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Thermo-mechanical Design for On-orbit Verification of MEMS based Solid Propellant Thruster Array through STEP Cube Lab Mission

Hyun-Ung Oh*, Heon-Woo Ha and Taegyu Kim*****

Space Technology Synthesis Laboratory, Department of Aerospace Engineering, Chosun University, 375 Seosuk-dong, Dong-gu, Gwangju 61452, Republic of Korea

Jong-Kwang Lee*

Micro Systems Laboratory, Department of Mechanical Engineering, Hanbat National University, 125 Dongseodaero, Yuseong-gu, Daejeon 34158, Republic of Korea

Abstract

A MEMS solid propellant thruster array shall be operated within an allowable range of operating temperatures to avoid ignition failure by incomplete combustion due to a time delay in ignition. The structural safety of the MEMS thruster array under severe on-orbit thermal conditions can also be guaranteed by a suitable thermal control. In this study, we propose a thermal control strategy to perform on-orbit verification of a MEMS thruster module, which is expected to be the primary payload of the STEP Cube Lab mission. The strategy involves, the use of micro-igniters as heaters and temperature sensors for active thermal control because an additional heater cannot be implemented in the current design. In addition, we made efforts to reduce the launch loads transmitted to the MEMS thruster module at the system level structural design. The effectiveness of the proposed thermo-mechanical design strategy has been demonstrated by numerical analysis.

Key words: MEMS thruster, Cube satellite, Thermal control, Micro-igniter

1. Introduction

Cube satellites (CubeSats) have become popular tools for orbital experiments, scientific investigations and verification of new technologies. They are a type of cube-shaped pico-class miniaturized satellite and extremely small compared with commercial satellites. This type of satellite usually has a volume of 10 cm3, and a mass of less than 1.33 kg for a standard size of 1U, and typically uses commercial off-the-shelf components [1].

Recently, CubeSats have been widely advocated by organizations and universities around the world to achieve increasingly complex missions to perform scientific, surveillance, interplanetary, and technology demonstration missions. CubeSats capable of orbit control can perform a wide range of scientific missions; their functionality in an extremely small package promises to yield numerous advanced technologies required for achieving challenging mission-related functions. As a technique to enable these missions, new types of micro-thrusters [2-5] that offer a wide range of impulse bits with much lower total mass are required. The development of micro-thrusters have been an active research area in recent years and the performance of various types has been investigated. Fabrizio et al. [2] developed a MEMS-based cold gas micro-propulsion system for attitude control to be tested on board the Ursa Maior CubeSat within the framework of the QB50 projects. The electrolysis propulsion systems [3] investigated by Cornell University are well suited for CubeSat-scale missions because of their simplicity, and flexibility in electrical power use, and dense propellant storage. These propulsion systems is estimated to capable of providing ΔV of 1 km/s, which is a significant

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* Professor
** M.S. Student
*** Professor, Corresponding author: taegyu@chosun.ac.kr

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improvement in the capabilities of CubeSats. A vacuum arc thruster for CubeSat propulsion [4] is also scheduled for in-space test on board the UIUC CubeSat. Lee et al. [5] proposed an improved MEMS-based solid propellant thruster array with a micro-membrane igniter. They improved the stability of the micro-igniter by using a glass membrane having a thickness of tens of microns. They also developed a process to fabricate the micro-igniter on a photosensitive glass wafer instead of on a dielectric membrane.

STEP Cube Lab (Cube Laboratory for Space Technology Experimental Project) is the first pico-class satellite being developed at the SSTL (Space Technology Synthesis Laboratory) of Chosun University, and is scheduled to be launched in the beginning of 2017 [6]. The main objective of its mission is to perform on-orbit verification of results from space-related research conducted at domestic universities. The MEMS-based solid propellant thruster array of Lee et al. [5] is one of the main payloads to be verified through the STEP Cube mission. However, because the array was developed for purely theoretical research, its thermo-mechanical design and verification test of MEMS thruster array for space use were not considered in the design phase. Therefore, in its current form, normal operation of the MEMS thruster array on-orbit cannot be ensured. One of the aims of the STEP project is to minimize additional efforts at the payload level such as design modifications or verification tests. To achieve this aim and to ensure that the project succeeds in on-orbit verification of the MEMS thruster array, thermo-mechanical design efforts at the satellite level are required to minimize the launch load transmitted to the MEMS thruster under launch environments and to provide a moderate temperature environment for its normal operation by proper system-level thermal design.

