A NONINVASIVE TECHNIQUE OF VERIFICATION OF EMBEDDED HEAT PIPES IN INTEGRATED SATELLITES

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ABSTRACT

In many real situations of preparation of flight hardware it can be established the requirements for verification of heat pipes embedded in the structural panels of satellites or payloads. The associated risks could be the lost of working fluid by micro-leakages or accumulation of NCG. An effective transient technique for verification of aluminum axially grooved heat pipes embedded in structural satellite panels is proposed. It is based on the concept of two small separate blocks that have both the function of being a source of heat flux and make it possible to acquire both temperatures in the region of evaporation as the condensation region of the heat pipe. The temperature profile acquired through these gage blocks allows the evaluation of the performance of the heat pipe. The repetitive test conditions allow also the performing the comparative analyses of characteristic curves in attempting to detect possible degradation time-tends through the periodical tests. This proposed technique was approved by program authorities and used on CBERS China-Brasil Earth observation satellite, specifically in CBERS4 structure with inserted heat pipes that was planned to be stored over 3 years. The applicability of the technique for the cases of completely assembled hardware can be analyzed by numerical simulations using thermal mathematical models developed with SINDA/FLUINT Thermal DeskTop software.

I. INTRODUCTION

Few papers was published about the performance of heat pipes embedded in structural panel's satellites, but do not contemplates the generation of non-condensable gas influence on the capacity of embedded heat pipes transport heat (Vlassov, 2005, 2008), (Guoqiang and Zengfu, 2007) and (Rassamakin et al, 2007, 2002, 1997).

A method to check the embedded heat pipes performance was presented in (Smirnov, 2009) showing preliminary results compared a mathematical model, but not established criteria to check the non-condensable gas generation.

According to CBERS 3&4 general schedule, the structure subsystem of these satellites (CBERS 3 and CBERS 4) shall be manufactured in a sequence, one after another. CBERS 3 satellite was planned to be launched by 2012, while CBERS 4 should be launched three or four years later. During this period of structure storage, the "health" of the heat pipes (HPs) embedded in the panels shall be verified by periodical specific tests.

The heat pipes present in CBERS 3&4 structures were approved in acceptance tests prior their insertion into the panels and, after the panels manufacturing, another functional test was performed, in order to verify heat pipe functional ability. All these tests were successful.

It is known that heat pipe performance can be affected by non-condensable gases (NCG) generated inside the tubes due to slow chemical reactions between aluminum and ammonia and due to presence of impurities. This effect is a function, among others, of the time elapsed after heat pipe manufacturing. Another risk of possible HP degradation is the partial or total loss of working fluid through micro-flaws due to ultra-slow leakage, undetectable by usual leakage tests.

In order to estimate qualitatively and quantitatively the performance of the heat pipes present in the panels of CBERS 4 satellite, during the time it will be stored waiting for assembling and launch, a specific test technique is proposed. Verifications shall be run periodically in the same conditions in order to detect possible degradation of heat pipes thermal effectiveness along time, beside the verification of HPs functionality.

II. TEST DEVICES DESCRIPTION

The test instruments are composed by two main parts: the Heating Block and the Monitoring Block. Each block holds 3 spring-backed temperature sensors. Both blocks are manufactured with Celeron®, an insulation material having k=0.4 W/m°C. This ensures that the most part of the heat flux provided by the heaters goes directly over the surface under which is located the heat pipe. By the same way, at the Monitoring Block the insulation material allows to detect small variations of temperatures at HP condenser zone. The block temperature sensor installation is presented schematically in figure 1.

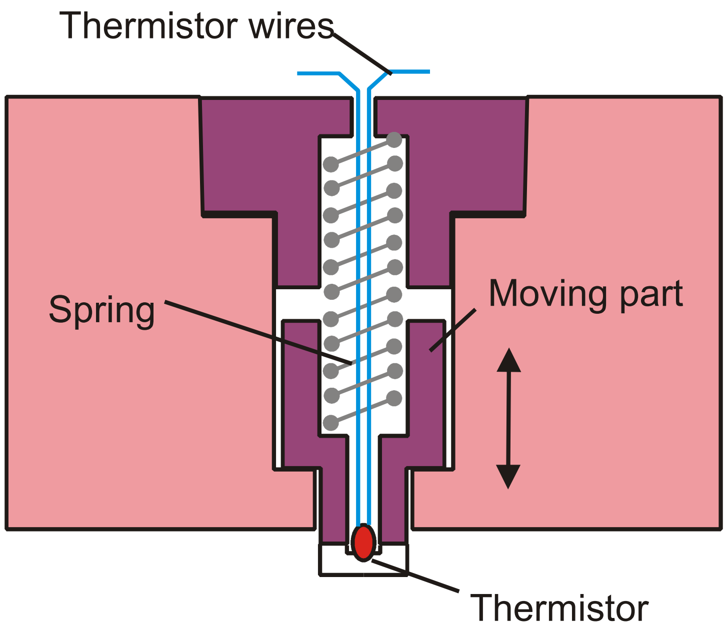

Figure 1. Measurement element built in the blocks

Springs provide the same pressure between the temperature sensor and the panel surface, ensuring the same thermal contact at every measurement, minimizing measurement errors. Thermistor specification is presented in Tab. 1.

Table 1. Thermistor specification

Zero power resistance at 25°C (Ω)	10 K ± 1%
β value 25/50 (K)	3950 ± 1%
Thermal dissipation coefficient (mW/°C)	≥ 2.0
Thermal time constant (sec)	≤ 7.0
Operating Temperature (°C)	-55 ↔ + 125
Rated power of testing (mW)	≤ 0.2
Insulation resistance (mΩ)	≥ 500
Withstanding voltage ($V/_{AC}$)	700

The heating block is used to provide heat and to monitor temperature at the same time. Figure 2 shows a conceptual sketch of the Heating Block, which is composed by four heaters, three temperature sensors and one electrical connector.

