ANALYSIS OF THE THERMAL INFLUENCE OF AN EXPERIMENTAL HEAT PIPE ON THE ITASAT SATELLITE

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Abstract. *This work presents results of preliminary study on thermal behavior of the ITASAT satellite under influence of an experimental heat pipe, which thermally connects two opposite panels. Hot and cold cases besides a parametrical analysis were evaluated under steady state condition (average external and internal heat loads). ITASAT will be the first Brazilian duty satellite developed by Brazilian universities. The Technological Institute of Aeronautics (ITA) in collaboration with other Brazilian universities conducts this program. The National Institute for Space Research (INPE) provides technical support and the Brazilian Space Agency (AEB) sponsors the program. On the thermal project, simulation tool SINDA/FLUINT/Thermal Desktop/RADCAD has been used as the main computational platform in the thermal analysis. Parameters such as orbit type and attitude of the satellite influence directly in the intensity of the external heat loads. By associating these heat loads with the equipment dissipation, it is possible to calculate the temperature distribution over the satellite. This study is a part of the thermal control project, which guarantees that high and low acceptable temperature limits for all equipment will not be violated. The main objective of these simulations is to investigate if the heat pipe inserted in the satellite structure performs acceptable thermal impact on temperature distribution. The presented results are physically coherent for spinning satellites in Low Earth Orbit, and have showed that the satellite thermal behavior is nearly similar with or without the experimental heat pipe.*

Keywords*: ITASAT, Heat Pipe, Thermal Control.*

1. INTRODUCTION

ITASAT program is a development multidisciplinary project, which involves Technological Institute of Aeronautics (ITA), Brazilian Space Agency (AEB), National Institute for Space Research (INPE) and other Brazilian universities. The ITASAT mission comprehends development, launching and operation of a university micro-satellite for use in low Earth orbit, capable of testing and operating the experimental payloads in orbit. Its mission shall also qualify in-flight and operate a developed transponder with updated technology which presents compatibility with those used in space segment of the Brazilian Environmental Data Collection System with view to industrial production for use in the future Data Collection missions. Also the satellite carries different technological and scientific experiments including heat pipe.

Two-phase capillary pumping devices, such as heat pipes (HP), are considered highly effective and reliable in thermal control of satellites, due to extremely low temperature gradients developed along the HP length even under significant heat loads and do not use moving parts (Holman, 1983). HPs allow the transfer of substantial quantities of heat through small cross section area over relatively long distances.

Heat pipes have been used in space missions since the 70's due to their effectiveness and passive thermal control behavior. HPs contain a working fluid (e.g., ammonia or acetone) in a saturated state that evaporates as soon as the heat from a source of high temperature is introduced into the evaporation region, carrying heat through evaporative - condensation cycle to the region of dissipation (heat source of lower temperature). The capillary forces promote the pumping of the liquid back to the heating region over the internal capillary structure.

In passive thermal control of satellites, heat pipes are widely used. This sort of expertise has been particularly applied in the family of China-Brazil Earth Resource Satellite (CBERS satellites), however all devices are actually supplied by China. Nevertheless, the use of this technology is also very important to Brazil, which could use it in applications in the national missions. Therefore, it is important to dominate and qualify this technology, to make it independent of what is now imported.

In order to evaluate the thermal influence of the heat pipe experiment over the satellite, a preliminary numerical thermal model of the entire satellite was built. It is used to predict the temperature distribution over structure, equipment and other components thermally interacting with each other and with surrounding environment. The Thermal Mathematical Model (TMM) development begins early in a satellite project, being permanently updated and completed along the satellite design refining and maturation. Final confirmation follows the thermal balance test, conducted in a vacuum chamber, when the TMM is correlated with the test results (Karam, 1998).

This paper presents results of a numerical simulation for the ITASAT satellite in steady state conditions (average external and internal heat loads). The temperature distribution and heat rate transferred by the heat pipe were obtained.

During analysis the flight extreme cases, hot and cold ones, as well as a parametrical analysis on satellite pointing error, have been studied. All analyses have been carried out with SINDA/FLUINT thermal analyzer.