For the purpose of on-orbit verification of MEMS solid propellant thruster array technology through the STEP mission, the thruster module should be operated within an allowable range of operating temperatures to avoid ignition failure by incomplete combustion due to a time delay in ignition. Suitable thermal control should also guarantee the structural safety of the MEMS thruster array under severe on-orbit thermal conditions. In this study, we propose an active thermal control strategy for a MEMS solid propellant thruster module, in which micro-igniters are used as heaters and temperature sensors. This thruster module must also survive the launch environment before on-orbit operation. Therefore, we also propose a mounting method that uses flexure-like brackets to support the MEMS thruster module. This method makes it possible to reduce the launch loads transmitted to the thruster module under launch environments; in addition, it allows the MEMS thruster module to be easily mounted to or dismounted from the fully integrated satellite structure without disassembling any of the satellite parts during the test and transportation to the launch site. The effectiveness of the thermo-mechanical design strategy proposed in this study was demonstrated by structure analysis and on-orbit thermal analysis.

2. STEP Cube Lab with MEMS Solid Thruster Array

2.1 STEP Cube Lab Mission

Figure 1 shows the configuration of the STEP Cube Lab, the design of which is based on a 1U standard CubeSat. The main objectives of the STEP Cube Lab mission are to identify core space technologies studied in industries or universities, and to verify them in orbit. Its primary objective is to perform in-orbit verification of candidate fundamental space technologies for future space missions. The payloads [6] to be verified in the STEP mission are a variable emittance radiator, a PCM (Phase Change Material), a MEMS-based solid propellant thruster5), a concentrating photovoltaic (CPV) power system, and a novel non-explosive holding and release mechanism triggered by nichrome burn wire heating. The function and performance of these technologies have been previously verified by laboratory-level research at universities [5], but their design effectiveness has never been qualified in outer space or on-ground simulated space environments. Therefore, whether these technologies will operate without any malfunction in an on-orbit environment is unclear. The MEMS-based solid propellant thruster located on the bottom of the CubeSat shown in Fig. 1 is also one of the main payloads to be verified through the STEP mission. To ensure successful on-orbit verification of the MEMS thruster array, thermo-mechanical design efforts at the satellite level are performed to minimize the launch load transmitted

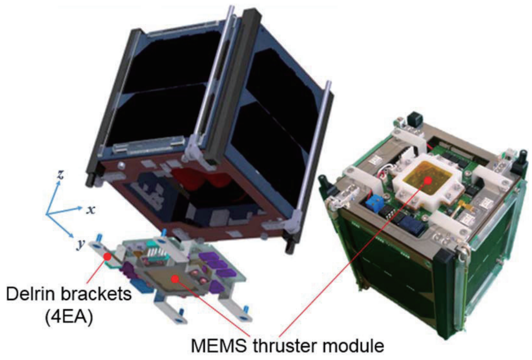

Fig. 1. Configuration of STEP Cube Lab with MEMS solid propellant thruster module

to the MEMS thruster under launch environments and to provide a moderate temperature environment for its normal operation on-orbit by proper thermal design.

2.2 MEMS Solid Propellant Thruster Array

Figure 2 shows a schematic of a 3×3 MEMS based solid propellant thruster array [5], which mainly consists of four layers of photosensitive glass, a micro-nozzle, heating coils, glass membrane, propellant chamber, and a solid propellant. A close-up view of the micro-igniter is also shown in Fig. 2. The MEMS solid propellant thruster array was fabricated by anisotropic wet etching, Pt/Ti sputtering, chemical-mechanical planarization (CMP) polishing, and thermal/UV bonding. Lead styphnate was selected as the solid propellant, given its ease of loading and low power consumption for ignition. A novel micro-igniter made of Pt (Platinum) electric heating coils was fabricated on a 40 μm thick glass membrane polished precisely by CMP.

