model is shown in Fig. 2(b). The transient temperature results are illustrated in Fig. 2(c) and (d) when primary heater circuits are activated under the worst cold condition at 25 and 28 volts of bus voltage. Heater powers are assigned as 2.17 and 2.72 watts at 25 and 28 volts of bus voltage, respectively. The heater for this module is expected to operate properly since thermal response shows cyclic motion. With increase in the spacecraft bus voltage, the thermal cyclic period becomes shortened due to increase in heat input, which causes a rapid temperature rise. This tells that the heaters are sized properly and meet the thermal requirements aforementioned.

Figure 3(a) represents the solid model for the filter and pressure transducer module along with node numbers. Heater is installed on the propellant filter, because the pressure transducer generates heat when it's operating. At 25, 28, and 34 volts of bus voltages, the corresponding heater power is assumed as 2.17, 2.72, and 4.01 watts. The transient temperature variation for the worst cold, nominal, and worst hot cases are shown in Fig. 3(b), (c), and (d), respectively. In Fig. 3(b), the heater is sized to provide sufficient power to meet the thermal requirements at the worst cold condition of 25 volts. In Fig. 3(c), the nominal case is assumed in which the pressure transducer dissipates 0.5 watts at all time with 28 volts of bus voltage. Due to continuous heat dissipation in pressure transducer, the cyclic period becomes

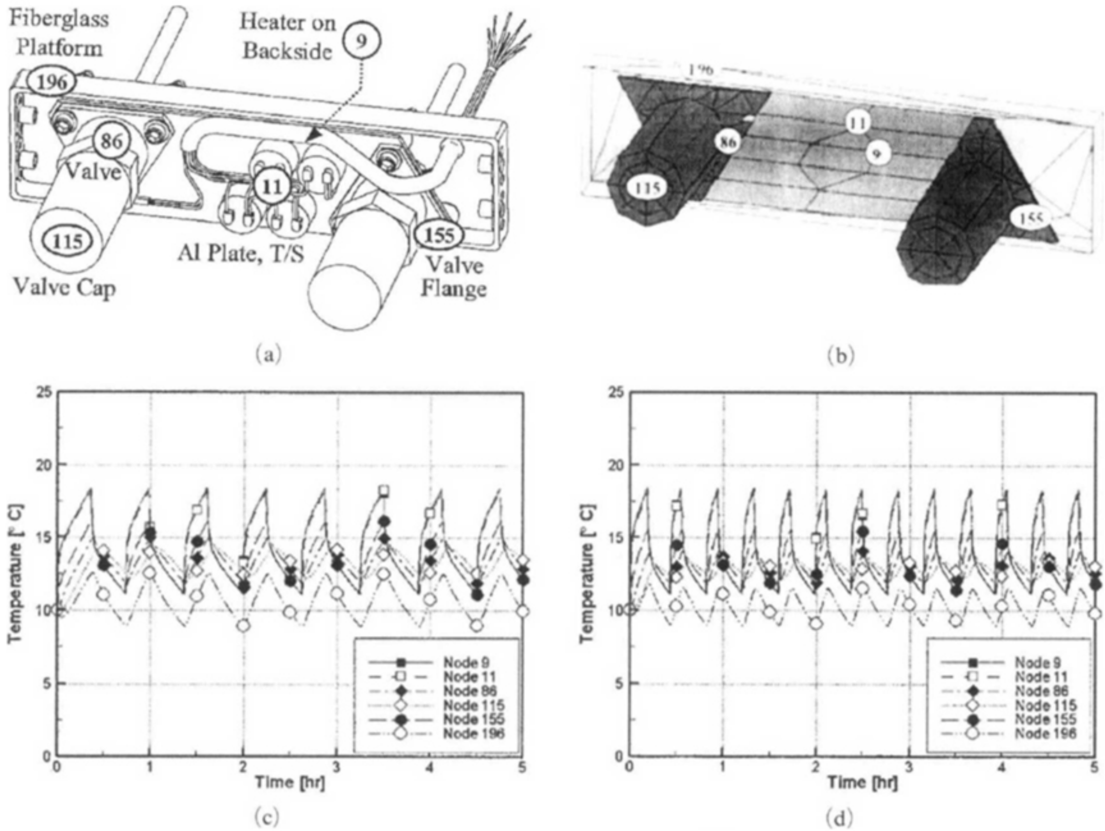


Fig. 2 Thermal analysis results for fill and drain valve module: (a) Solid model and important nodes, (b) 3-D thermal model, (c) Transient thermal response at 25 volts, and (d) 28 volts of bus voltage

lengthened more compared to the worst cold case. Fig. 3(d) shows the worst hot case, where the maximum heat dissipation (2.5 watts) in the pressure transducer is considered with the maximum bus voltage, i.e., 34 volts. In this case, the heater does not turn on as the thermostats turn it off in the beginning. The highest temperature is stabilized around at 60℃ : node 202 of clamp. Therefore the average heater power estimated for this module will be zero. It is noted that the predicted temperatures of the filter and pressure transducer (node 1 and 138) do not exceed 45℃. It does not violate the thermal requirement of the maximum allowable temperature, i.e., 49℃.