1.1. ITASAT satellite

A preliminary ITASAT configuration definition is that the satellite has two modes: one is operational and the other is experimental. The operational mode is to collect environmental data (mainly weather data). For this purpose, ITASAT will have a data collection transponder as a main payload. The intention is to replace the INPE's Collect Data Satellites SCD1 and SCD2, which were launched in 1993 and 1998, respectively. The ITASAT satellite will utilize polar low Earth orbit with approximately 600 km altitude and inclination of 98 °. Orbits whose maximum altitude are less than approximately 1800 kilometers are generally considered as low Earth orbits (LEO), and have periods around 100 minutes (Gilmore, 2002).

ITASAT will spin around its "Z" axis, with approximately 4.19 rad/s (40 rpm) in the normal operation mode. Main views of the satellite are shown in Fig. 1.

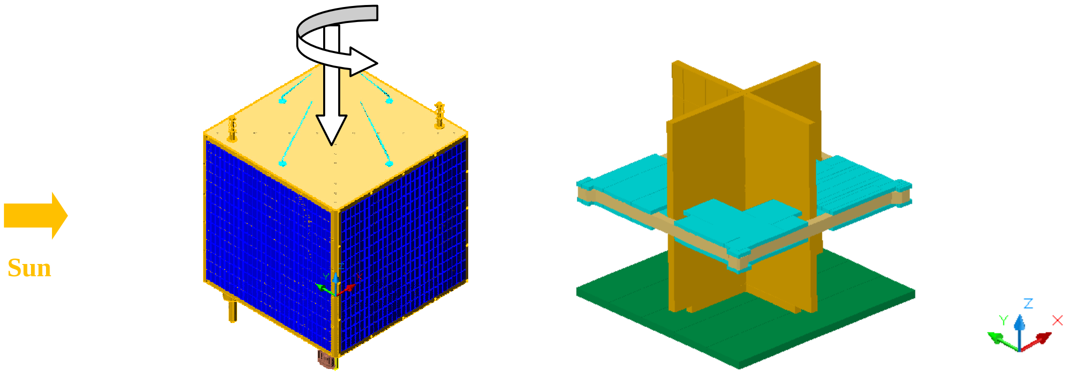


Figure 1. ITASAT's external and internal structure.

The satellite's shape approximates a cube, measured of 0.60 m in all directions. The satellite, including the antennas and other external equipment, must be compatible with a cylindrical shell of approximately 1 m in diameter, to ensure compatibility with the launch vehicle, and its mass should not exceed 80 kg.

The solar array cells will be placed on the lateral panels of the satellite, and. equipment will be installed on internal panels. ITASAT will be composed by the structure subsystem, electrical power/distribution subsystem (EPS or EPDS), telemetry, tracking and command subsystem (TT&C), attitude/velocity control subsystem (ACS or AVCS) and thermal control subsystem (TCS).

The thermal control subsystem (TCS) is dispersed over entire satellite. Its purpose is to maintain all equipment within their respective temperature limits. There are several different sources of thermal energy acting on a satellite and influence its temperatures: solar radiation, albedo (solar flux reflected by the Earth), Earth emitted infrared flux, and, finally, internal heat generated by on-board equipment. Therefore, the thermal control subsystem is specific for every satellite. In general, TCSs are usually classified separated in two types: passive and active. A passive system relies on conductive and radiative heat paths and has no moving parts or electrical power input. Active systems rely on thermostats, and heaters, controllers, sometimes use moving parts, and require electrical power (Fischer, 1995). An active system is used in addition to the passive system when passive system is not sufficient.

The thermal features of the ITASAT are low generated power, small size, low Earth orbit and spin-stabilized attitude control. From a thermal point of view, the spin-stabilization results in a temperature homogenization, that collaborates to narrow the equipment temperatures limits, making possible only passive thermal control. The TCS concept for the ITASAT satellite follows similar SCD-1 satellite thermal concept, where only passive thermal control approach was employed.

2. EXPERIMENTAL HEAT PIPE

Two-phase heat transfer devices are extremely important and widely employed in satellite thermal control. In Brazil, some experiments in microgravity environment were performed on board of the ISS, during the Centenary mission. These research activities also included investigations on copper-water mini-heat pipes, called Mini Heat Pipe Experiment - MHP, and also on aluminum-water LHP, known as the Capillary Evaporator Microgravity Experiment - CEM (Bandeira et al, 2007). However aluminum grooved HPs, which are capable to operate in the temperature range from -20°C to +55°C, which are mostly applicable in TCS of many satellites, have never developed nor qualified nor validated in orbit in Brazil until now. Thus, ITASAT project becomes a very important opportunity to confirm the viability of this technology to the country. Aiming this technological development, INPE`s thermal group in association with ITASAT`s thermal group are focused on implementation of the HP experiment in the ITASAT program, dubbed TUCA (TUbos de CAlor, in Portuguese), which includes activities of design, specification, fabrication, assembling and testing.