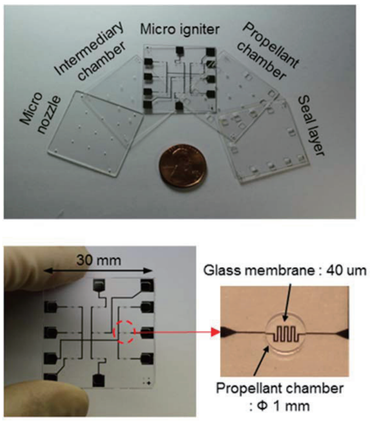

Fig. 2. Configuration of MEMS-based solid propellant thruster array and close-up view of micro-igniter [5]

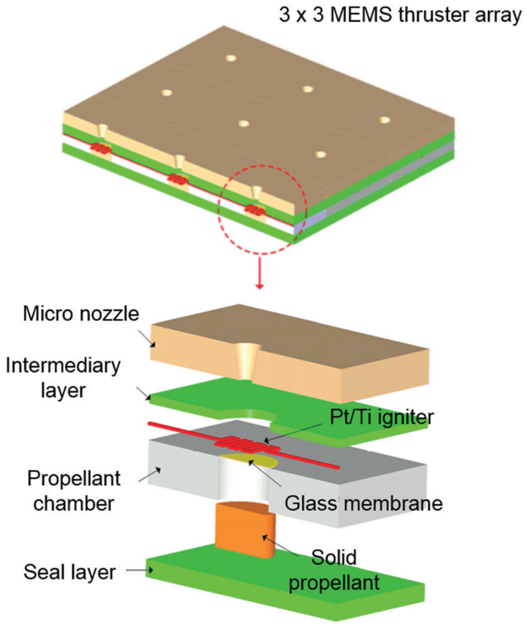

Fig. 3. Cross sectional schematic view of MEMS thruster [5]

Figure 3 schematically shows a cross-sectional view of the MEMS thruster. The micro-nozzle is located at the first layer and the third layer contains the micro-igniter made of Pt coil with width of 40 μm. The operating principle is that the solid propellant located under the glass membrane is ignited by the micro-igniters when the temperature of the propellant reaches the ignition temperature. The membrane is subsequently broken when high-temperature and -pressure combustion gases are generated by micro-igniter activation and thrust is generated through the micro-nozzle. The ignition temperature of the propellant is 260 °C at an input power of 285 mW. The specifications of the MEMS thruster array are summarized in Table 1.

3. Thermo-mechanical Design of MEMS Solid Propellant Thruster Array

3.1 Structural Design and Analysis

Figure 4 shows an exploded schematic view of the MEMS solid propellant thruster array module, which is mainly composed of the MEMS thruster array and its control board for controlling an activation of the propellants according to the ignition commands. The MEMS thruster module is accommodated in the middle of the communication antenna board as shown in Fig. 1. Electrode pads combined with spring-loaded pogo-pins were proposed (instead of soldering electric wires generally used in the MEMS fabrication process) to achieve reliable electrical contact between thruster and control board under launch vibration and thermal vacuum environments. The electrical interface

Table 1. Specifications of MEMS-based solid thruster array [5]

Items	Specification
Total Mass	5 g
Dimensions	30 mm×30 mm×2.5 mm
Propellant	Lead Styphnate (0.02 g)
Burning Time	0.23 ms
Max Thrust	3.62 N
Specific Impulse	62.3 s

on the MEMS thruster is directly connected to the pogo-pins on the thruster control board and fixed by a plastic cover made of Delrin® with space heritage as shown in Fig. 4. This design makes it easier to access and replace the MEMS thruster from outside without de-mating the other parts of the CubeSat because frequent replacements of the thruster are required during the verification test. For example, a dummy thruster without solid propellant will be used to prevent ignition during a full function test of the system level thermal vacuum test. This will also be replaced by a flight model of the thruster with solid propellant before the launch campaign.

For successful on-orbit verification of the MEMS thruster module, mechanical design efforts at satellite level are performed to minimize a transmitted launch load to the MEMS thruster module. This is achieved by mounting the MEMS thruster module on flexure-like brackets made of Delrin® plastic material as shown in Fig. 1. The total mass of the thruster module is 60g including the 8g mass of support brackets. The mass of the thruster and control board is 5g and 47g respectively. The overall dimension of the MEMS thruster and its control board are shown in Fig. 2 and Fig. 4.