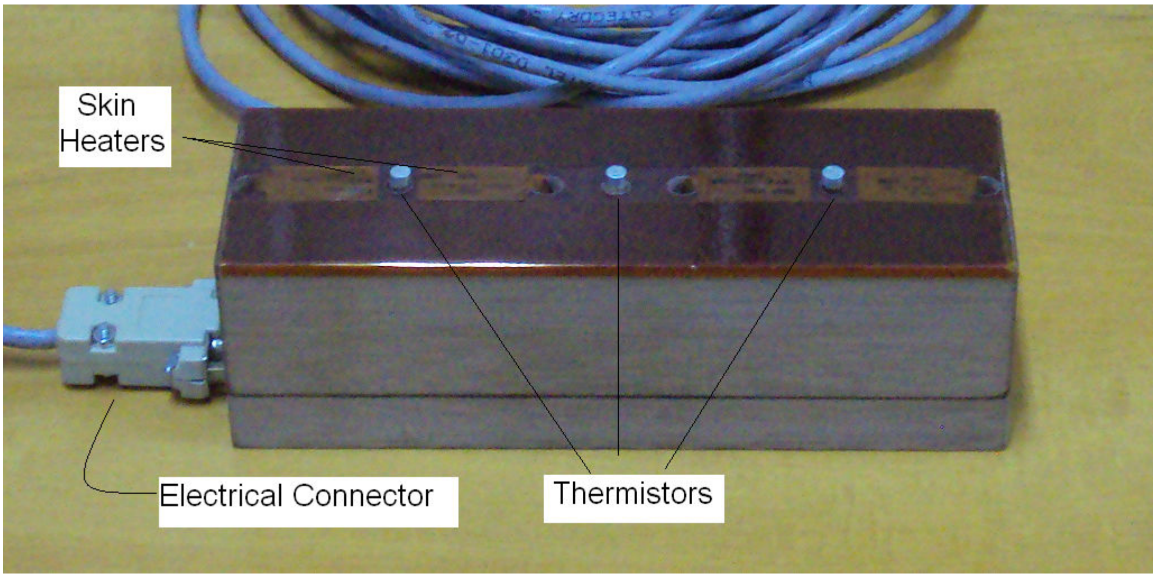

Figure 2. Concept diagram of Heating Block

The heaters are positioned to ensure uniform heating of the panel over HP evaporator zone. The heater specification is MINCO® HK 5574, manufactured with Kapton (Polymide), heaving dimension 12.70mm x 25.4mm each, electrical resistance of 5.4 Ω each, and maximal power density of 10.0 W/cm2.

The Monitoring Block is similar to the Heating Block, having the same dimension, with the difference that it does not have heaters built-in its contact surface, but only thermal sensors. Its main task is to check the temperatures in the region of the condenser zone at the end of heat pipe.. The Monitoring Block also carries an additional thermistor in order to measure the ambient temperature (Figure 3).

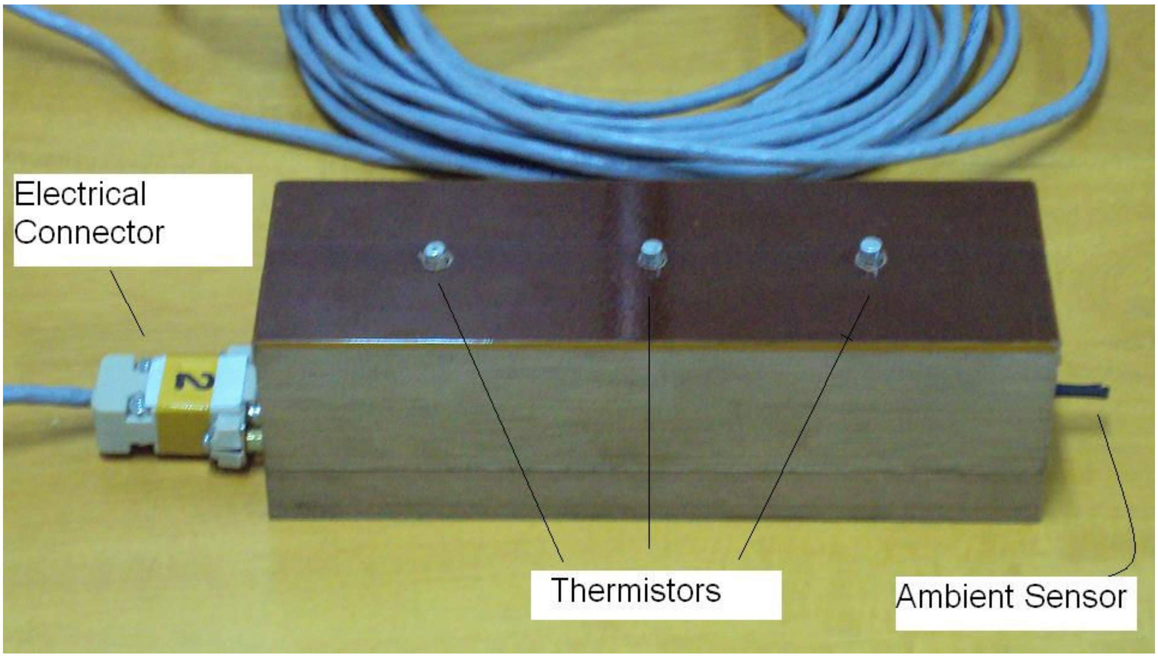

Figure 3. Thermistors positioning along the Monitoring Block

The ambient temperature is usually subtracted from the temperatures measured by the others sensors; therefore the influence of ambient temperature variation from one test to another is eliminated.

III. METHODOLOGY

The test aims to estimate qualitatively and quantitatively any degradation or thermal performance variation with time of heat pipes inserted into the structural panels of a satellite during storage. The technique is based on comparison of the temperature curves obtained by periodical heat pipe testing every six months. This way, it is expected it would be possible to identify any anomaly in the heat pipes behavior by comparing the characteristic curves during the time CBERS 4 satellite will be kept stored.

The heater block is positioned on the panel's surface at one HP end, and monitoring block - at another, like is possible to see in figure 5, which shows the monitoring blocks position in relation to embedded heat pipe.

Figure 4. Position Monitoring Blocks in relation to Embedded Heat Pipe

The evaporator zone is heated during 10 min., after which the power is turned off, with posterior temperatures reading for at least 10 min while the panel is cooling by natural convection.. The whole test campaign shall be repeated every six months.

Horizontal leveling of the panels and test blocks positioning shall be always the same to ensure test repeatability and allow data comparison. In order to ensure the same positioning of the blocks over the heat pipe during each test, appropriate tags are positioned on the panels. These tags shall be kept on the CBERS 4 structure while it remains stored. Instrumentation and power supply for heating shall be kept the same. Panels leveling which cannot be detached from the satellite structure shall be performed by leveling the entire satellite structure.