The heater power for the propulsion system estimated through the thermal analysis at the worst bus voltage, i.e., 25 volts, is summarized in Table 3. The total average heater power for the propulsion system becomes 22.02 watts when only one redundant catalyst bed heater (total 4 units) is turned on. And for the preparation of thruster firing (with 3 primary and 1 catalyst bed heaters turn-on in 1 module: total 16 units), the total average heater power reaches 25.93 watts.

5.2 Thermal analysis of propulsion system and its validation

STM is developed prior to buildup of an actual flight model. It is equivalent to the flight model in terms of structural and thermal point of view. To verify the TMM of KOMPSAT-2, a thermal vacuum test of STM is carried out. The feature of STM is being installed in the thermal vacuum chamber as can be seen in Fig. 4(a). Fig. 4(b) shows the temperature variation of the propulsion platform, where the propulsion components are installed. The history of temperature exhibits slightly different value near −10℃ depending on

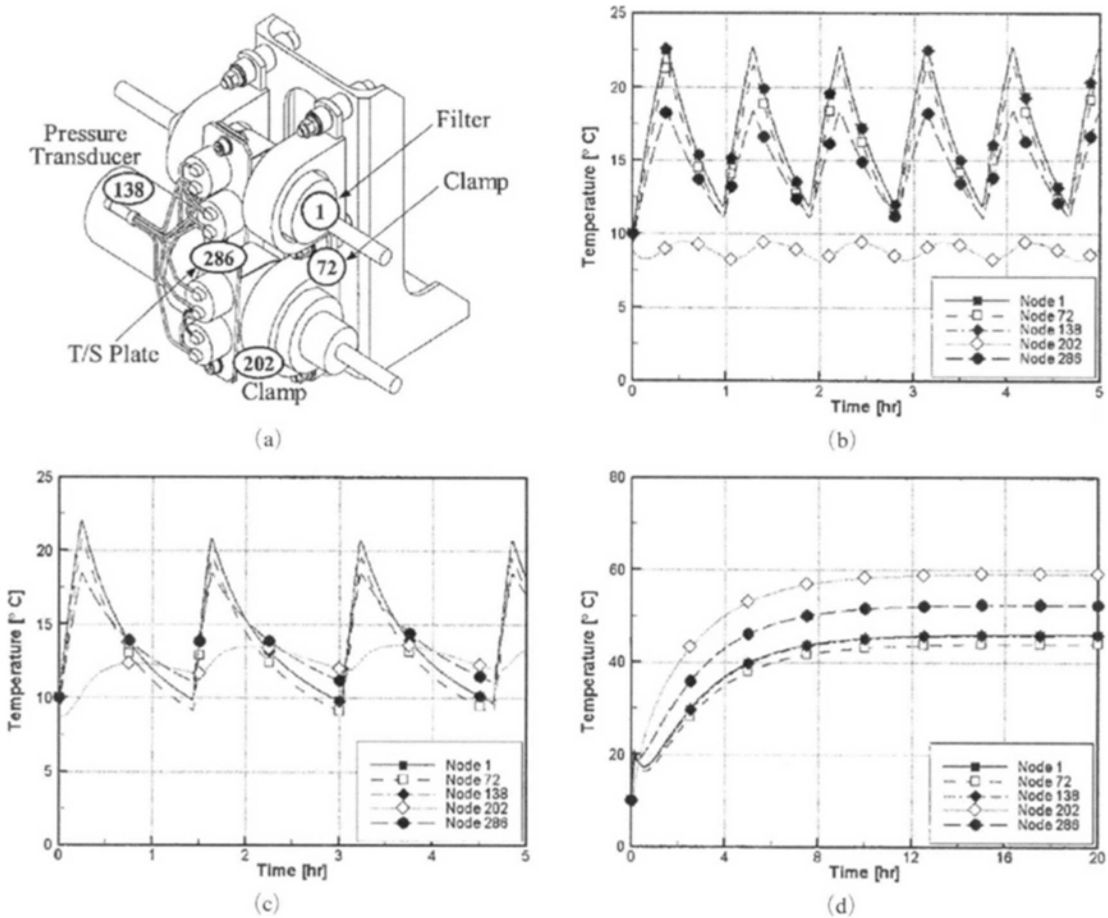


Fig. 3 Thermal analysis results for filter and pressure transducer module : (a) Solid model and important nodes, (b) Worst cold case, (c) Nominal case, and (d) Worst hot case