The proposed design was verified through vibration tests at qualification level such as sine burst test, sine vibration test and random vibration test. Figure 5 shows the vibration test set-up of the MEMS thruster module. The qualification test level is based on the QB50 test specifications [7]. An accelerometer sensor, used to apply the input test loads on the mechanism is located on the test fixture of the vibration shaker. The eigen frequency variation of the thruster module to judge the structural safety of the MEMS thruster module before and after full level vibration test is investigated by accelerometer attached on the main chips located on the center of the control board. Table 3 compares the 1st eigen frequencies obtained from the LLSS (Low Level Sine Sweep) test performed before and after each vibration test. The maximum variation of the 1st eigen frequency of the thruster module was within 1.15% for random vibration test in z-axis, which meets the requirement of within 5% variation.

The one of the main test objectives is survivability of the electrical function of the thruster module before and after vibration test. This is checked by the comparison of the measured resistance values on the micro-igniter. Figure 6 compares the measured resistance values of the micro-igniters before and after launch environment tests at qualification level. The variation of the values were less than 0.5% and all functional requirements were also successfully verified after vibration test.

These results indicate that the structural design that uses flexure-like brackets and pogo-pins are effective for ensuring the structural safety and stable electrical function of the MEMS thruster. Therefore, survivability in harsh launch environments before on-orbit operation of the MEMS

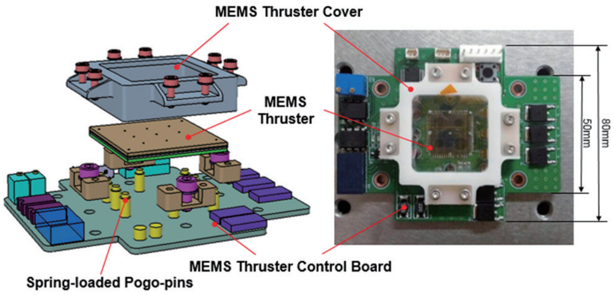

Fig. 4. Exploded schematic view of MEMS solid propellant thruster array module

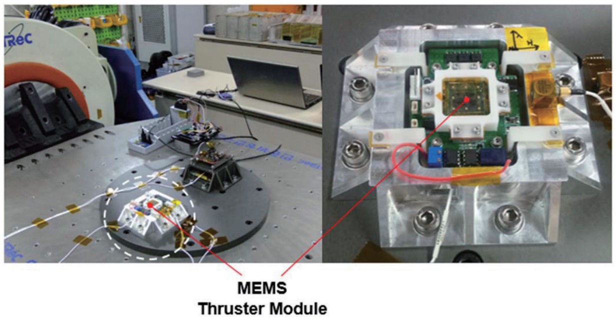

Fig. 5. Vibration test set-up for MEMS thruster module

Table 2. Material properties of MEMS thruster

	Material	Density [kg/m^3]	Young's Modulus [GPa]	Poisson's Ratio	Yie. Stress [MPa]	Ult. Stress [MPa]
Bracket	Delrin	2700	68.9	0.33	73	-
MEMS thruster I/F board	FR4	1850	18.73	0.136	-	242
MEMS thruster	Quartz Glass	2370	77.8	0.22	70	70

thruster might be increased although it has never been designed and tested for space use.

3.2 Thermal Design and Analysis

To guarantee successful on-orbit operation of the MEMS thruster array, it should be operated within an allowable range of operating temperatures to prevent ignition failure by incomplete combustion due to a delay in ignition time. The structural safety of the MEMS thruster can also be guaranteed by suitable thermal control. However, the MEMS thruster has been developed for purely academic research and its function and performance have been verified at the laboratory level experiments. In addition, it is not allowed to attach the additional heater and sensor on the thruster due to its dimensional and space constraints. Therefore, thermal design at the system level is important to guarantee successful on-orbit operation of the MEMS thruster.

The allowable non-operating temperature range of the MEMS thruster is -20 ˚C to 50 ˚C. However, if the temperature decreases to below 0 ˚C, incomplete combustion occurs owing to a time delay in ignition [5]. Therefore, the solid propellant located under the membrane with the micro-igniter should be kept within the temperature range above for successful ignition. The solid propellant may be easily maintained within the allowable minimum temperature range by attaching additional heaters and sensors. However, in practice, this is not feasible to attach additional heaters and sensors on the front side of the thruster due to the existence of the micro-nozzle. Spatial constraints also preclude this method for the opposite side of the thruster. Therefore, we proposed an active thermal control strategy for successful on-orbit operation of the MEMS thruster module, in which micro-igniters are used as a heater and temperature sensor without any design modification of the current thruster model.