The first test performed shall be repeated twice on each HP in order to evaluate initial uncertainties due to matters of procedure. Characteristic curves related to each test will be compared against the first result obtained, which shall be taken as a reference. Ambient temperature shall be subtracted from the measured temperatures in order to eliminate the influence of laboratory temperature variation from one test to another.

The test setup is arranged by such a way the temperature measurement can be performed on both, removable stand-alone panels or panels fixed horizontally to the satellite structure. A typical test setup is shown by figure 5.

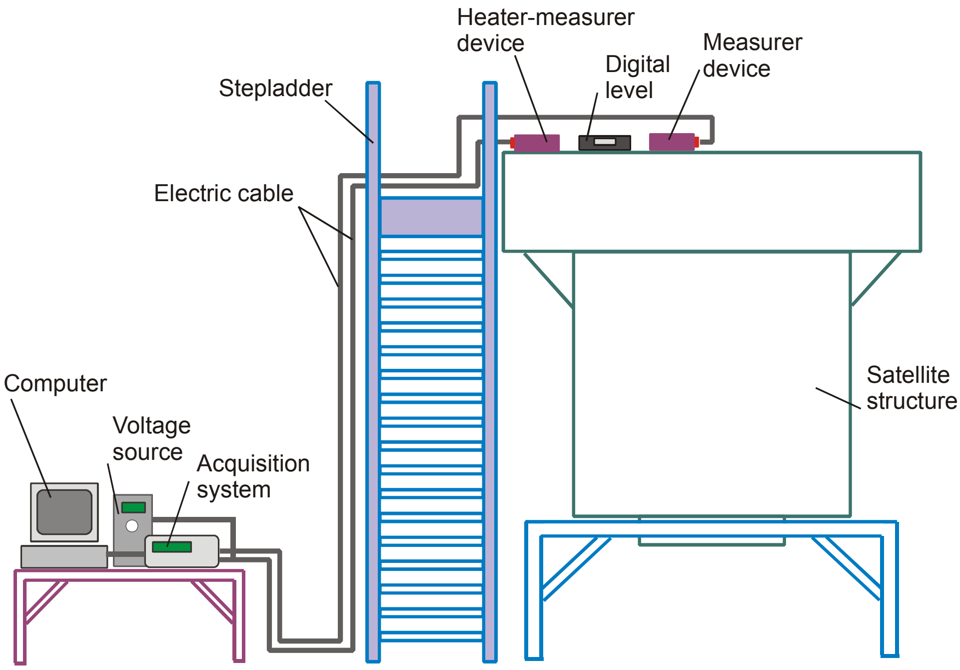

Figure 5. Test setup for temperature measurement on the top of the satellite structure

Before each test, the panel or the satellite structure shall be leveled horizontally by means of a (Fig. 11). The precision of the panel horizontal leveling, measured by a digital level sensor shall be within (-0...+0.15°) in the direction of the HP length. For curved HPs, this same precision shall be reached in two orthogonal directions. The positive inclination is referred to the favorable HP inclination, when HP condenser zone is positioned slightly above the evaporator zone.

. When the panel contains more than one HP, after heating the first HP, the Heating Block shall be repositioned to the opposite end of the next HP. The interval between tests on each HP is specified in 10 minutes and it shall be kept unchangeable at every 6-month test campaign. The heating sequence of each HP in each panel shall be also kept unchangeable.

After test setup assembling, each HP test shall observe the following steps:

1. Leveling the panel within the tolerance of ($0...0.15^{O}$) by digital level sensor
2. Positioning precisely the Heating and Monitoring blocks
3. Switch on the Data Acquisitions System (DAS).
4. Adjust the power supply output to 35±0.1 V, providing around 60 W heat dissipation to the panel. Apply heat during 600 sec.
5. Switch off the power supply. Wait for the cool down during 600 sec.
6. Switch off the DAS and relocate the blocks for the next HP heating if necessary. Wait enough time (usually for several hours) until the temperature on the panel become homogeneous again and the temperature difference on opposite ends of next HP to be tested does not exceed 0.5 C. Meanwhile, cool down the Heating Block using an ambient fan until it temperature achieve ambient with the same precision of 0.5 C. When start the next heating (repeat since step 3).

Total 5 characteristics curve shall be plotted from DAS to perform the comparative analysis:

1. Main HP temperatures above the ambient temperature.
2. Temperature difference between characteristic evaporator temperature and condenser temperatures.
3. The temperature difference between the average condenser temperature and TH06 condenser temperature.
4. HP start – up.
5. HP shut down.

Each of curves may content signals of HP performance degradation. In the section of results the acceptance criteria are explained in more details.

SIMULATION MODEL

The numerical simulation aims to reproduce the embedded heat pipes in integrated satellites performance measured by the temperature profile in order to investigate hypotheses that explain this profile behavior. Fig. 6 shows the model built using the SINDA FLUINT software, on which were also placed the two measuring blocks used in the experimental setup.