There is a prospect of demand from new satellite missions, which involve LEO observation and scientific satellites as well as geo-stationary and telecommunications satellites. Since this HP technology be flight proved, the national heat pipes would be able to operate in these future satellites. The Division of Space Mechanics and Control at INPE (DMC/ETE), already counts with the necessary infrastructure for this development, as well as qualification staff to reach the desired results.

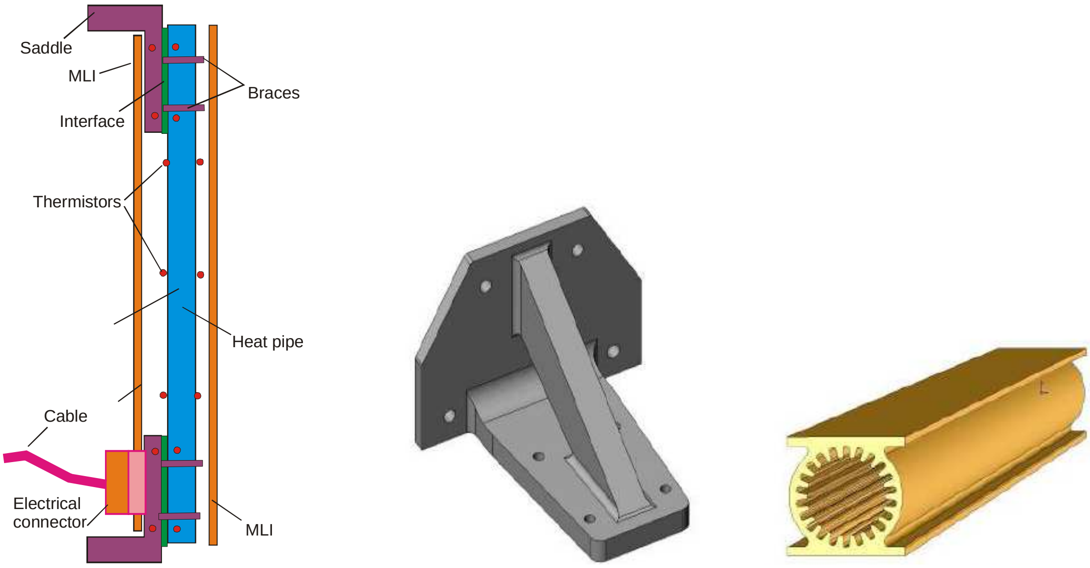
The technological expertise has been acquired during the research and development of the most advanced systems, called Loop Heat Pipes, LHP (Riehl and Vlassov, 2005). Thus, the experience in manufacturing techniques, testing and qualification can be applied in the heat pipes under development, since these devices are simpler than LHP.

As this paper is focused on the thermal effect of the experimental heat pipe to the satellite and not on its design, the details for heat pipe design aspects and performance can be found in any HP handbook like, for instance, (Reay and Kew, 2006).

2.1. Characteristics of the heat pipe

A grooved aluminum heat pipe with acetone as a working fluid has been selected to be onboard experiment of the ITASAT satellite. Instead of conventional and effective ammonia, that is a high pressure and toxic fluid, the developed heat pipe uses low-pressure and non-toxic acetone as a more natural-friendly alternative fluid. Besides that, acetone has the peak performance in the temperatures about +40° C to +50° C with increasing feature, where ammonia already has degradation, having its peak about -10° C to -20° C, which is well outside of the temperature range of equipment with high dissipation in hot case conditions. Due to the possibility of obtaining the extruded grooved aluminum profiles from national industries, the profile was designed to adopt the acetone thermo-physical properties Also, acetone and aluminum has showed good compatibility, and such negatives effects as corrosion or generation of non-condensable gas has never been occurred in ground testing (Reay and Kew, 2006).