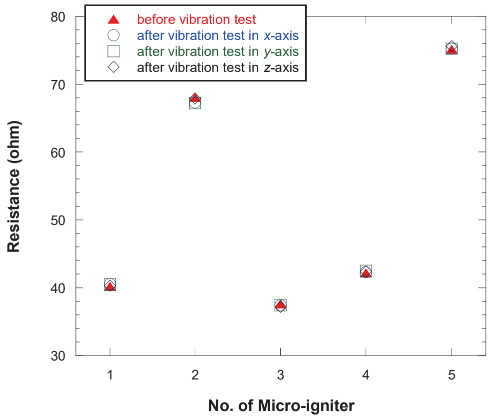

Fig. 6. Measured resistance values of the micro-igniters before and after launch environment

3.2.1 Thermal Mathematical Model of MEMS Thruster

To investigate the effectiveness of the proposed thermal control strategy, we performed on-orbit thermal analysis of the CubeSat with the MEMS thruster module. Figure 7 shows the TMM (Thermal Mathematical Model) of the MEMS solid thruster. The MEMS thruster shown in Fig. 3 is simplified as a three-layer TMM. The top layer includes the micro-nozzle and intermediary layers. The middle and bottom layers represent the propellant chamber with micro-igniters and seal layer, respectively. In addition, the MEMS thruster module is conductively and radiatively decoupled by the MLI (Multi-Layer Insulator) and thermal washer.

Table 3. LLSS(Low Level Sine Sweep) Test Result

Item	Test	Axis		1st Freq. [Hz]	Difference [%]
MEMS Thruster Module	Sine Vibration	X	Before	210.99	0
			After	211	
		Y	Before	192	0
			After	192	
		Z	Before	176	0
			After	176	
	Random Vibration	X	Before	211	0.96
			After	209	
		Y	Before	192	0.52
			After	191	
		Z	Before	176	1.15
			After	174	

The micro-igniters used as heaters for active thermal control of thruster module are modeled as heat sources on each node of the middle layer. The three layers in the TMM are connected by node-to-node conductors because they are bonded together by a UV bonding process through the MEMS fabrication process. The material and thermo-optical properties that were used in the thermal analysis are summarized in Table 4.

For practical use of the micro-igniter for both active heater control and solid propellant ignition, we proposed an operation concept to use igniter 5 as a heater and igniters 3, 6, and 9 sequentially as temperature sensors. To prevent tumbling of the CubeSat by asymmetric ignition, two micro-igniters positioned along the diagonal direction are activated simultaneously. For instance, igniters 1 and 9 are activated when their temperatures are within the allowable operating temperature range of 0˚C, which is achieved by active heater control using igniter 5 as a heater and igniter 6 as a temperature sensor. The igniter used as the temperature sensor is sequentially changed according to the ignition scenario on-orbit.

3.2.2 Thermal Analysis Results

To confirm the effectiveness of the proposed active thermal control strategy, on-orbit thermal analysis is performed under the worst hot and cold orbit environments. The orbital thermal conditions used for the on-orbit thermal analysis are described in Table 5. The orbit is a sun-synchronous orbit with an altitude of 600 km. Attitude control is based on the permanent magnet stabilization method[8]; the orbital profiles of the CubeSat are shown in Fig. 8. The figure also shows the TMM of the CubeSat with the TMM of the MEMS thruster described in Fig. 7.