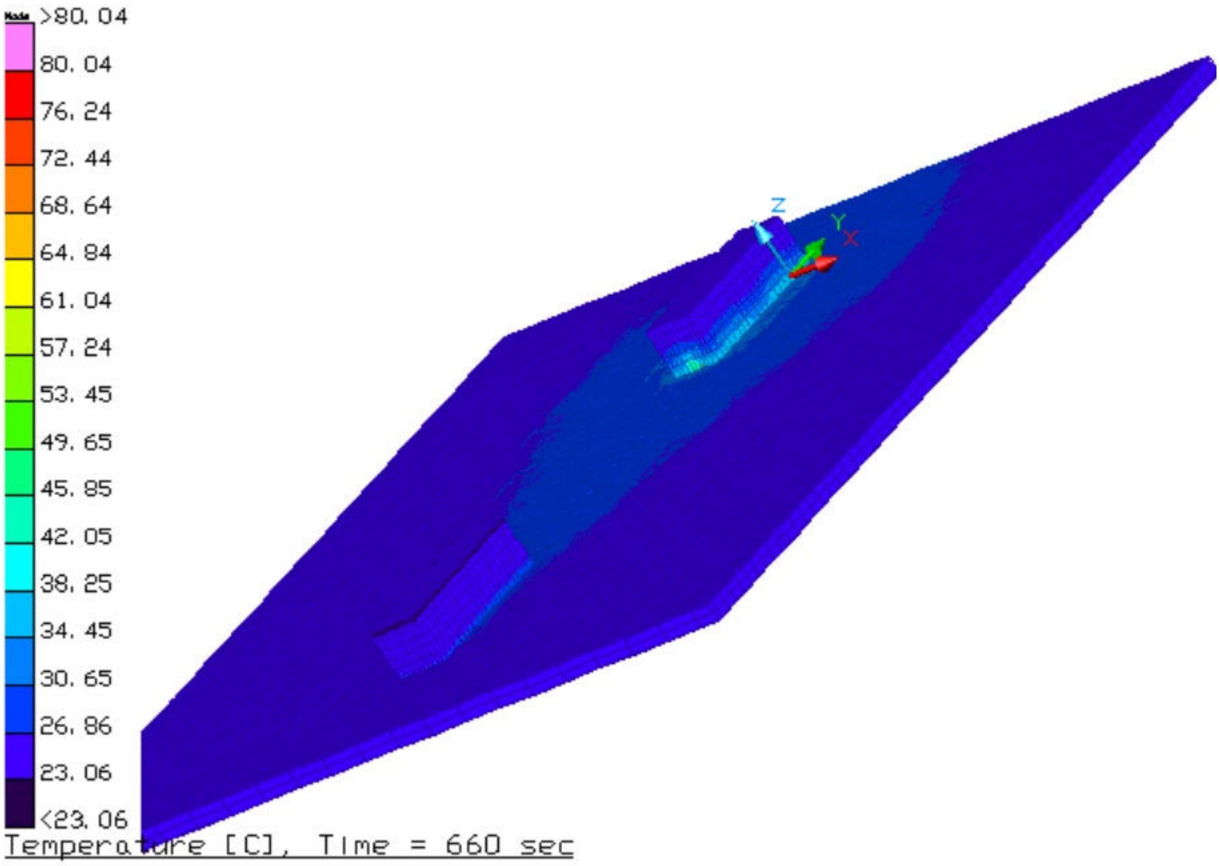

Figure 6. Modeling of temperature map over the honeycomb panel during verification test.

The model consists of 14 sub models and contains total 6652 nodes. The heat pipe embedded in structural panel, Fig. 5, is simulated with 3 main parts: heat pipe cross section, vapor channel and non-condensable gases blocked zone with adjustable length to simulate different experimental results possibilities. Vapor core channel at the length from evaporator to NCG blockage is simulated as a solid cylinder, having very high equivalent effective conductivity.

The boundary conditions in the model reproduce the experimental setup and laboratory environment. Natural convection was taken into account in the model to precisely describe the experiment conditions.

The components used in the model to reproduce the temperature profile along the HP length can be seen in figure 7.

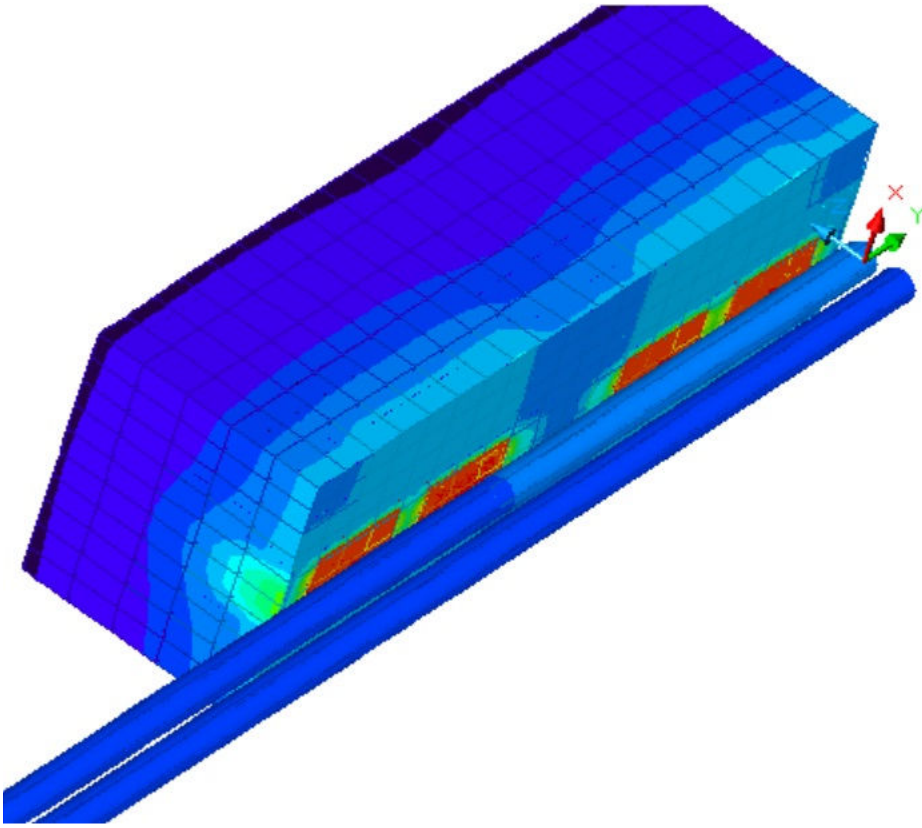

Figure 7. Temperature distribution over the test evaporator block and HP vapor cores.

The hypothesis to be investigated through simulation model is the change of the characteristic curves because of formation of a NCG blockage in the channel vapor decreasing the heat pipe heat transport capacity. The influence of this NCG blockage is simulated by insertion of low conductivity solids in the model, which are coupled to high conductivity solids that simulates vapor channel.

Results obtained from the mathematical model are showed in figure 8. These results reproduce the thermal behavior obtained from experimental setup considering that non condensable gas wasn't generated.