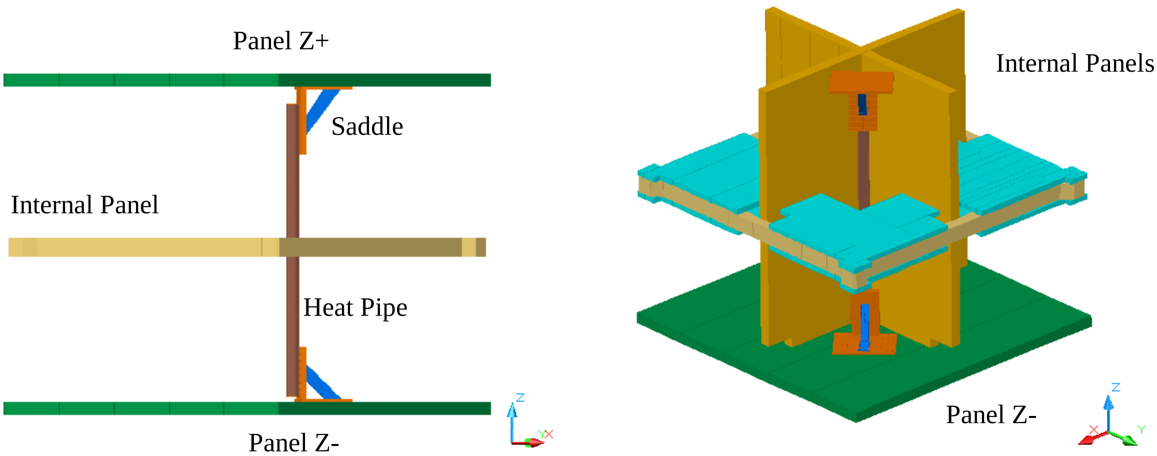
In the experimental configuration, the heat pipe will be wrapped by multilayer insulation blankets (MLI), and braces will attach it to saddles. The fixation between braces and saddle, saddle and structural panel and saddle and connector will be made by stainless steel screws. Precise thermistors will be employed to measure the temperature and they will be placed on different parts of the experiment. Figure 2 presents the experiment layout including main parts. In Fig. 2a the experiment assembly is shown, Fig. 2b presents the saddle, and the extruded HP aluminum profile is demonstrated in Fig. 2c.



a) b) c)

Figure 2. a) Experiment assembly; b) Saddle; c) HP profile.

The saddles will attach the heat pipe to the structural panels Z- and Z+. The positioning of the experiment inside satellite is shown in Fig. 3.



a)

b)

Figure 3. a) HP between Z-, internal and Z+ panels; b) HP inside satellite.

2.2. Technological and scientific returns of the experiment

There are some scientific and technological returns expected from the TUCA experiment in orbit. These benefits are presented below:

- For the first time the aluminum-acetone heat pipe will flight as an orbital experiment providing novel data of the behavior of such pair in space conditions;
- For the first time a heat pipe will perform in a spin-stabilized satellite;
- For the first time the feasibility of substitution of ammonia by acetone in aluminum heat pipes will be flight-proven;
- The heat pipe flight experiment will demonstrate the Brazilian industry readiness to build aluminum-acetone grooved heat pipes for space applications;
- The heat pipe experiment will flight qualify the aluminum-acetone heat pipe for application in Brazilian space programs.

Thus, as explained, the validation of such experiment will represent significant advances in Brazilian space programs, and expected new results will also benefit a world HP community.

3. SIMULATION CHARACTERISTICS

3.1. Orbital parameters and governing equations

To contend with tolerances and spacecraft environmental uncertainties, thermal engineers should adopt hot and cold cases analyses, to define upper and lower bounds on predicted temperatures. The power profile for a hot case analysis corresponds to the operation in which the electronic equipment result in high dissipation, while the orbit is such that the radiators are exposed to considerable combined solar, albedo and Earth heating. Biased margins and tolerances are then imposed on power, environment heating fluxes, and thermal properties, as for instant End of Life (EOL) optical properties degradation, in a direction that makes the analysis to give the maximum possible temperature. Similarly, the input data from the cold case combined with Begin Of Life (BOL) thermal-optical properties are selected to result in a calculated lowest temperature (Karam, 1998). In this paper, other heat sources as free molecular heating effect due to friction with rarefied upper atmosphere are not considered because of negligible effect. Also the orbital nominal case, with intermediate characteristics between the hot and cold cases is considered. The orbital parameters employed in the simulation are shown in Tab 1.