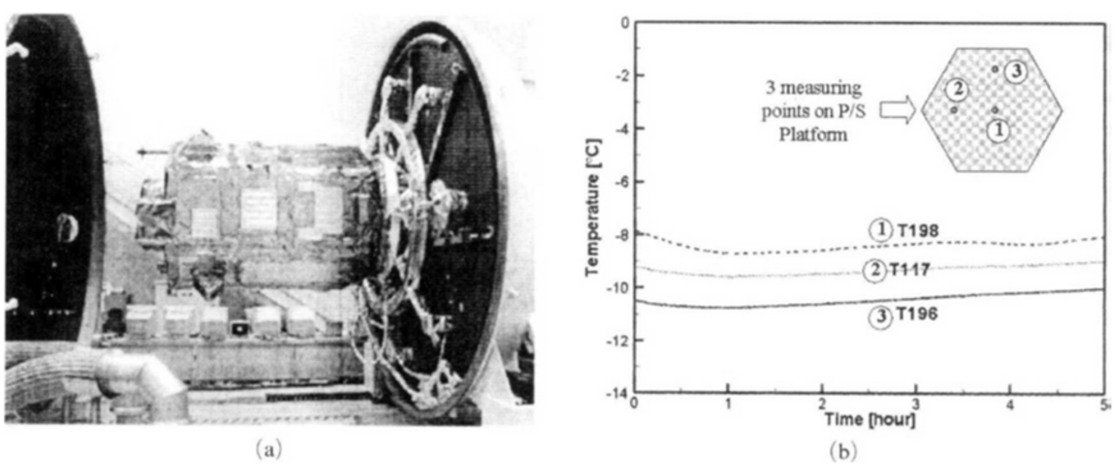


Fig. 4 Thermal validation test : (a) STM installed in thermal vacuum chamber, and (b) Temperature variation of propulsion platform at 3 measuring points

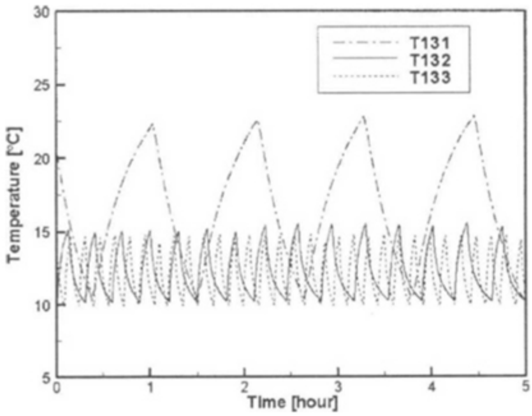


Fig. 5 Propulsion module thermal validation results

the position of its measuring points. During this test stage, there were no heat dissipation from the dummy electrical boxes and all of the flight heaters except the propulsion ones were kept turned off. Also, the space environment condition was simulated on the spacecraft radiators by using environmental heaters under the worst cold condition. During this stage, the propulsion flight heaters should be capable to maintain the propulsion components above 7℃ at 25 volts, i.e., the worst bus voltage.

Some typical temperature variations of the propulsion components are illustrated in Fig. 5. The legends of T131, T132, and T133 indicate the temperature histories measured on filter/pressure transducer, latching isolation valve, and fill/drain valve modules, respectively (see Fig. 6(a)).

In parallel with the test, thermal analysis of the propulsion module was performed. The propellant tank is not shown in Fig. 6(a) due to its clarity. Thermal model generated by TAS for the propulsion system including platform is shown in Fig. 6(b). During the thermal vacuum test, the redundant heater circuits were activated in the worst cold case so that the heaters were turned on and off nominally at 7℃ and 17℃ through the thermostats. However, the thermostats have their own temperature tolerances of ±2.2℃ at on/off set-points of 7℃ and 17℃. Nevertheless, the nominal thermostat range, 7℃～17℃, is incorporated with the thermal analysis.