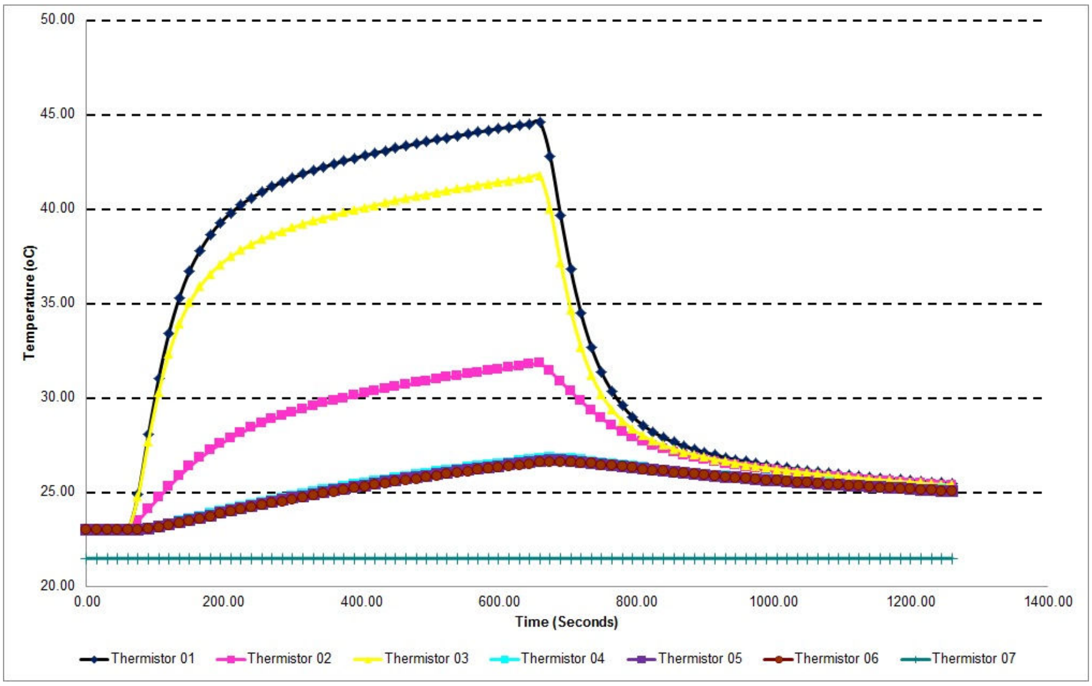

Figure 8. Temperature profile obtained from numerical simulations.

The criteria used in this study to determine if there was non-condensable gas generation were applied to the results obtained from the numerical model presented. This hypothesis was simulated considering a blocked zone in the embedded heat pipe vapor channel. Results are presented in figure 9 – 11.

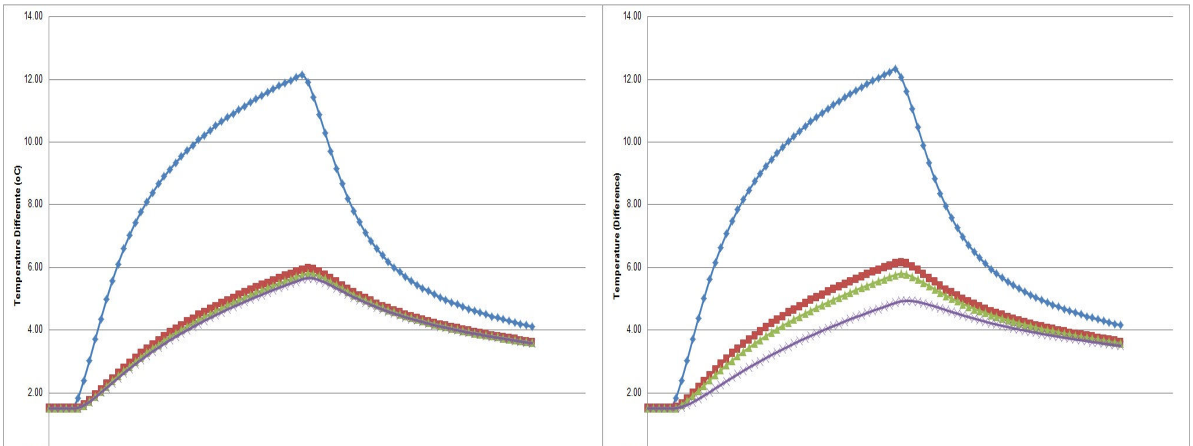

Figure 9. Main HP temperatures above the ambient, i.e. (TH02-TH07), (TH04-TH07), (TH05-TH07), (TH06-TH07), without and with NCG respectively.

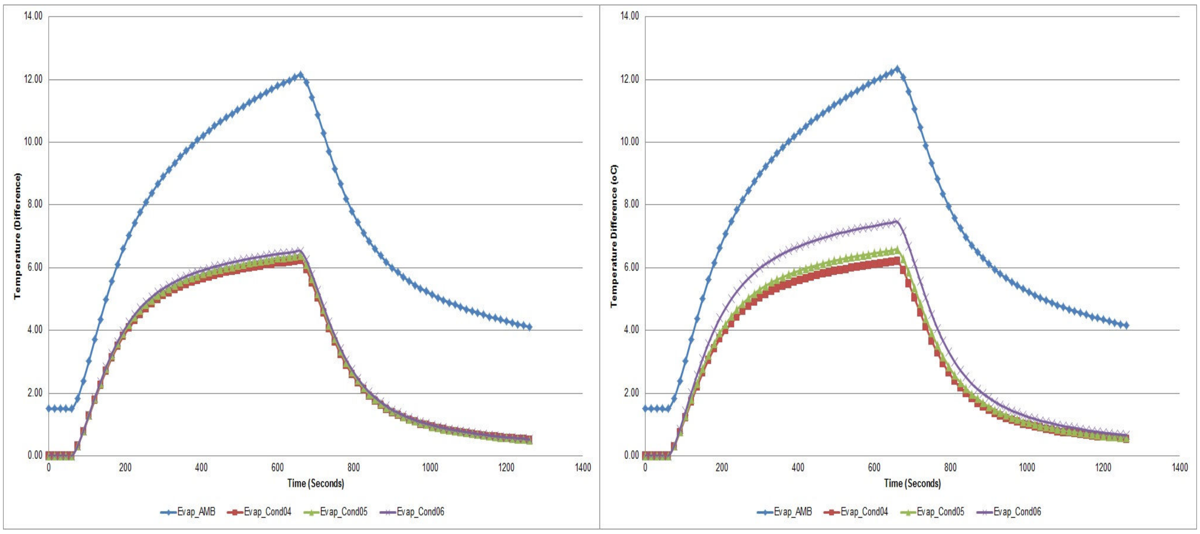

Figure 10. Temperature differences between characteristic evaporator temperature (TH02-TH07) and condenser temperature, i.e. (TH02-TH04), (TH02-TH05) and (TH02-TH06), without and with NCG respectively.