Table 1. Orbital parameters.

Parameter	Cold Case	Nominal Case	Hot Case
Beta angle	0 °	17.6 °	90 °
Solar radiation	1300 W/m²	1350 W/m²	1400 W/m²
Albedo	38%	42%	46%
Earth radiation	198 W/m²	236 W/m²	274 W/m²
Eclipse time	2129.4 s	2088.7 s	0 s

To simulate the temperature distribution over satellite structure and equipment, it is necessary to create the TMM of the satellite. It is based on a system of balance equations of energy conservation being solved. The governing equations consist of transient, conduction, and radiation couplings plus the boundary conditions as source terms. For each element of the numerical mesh, the base equation can be written as Eq. (1) (Sorice, 2007).

$$m_i Cp_i \frac{dT_i}{dt} = \sum_{j=1}^{n+1} R_{ji}\sigma\left(T_j^4 - T_i^4\right) + \sum_{j=1}^{n} B_{ji}\left(T_j - T_i\right) + Q_i + A_i\alpha_i q_s + A_i\varepsilon_i q_{ir} \qquad i=1...n \tag{1}$$

Where:
T_i e T_j are the absolute temperatures of nodes i and j;
t is the time;
m_iCp_i is thermal capacitance from node i;
R_{ji} is the radiative-conductance between nodes j and i;
σ is the Stefan-Boltzmann’s constant;
B_{ji} is the conductive-conductance between nodes j and i;
Q_i is the internal heat generation in node i;
A_i is node’s i surface exposed to environment;
α_i is the solar absorptivity from node i;
ε_i is the infrared emissivity from node i;
q_s is the solar spectrum radiation’s intensity that incises on i;
q_{ir} is the infrared spectrum radiation’s intensity that incises on i;
n is the satellite’s number of nodes which is separated;
$n+1$ is the node that represents the environment (or space).

In steady-state condition, the left term in Eq. (1) is equal to zero. The conductive couplings can be presented in various ways, depending on object configuration. In cases where nodes i and j represent parts on the same panel, B_{ij} can be calculated by Eq. (2) (Sorice, 2007).

$$B_{ji} = \frac{kA}{L} \tag{2}$$

Where:
B_{ji} is the conductive-conductance between nodes j and i;
k is the material’s thermal conductivity;
A is the heat exchange section’s area;
L is the distance between nodes i and j.

The radiative couplings can be obtained as defined by Eq. (3) (Gordon, 1981).

$$R_{ij} = \varepsilon_i A_i \left[\sum_{k=1}^{n} F_{ik}\left(\delta_{jk} - \left(1-\varepsilon_j\right)F_{jk}\right)^{-1}\right]\varepsilon_j \tag{3}$$

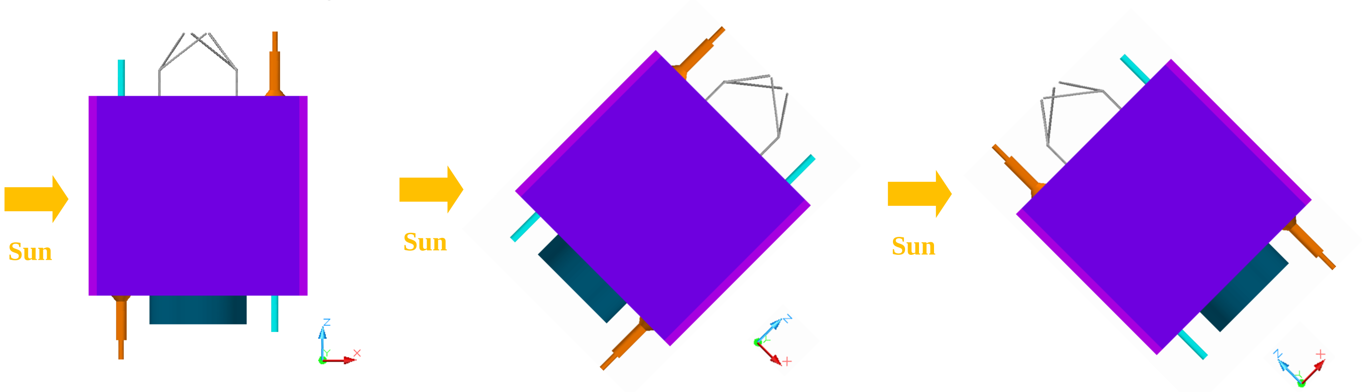
Where:
R_{ij} is the radiative-conductance between nodes j and i;
ε is the surface’s emissivity;
F_{ik} is the shape factor between surface i and adjacent surfaces;
A_i is the surface’s area;
δ is the Kronecker’s delta-function.