The general heat-balance equation for element *i* that is coupled with elements *j* through *n* is given as

$$C_i \frac{dT_i}{dt} = Q_i - \sum_{j=1}^{n} C_{ij}\left(T_i - T_j\right) - \sum_{j=1}^{n} R_{ij}\,\sigma\left(T_i^4 - T_j^4\right) \quad (1)$$

where, C_i is the heat capacity of node *i*; T_i and T_j are the temperatures of nodes *i* and *j*, respectively; Q_i is the power

Table 5. Orbital parameters for thermal analysis under worst hot and cold conditions

Parameter	Orbit Condition	
	Cold Case	Hot Case
Orbit Type	Sun-Synchronous (Circular)	
Inclination Angle	97.78°	
Attitude (km)	600	
Local Time Ascending Node	AM 10:30	
Beta Angle	15.83°	-16.31°
Solar Flux (W/m^2)	1287	1420
Albedo	0.3	0.35
IR Flux (W/m^2)	227	245
Season	Summer Solstice	Winter Solstice

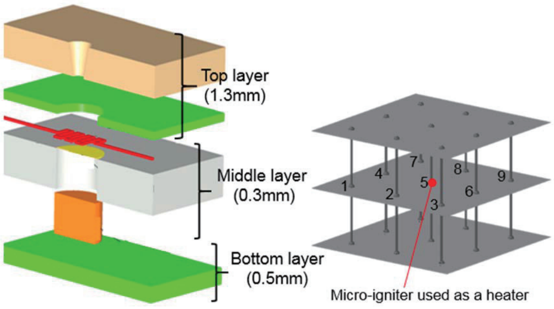

Fig. 7. TMM of MEMS solid propellant thruster

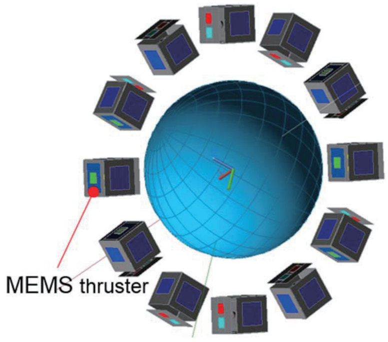

Fig. 8. Orbital profiles of the CubeSat with MEMS thruster

Table 4. Material and optical properties for MEMS thruster

Material Property	Conductivity (W/mK)	Density (kg/m^3)	Specific Heat (J/kgK)
MEMS Thruster (Photosensitive Glass)	1.5	2210	0.198
MEMS thruster Control board (FR4)	0.23	1900	1200
Optical Property	**Absorptivity**		**Emissivity**
Photosensitive Glass	0.1		0.9
FR4	0.6		0.6

input of node *i*; C_{ij} is the linear conductance from element *i* to element *j*; and R_{ij} is the radiation coefficient of nodes *i* and *j*. In this study, a TMM was constructed in Thermal Desktop, a CAD-based geometric interface in SINDA/FLUINT [9] (Systems Improved Numerical Differencing Analyzer/Fluid Integrator). TMM and the output of RadCAD, which is a module to calculate radiation exchange factors and orbital heating rates, are analyzed by SINDA/FLUINT as input. For on-orbit thermal analysis using SINDA/FLUINT, the heat-balance equation described in Eq. (2) is calculated by the average of the temperature derivatives at the current and next time steps to predict the overall temperature change, as shown in the following equation:

$$\begin{aligned}\frac{2C_i}{\Delta t}(T_i^{n+1}-T_i^{n}) = 2Q_i + \textstyle\sum_{j=1}^{N}\left[G_{ji}(T_j^{n}-T_i^{n}) + \widehat{G_{ji}}\left(\left(T_j^{n}\right)^4-(T_i^{n})^4\right)\right] \\ + \textstyle\sum_{j=1}^{N}\left[G_{ji}(T_j^{n+1}-T_i^{n+1}) + \widehat{G_{ji}}\left(\left(T_j^{n+1}\right)^4-(T_i^{n+1})^4\right)\right]\end{aligned} \qquad (2)$$

where, T_j^n is the temperature of node *j* at the current time step *t*, T_j^{n+1} is the temperature of node *j* at the next time step $t+\Delta t$, G_{ji} is a linear conductor that attaches node *j* to node *i*, $\hat{G}_{ji}$ is a radiation conductor that attaches node *j* to node *i*, and C_i is the thermal capacitance of node *i*, Q_i is the source/sink for node *i*.

To confirm the effectiveness of the thermal control strategy proposed in this study, the following three case of analyses were performed considering the orbital thermal conditions described in Table 6.

Case 1

The objective here is to verify the effectiveness of the proposed thermal control strategy. The micro-igniter 5, positioned in the middle layer of the thruster, is used as a heater. The micro-igniter 6 in the same layer is used as a reference temperature sensor for active heater control.