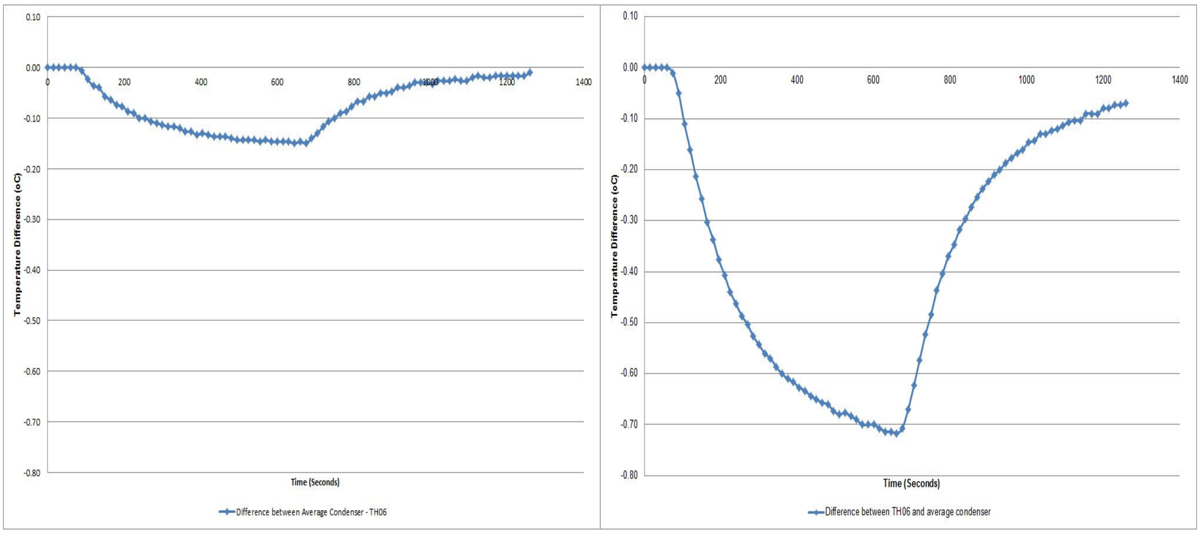

Figure 11. Temperature difference between the average condenser temperature and the last condenser temperature, i.e. (TH06 - (TH04+TH05+TH06)/3), without and with NCG respectively.

Comparing the temperature profiles obtained from the simulation of the embedded heat pipe with and without non condensable gas generation is possible to observe some differences in function of heat transport capacity decreasing.

TEST RESULTS AND DISCUSSION

The measured temperatures have been obtained on one HP of one of CBERS4 panels and are presented in figure 12.

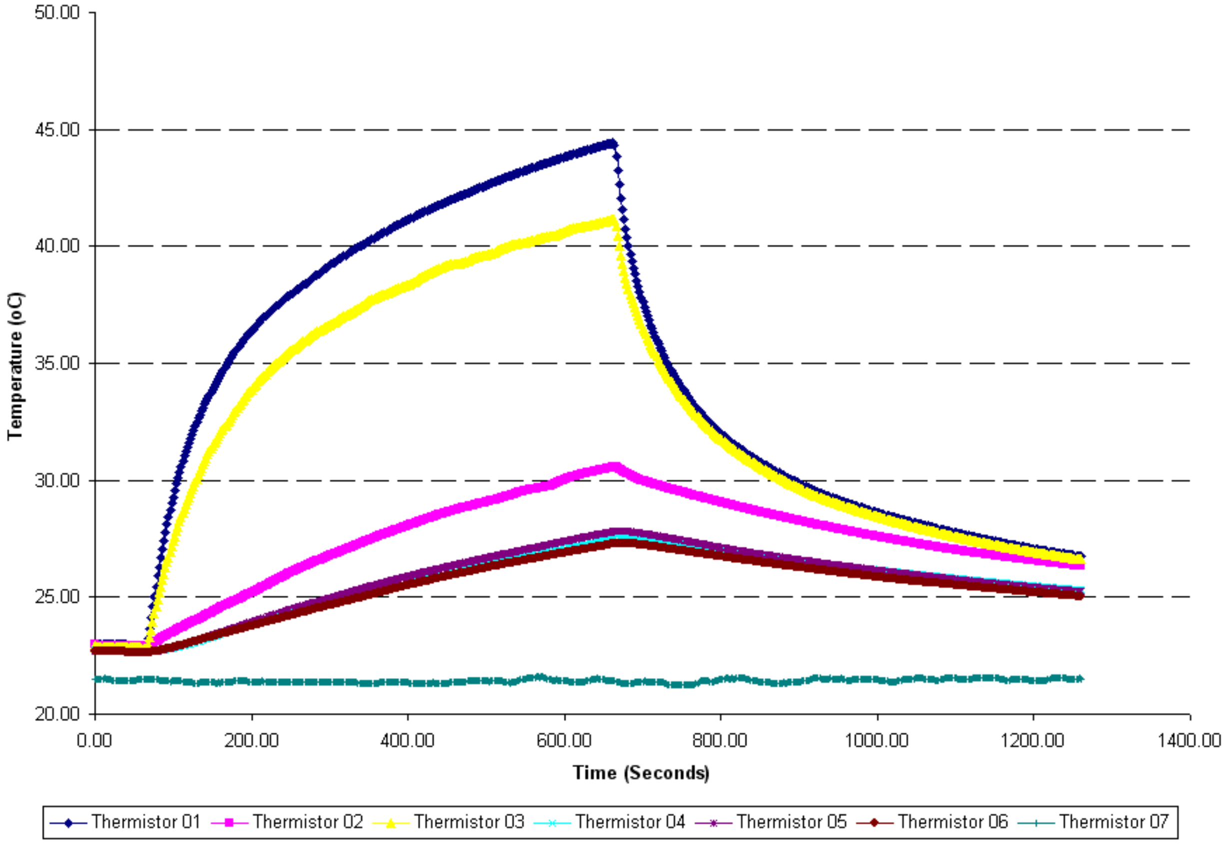

Figure 12. Measured HP transient temperature profiles.