The SINDA/FLUINT thermal analyzer works on Eq. (1) handling. The Eq's (1) system`s solution results in n node temperatures; the coefficients m_iCp_i, R_{ij} , B_{ji}, A_i, α_i e ε_i are inherent to the satellite's physical configuration, while Q_i are on-board equipment heat dissipation, q_s and q_{ir} depending on environmental conditions that the satellite will be exposed in.

The heat transfer by radiation between the heat pipe and the satellite approaches zero, since the heat pipe will be isolated with MLI blankets. Thus, only heat conduction between the saddle and heat pipe has been considered in this analysis.

3.2. Cases under evaluation.

In order to analyze the thermal influence of the experiment, a number of possible combinations were considered. These include variation on satellite`s pointing error and the hot and cold cases analysis. The variations on satellite`s orientation are shown in Fig. 4.



a) b) c)

Figure 4. a) Normal orientation; b) Clockwise rotation; c) Anticlockwise rotation.

The solar vector will be perpendicular to satellite`s solar panel in the normal operation mode, as presented in Fig. 4a. A positive inclination between the Sun flux vector and satellite's rotation axis will occur in the clockwise orientation, as presented in Fig. 4b, while a negative inclination occurs in anticlockwise orientation (Fig. 4c).

4. RESULTS OF THE SIMULATION

Much of the preceding experience relates to evaluating the satellite temperatures under steady-state conditions, defined either by orbit average values of absorbed flux and average equipment dissipations, or as extended durations in a fixed satellite orientation with respect to the heating sources. It has been noted that averaging is often used in evaluating the thermal performance of platforms laden with massive electronics. The approach is suitable for predicting mission temperature limits and it is very convenient in that solution routines do not involve numerical stability or complicated convergence criteria.

Monitored thermistor data from orbiting satellites gives credence to orbital averaging for component platforms where variations in the electronics dissipation are not too significant during the course of an orbit. Thermal designs of main satellite platforms are generally directed towards reducing the influences of environment fluxes, and in most cases of normal operation of the small satellites the structure temperature fluctuations are within ± 2°C of the orbital profile. These variations, and others that might occur momentarily during special events, can be predicted from greatly reduced models confined to the particular component and its immediate neighborhood, with the truncated surroundings usually replaced by sinks at constant orbital average temperature (Karam, 1998).

Due to the small temperature variation in the satellite equipment, the average orbital heating rates supply significant information with a reduced cost of analysis and tests. Figure 5 presents the heat rate transferred between inferior and superior panels (panel Z- and panel Z+, respectively), as a function of pointing inclination in nominal orbit condition.