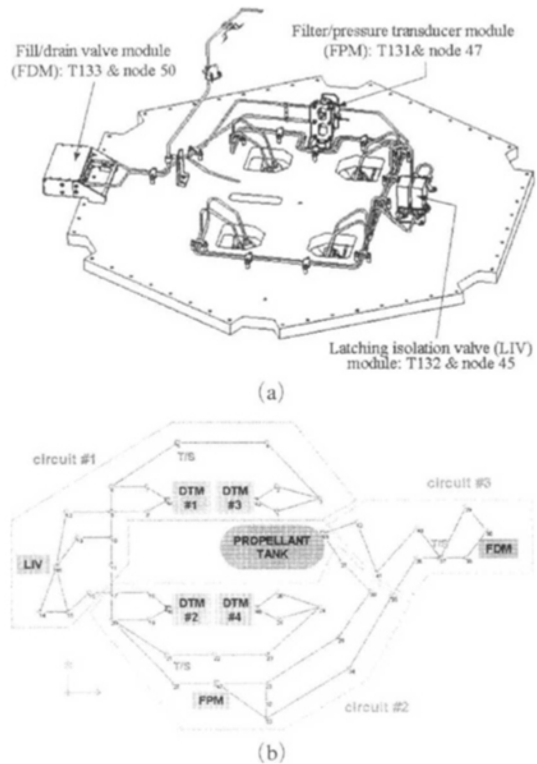


Fig. 6 Propulsion module: (a) Configuration without propellant tank, and (b) Thermal analysis model

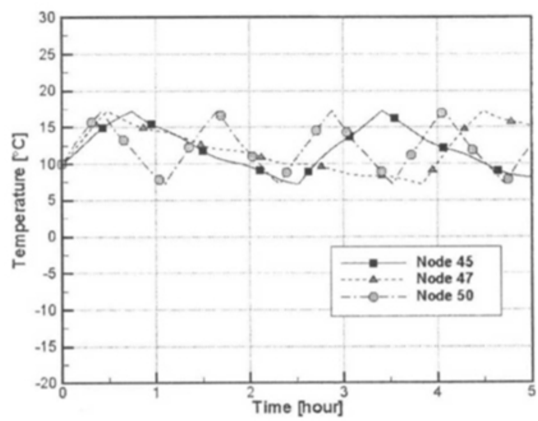


Fig. 7 Thermal analysis results of propulsion module under worst cold condition

To compare the analysis results with those of STM test, three typical nodes 45, 47, and 50 are selected in TMM. They correspond to T132, T131, and T133 in the test, respectively, as can be seen in Fig. 6(a). The temperature variation from thermal analysis results is depicted in Fig. 7 whereas the thermal vacuum test results are shown in Fig. 5.

In Fig. 5, T132 and T133 temperatures vary from about 10℃ to 15℃. On the other hand, corresponding nodes 45 and 50 in Fig. 7 show the cyclic motion with the temperature range of about 7℃ to 17℃. When considering the uncertainty of ±2.2℃ in actual thermostats, these seem to be quite reasonable. Meanwhile, the test data of T131 in Fig. 5 shows an overshoot up to about 23℃. However this result does not violate the thermal requirement : less than 49℃. The analysis result at node 47 in Fig. 7 does not predict such an overshoot. Nevertheless, the two outputs (T131 and node 47) exhibit a longer cyclic period than the other nodes in Fig. 5 and Fig. 7. In addition, the results of analysis are in a qualitative agreement that the platform temperature varied during the test (see Fig. 4(b)) where the value was fixed at −10℃ in the analysis.

There are some quantitative discrepancies between the test and analysis results due to slightly different temperature boundary conditions and the uncertainties coming from thermostats. However, the comparison shows good qualitative agreement between the analysis and test. As a consequence, the heater sizing, the main purpose of this analysis, is achieved and validated successfully.

6. Concluding Remarks

Thermal vacuum test and the analysis were carried out to validate the heater sizing of KOMPSAT-2 propulsion system. Based on the analysis, the average heater power consumption for propulsion system amounts to 22.02 watts with only one redundant catalyst bed heater (total 4 units) kept turned on. And 25.93 watts of the total average power were required for the preparation of thruster firing (3 primary and 1 redundant catalyst bed heaters in 1 module turned on : total 16 units).

TMM for the propulsion system was verified by comparing the numerical results with the ones obtained from the thermal vacuum test of STM. Despite slight discrepancies between the test and analysis conditions and hardware uncertainties, e.g., temperature variation of the propulsion platform and the uncertainty of thermostats etc., these results are qualitatively compatible even though they are not that quantitatively.

In conclusion, it was numerically and empirically demonstrated that all heaters for the propulsion components were properly selected and tested. All of the results met the thermal requirements of the propulsion system under the worst cold condition with the lowest bus voltage, i.e., 25 volts. Finally, the selected heaters were successfully proved to have the capability prevent the propellant from catastrophic freezing in the practical on-orbit operation.

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