The following characteristic transient curves which present the criteria non – condensable gas detection applied to experimental results.

The criteria applied in the experimental results were the same applied over the theoretical results that try to reproduce the experimental thermal profiles.

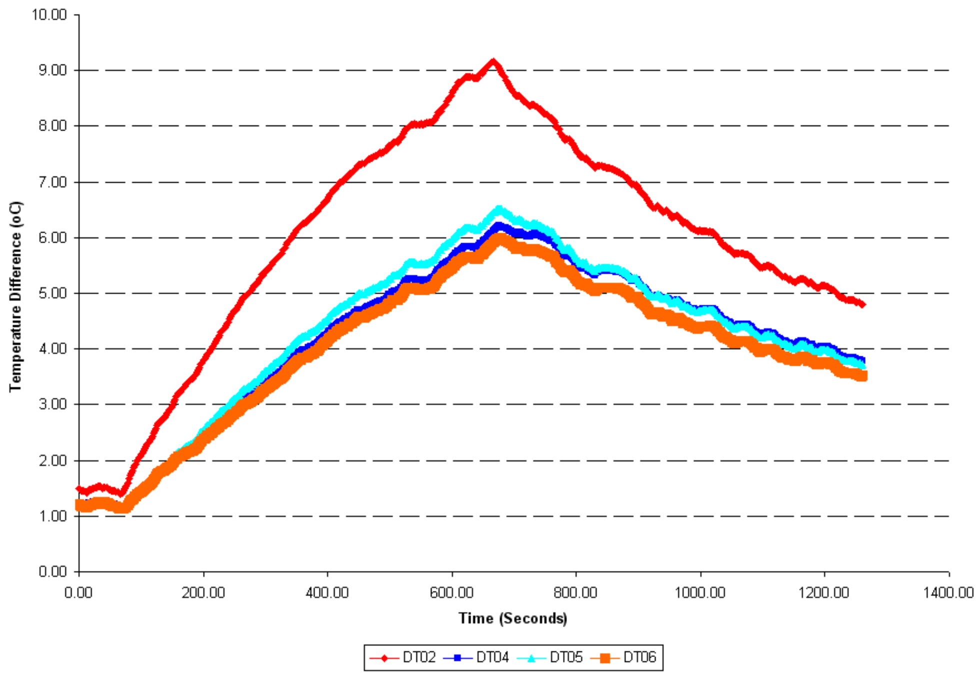

Figure 13. Main HP temperatures above the ambient, i.e. (TH02-TH07), (TH04-TH07), (TH05-TH07), (TH06-TH07).

Figure 13 shows main HP temperatures above the ambient temperature as a function of time during each test, i.e. (TH02-TH07), (TH04-TH07), (TH05-TH07), (TH06-TH07). If, between periodic verifications, a clear tendency of temperature increase at the evaporator zone (TH01-TH03) and/or temperature decrease at the condenser zone (TH04-TH06) is observed, then it may indicate the NCG presence or HP failure. In general, this temperature increase/decrease shall not be higher than 2°C between two consecutive verifications, and 3°C between last and first verification of each HP. Theoretically, first indication of degradation is detected when TH06 thermistor presents a temperature decrease between tests.

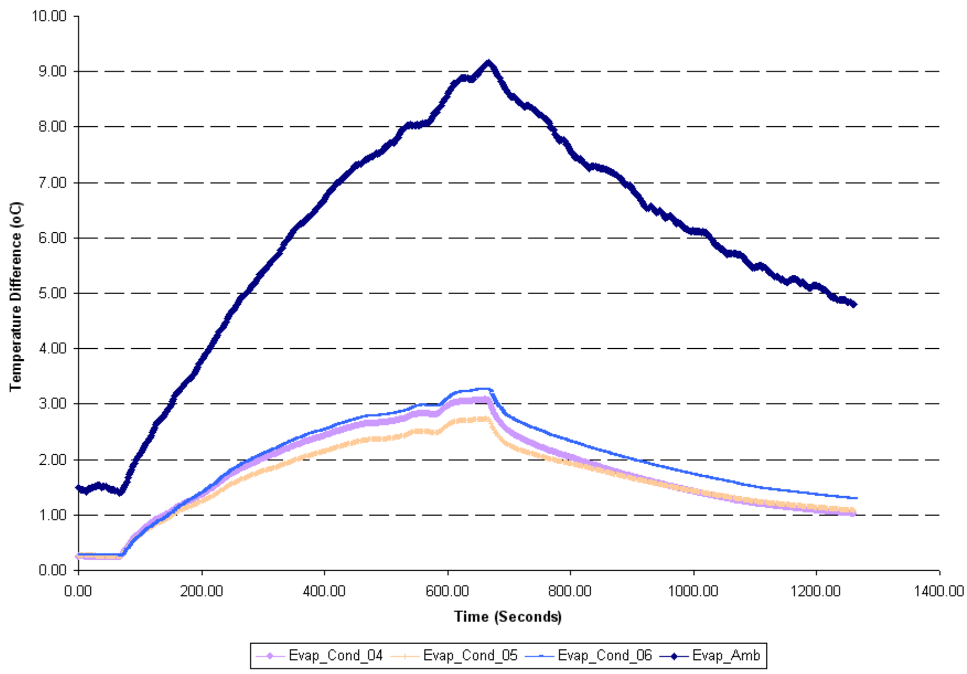

Figure 14. Temperature differences between characteristic evaporator temperature (TH02-TH07) and condenser temperature, i.e. (TH02-TH04), (TH02-TH05) and (TH02-TH06).

Figure 14 shows temperature difference between characteristic evaporator temperature and condenser temperatures, i.e. (TH04-TH02), (TH05-TH02) and (TH06-TH02). If, between periodic verifications, a clear tendency of temperature increase of these temperature differences is observed, then it may indicate the NCG presence or HP failure. In general, this difference temperature increase shall not be higher than 1.5°C between two consecutive verifications, and 2°C between last and first verification of each HP. Theoretically, first indication of degradation may be when the difference (TH06-TH02) presents a temperature decrease between tests.