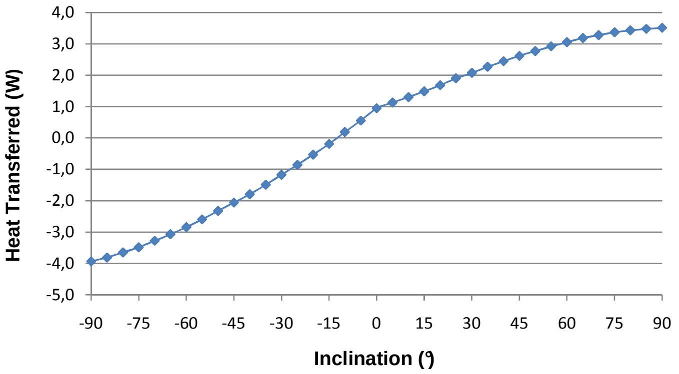
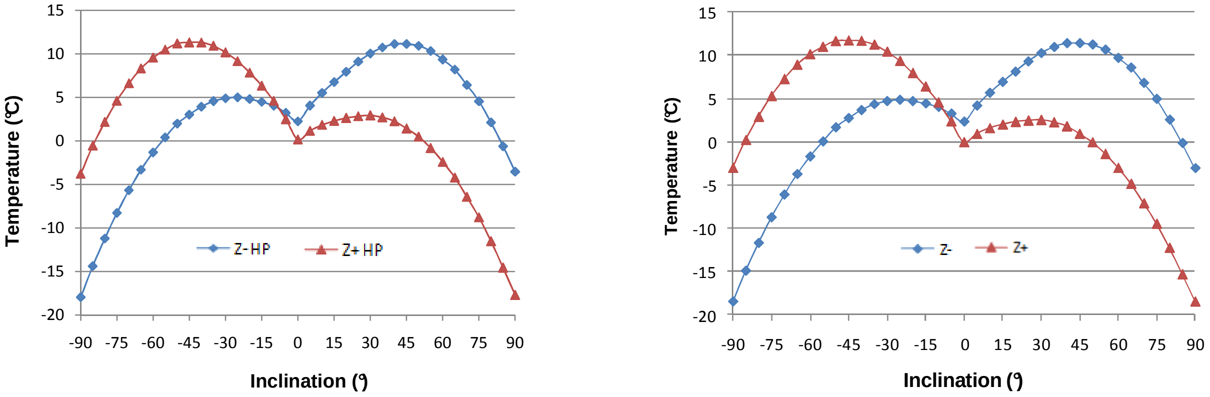


Figure 5. Heat transferred between Z- and Z+ panels.

By analyzing Fig. 5 it should be noted that the maximum heat transferred between the panels is approximately 4W. The negative sign on heat transferred axis indicates the inversion on heat flux direction (in such case heat is flowing from Z+ to Z- panel).

The HP experiment, being installed in the satellite as shown in Fig. 3, provides an additional thermal coupling between Z+ and Z- panels. This case was simulated and the thermal impact was evaluated. The average temperature on Z- and Z+ panels with and without the experiment influence, as a function of pointing error inclination for the nominal orbit case, is presented in Fig. 6.



a)

b)

Figure 6. a) Average temperature in Z+ and Z- panels: a) With HP influence; b) Without HP influence.

As presented in Fig. 6, the average temperature range on Z- and Z+ panels decreases slightly with the action of the heat pipe. The maximum temperature difference between the two analyses, reaches approximately 0.8°C.

The results with and without heat pipe for hot and cold cases, when a 5° of inclination in pointing error is performed, are presented in Tab. 2.

Table 2 - Results for hot and cold cases.

Parameter	Cold with HP	Cold without HP	Hot with HP	Hot without HP
Heat transferred (W)	0.63	-	0,6	-
Z- average temperature (°C)	-7.83	-7,84	14,08	14,15
Z+ average temperature (°C)	-8.65	-8,83	13,76	13,8

The magnitude of 5° of inclination in pointing error is normally expected to occur in orbit, and the results presented in Tab. 3 indicates that the thermal influence of the experiment is very small in contrast to the case where no heat pipe was simulated. Therefore, the thermal project of satellite does not affect the HP presence either in operational or non-operational state.

On the other hand, such small heat rate transferred through the HP, is quite enough to detect if HP operates or fails. Detailed simulation of the TUCA experiment was performed using the same SINDA software. The numerical FEM mesh and temperature map over the HP and attached saddles, obtained through the modeling in transient mode, are shown in Fig. 7. Taking the coldest case, which is most critical, two situations were simulated, when HP operates and when it does not. Graphs in Fig. 8 demonstrate the simulation results for 4 subsequent orbits. In this figure, HP.T<No> means HP temperatures at HP extreme ends and HP_SDL<No> means temperature at the saddles at the points near the HP interfaces. All these temperatures will be measured by high precision interchangeable thermistors of ±0.2°C announced uncertainty and when transmitted via telemetry channel of 0.1°C digital resolution. It is seen from the figure that the HP eventual failure occurrence will be well detectable and clearly recognizable through the telemetry from the temperature sensors even under low heat transferred rate of order of 1-2 W.