Case 2

The objective here is to qualitatively check the effectiveness of the proposed thermal control strategy by comparison with the generally used heater control strategy under assumption that the additional heater is implemented on the external bottom side layer despite the spatial constraints in attaching the additional heater on the existing H/Ws. The node beneath micro-igniter 5 on the bottom layer of the thruster is used as a heater. The micro-igniter 6 is used as the reference temperature sensor for active heater control.

Case 3

The objective here is to estimate the heater power and duty required to obtain the same temperature as case 1. The positions of the additional heater and temperature sensor are the same as in case 2.

In all cases, the reference temperature set points for active heater control were set to 5 ˚C and 10 ˚C for heater on and heater off, respectively, to avoid incomplete combustion by a time delay in ignition. The input heater power for heater control is set to 0.02 W, given that the required power for propellant ignition is 0.34 W [5].

Figure 9 shows an example of the temperature contour map on the middle layer of the MEMS thruster obtained from case 1. The result indicates that the temperature of the middle layer, which represents the propellant chamber with the micro-igniter, is controlled as intended. The temperatures of all nodes where the micro-igniters are positioned on the middle layer are effectively controlled by heater control, using micro-igniter 5. Figure 10 shows the on-orbit time profiles of temperatures at all nodes of the middle layer under the worst case cold condition (case 1). The on/off profile of micro-igniter 5 is also plotted in this figure. The result indicates that the temperature of node 5 is suitably controlled by the heater control set points. As a result, the temperatures of all nodes where the micro-igniters are positioned on the middle layer are effectively

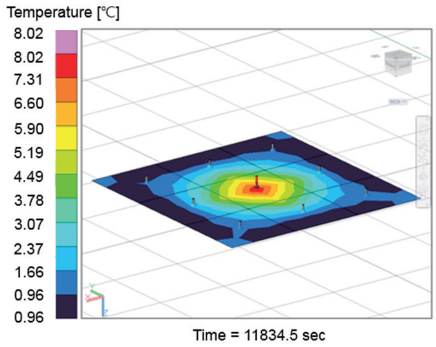

Fig. 9. Example of temperature contour map on middle layer of MEMS thruster obtained from case 1

Table 6. Summary of thermal analysis results

Case	Heater Node	Heater on/off (°C)	Heater Power (W)	T_{min} (°C)	Heater Duty (%)
1	ML-5	5/10	0.02	1	36
2	BL-5	5/10	0.02	-4	36
3	BL-5	7/12	0.08	1	40

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controlled above the target operating temperature of 0 ˚C to avoid incomplete combustion of the solid thruster, although the other remaining nodes are lower than the heater set point of 5 ˚C. However, the simulation result of Fig. 11 shows that the temperature of all nodes obtained from the case 2 are below the allowable operating temperature of 0 ˚C, although the heater on the external bottom layer is switched on correctly in accord with the heater set point owing to the low conductivity between bottom and middle layers by UV bonding.

Table 6 summarizes the results obtained from cases under the worst cold condition. The analysis result obtained from case 3 requires additional heater power of 0.08 W to obtain the same temperature as that obtained from case 1 based on the proposed control strategy and a 4% increase in heater duty.

These results indicate that the thermal control strategy using the micro-igniters as the heater and temperature sensor is effective for thermal control of the MEMS solid thruster.

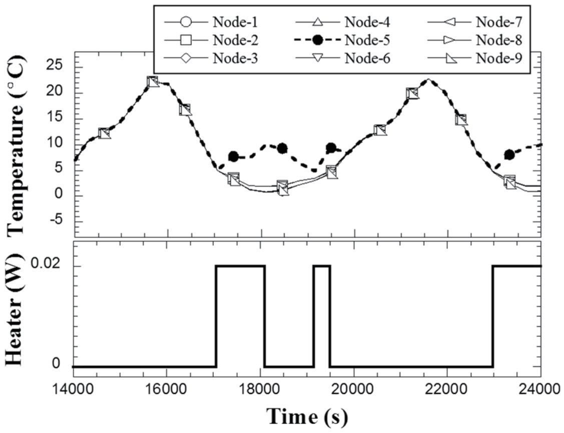

Fig. 10. On-orbit time profiles of temperatures at all nodes of middle layer obtained from case-1