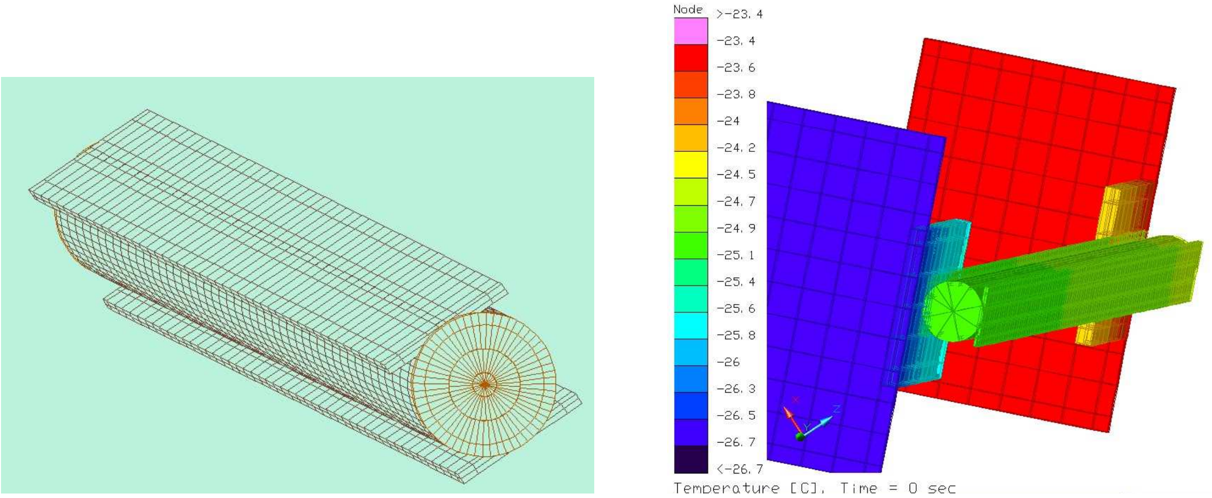


Figure 7. TUCA HP detailed SINDA model visualization and obtained temperature map

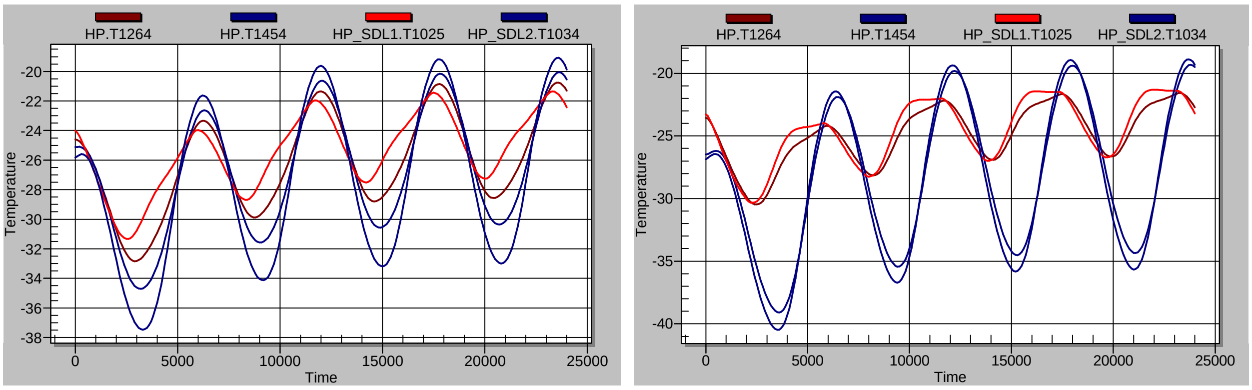


Figure 8. TUCA HP transient simulation for 4 orbits under a cold case:
HP operates (left) and does not-operates (right).

5. FINAL REMARKS

The results, obtained in these numerical simulations, provide a good preliminary reference for the ITASAT thermal control design. The values obtained for the heat transferred by the heat pipe and the average temperature of the superior and inferior panels are extremely relevant, and can supply significant information on the satellite thermal design. Since the thermal effect of the HP TUCA experiment over the satellite is very small, as presented by the results, it can be installed into the satellite without any concern in regards to thermal issues. Eventual HP failure, if it occurs, would be well detectable and clearly recognizable through the telemetry from the temperature sensors even under low transferred heat rate.

6. ACKNOWLEDGEMENTS

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