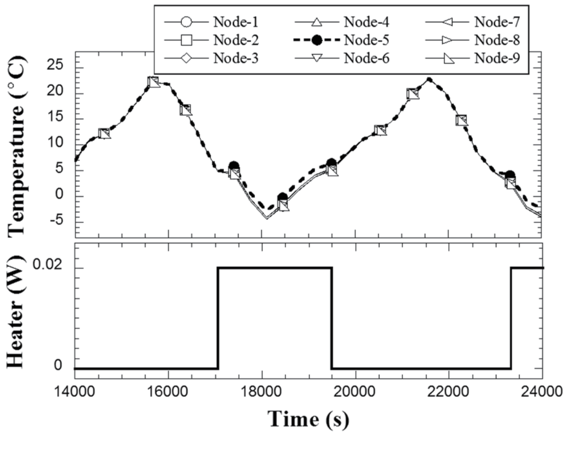

Fig. 11. On-orbit time profiles of temperatures at all nodes of middle layer obtained from case-2

This approach is suitable for the aims of the STEP cube lab mission to minimize additional efforts at the payload level such as design modifications or verification tests through design efforts at satellite level to keep the current design of existing H/Ws.

4. Conclusion

To guarantee survivability and normal operation of the MEMS solid propellant thruster array under launch and on-orbit environments, a system-level thermo-mechanical design for on-orbit verification of thruster module was introduced. For successful on-orbit verification of the thruster module, mechanical design efforts at the satellite level are proposed to minimize a launch load transmitted to the MEMS thruster module by mounting the MEMS thruster module on flexure-like brackets. This approach enables easier access and replacement of the MEMS thruster from the outside without de-mating of the other parts of the CubeSat during the verification test. An adequate margin of structural safety is guaranteed by applying the proposed strategy. For on-orbit thermal control, a strategy to use micro-igniters as heaters and temperature sensors for active thermal control is proposed. This strategy is effective for thermal control of the MEMS thruster without design modification of existing H/Ws because an additional heater cannot be implemented in the current design. The thermal analysis results also showed that the proposed strategy is effective for satisfying operating temperature requirements to prevent incomplete combustion of the MEMS solid thruster due to a time delay in ignition. The analysis results indicate that the design approaches proposed in this study coincides with the aims of the STEP Cube Lab mission to minimize additional efforts on the existing H/Ws through the design efforts at system level.

Acknowledgements

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References

[1] Kitts, C. A. and Twiggs, R. J., "Initial Developments in the Stanford SQUIRT Program", *Progress in Biomedical Optics and Imaging*, No. 2317, 1995, pp. 178-185.

[2] Piergentili, F., Balucani, M., Crescenzi, R., Piattoni, J.,

Santoni, F., Betti, B. and Onofri, M., "MEMS Cold Gas Micro Thruster on URSA Maior Cubesat", *The 64th International Astronautical Congres*s, 2013, IAC-13.C4.5.1.

[3] Zeledon, R. A. and Peck, M. A., "Electrolysis Propulsion for Cubesat-scale Spacecraft", *AIAA Space 2011 Conference & Exposition*, 2011, pp. 458-464.

[4] Rysanek, F., Hartmann, J., Schein, J. and Binder, R., "Microvacuum Arc Thruster Design for a CubeSat Class Satellite", *16th Annual/USU Conference on Small Satellites*, 2002, SSC02-I-2.

[5] Lee, J. K. and Kim, T. K., "MEMS Solid Propellant Thruster Array with Micro Membrane Igniter", *Sensors and Actuators A*: Physical, Vol. 190, 2013, pp. 52-60.

[6] Oh, H. U., Jeon, S. H. and Kwon, S. C., "Structural Design and Analysis of 1U Standardized STEP Cube Lab for On-orbit Verification of Fundamental Space Technologies", *International Journal of Materials, Mechanics and Manufacturing*, Vol. 2, No. 3, 2014, pp. 239-244.

[7] QB50 System Requirements and Recommendations

[8] Gerhardt, D. T. and Palo, S. E., "Passive Magnetic Attitude Control for CubeSat Spacecraft", *24th Annual AIAA/USU Conference on Small Satellites*, 2010.

[9] Timothy, D., *Sinda/Fluint Thermal Desktop User's Manual*, C&R Technologies, Version 5.2, 2008.

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