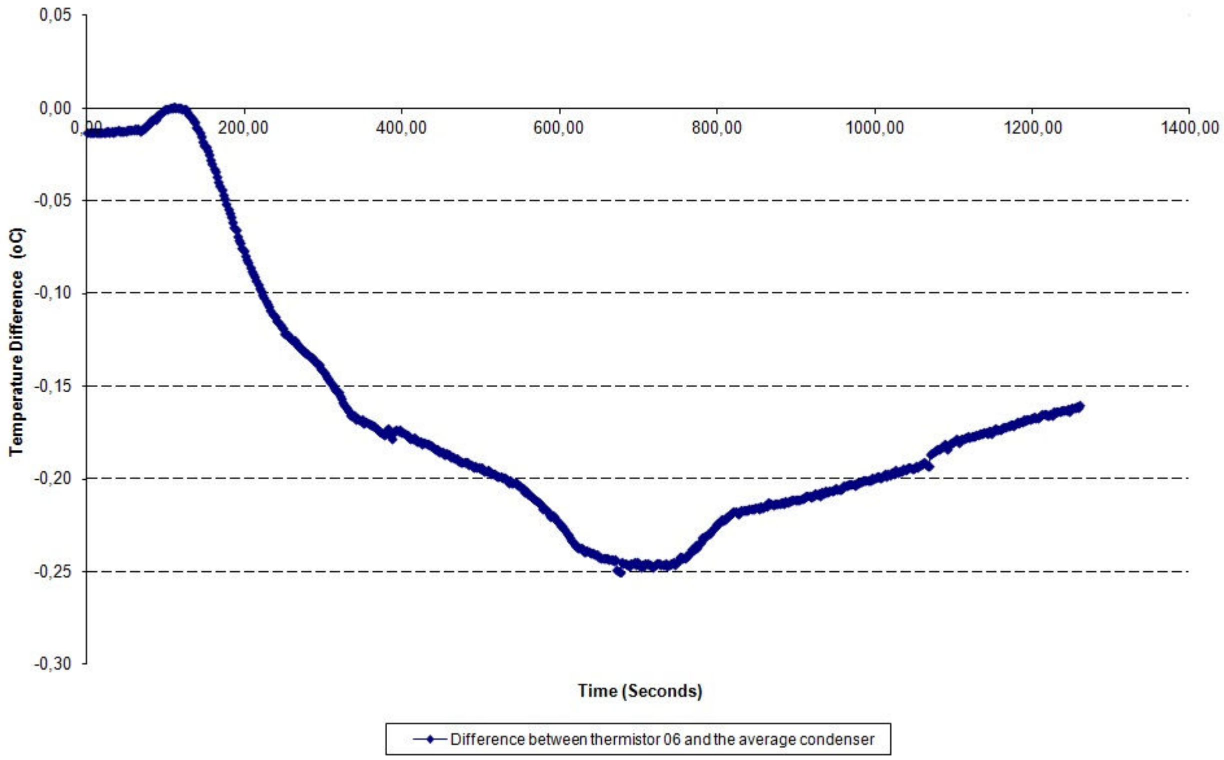

Figure 15. Temperature difference between the average condenser temperature and the last condenser temperature, i.e. (TH06 - (TH04+TH05+TH06)/3).

Figure 15 shows the temperature difference between the average condenser temperature and TH06 condenser temperature, i.e. (TH06 - (TH04+TH05+TH06)/3). Temperature values less or equal to -0.15°C (TBC), at the moment the heaters are switched-on, may indicate the beginning of the degradation process due to formation of non-condensable gases (NCG). The tendency of this temperature difference increase should be clearly detected from one verification to another.

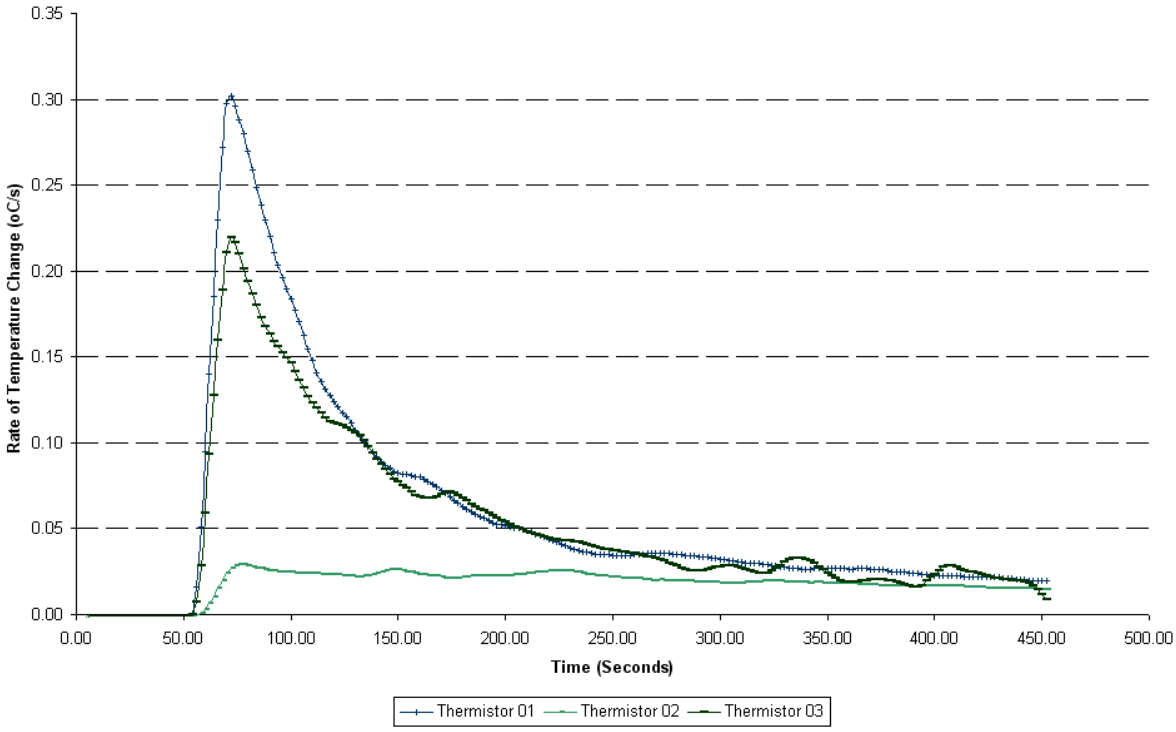

Figure 16. Rate of evaporator temperature change at the HP start – up (°C/sec).

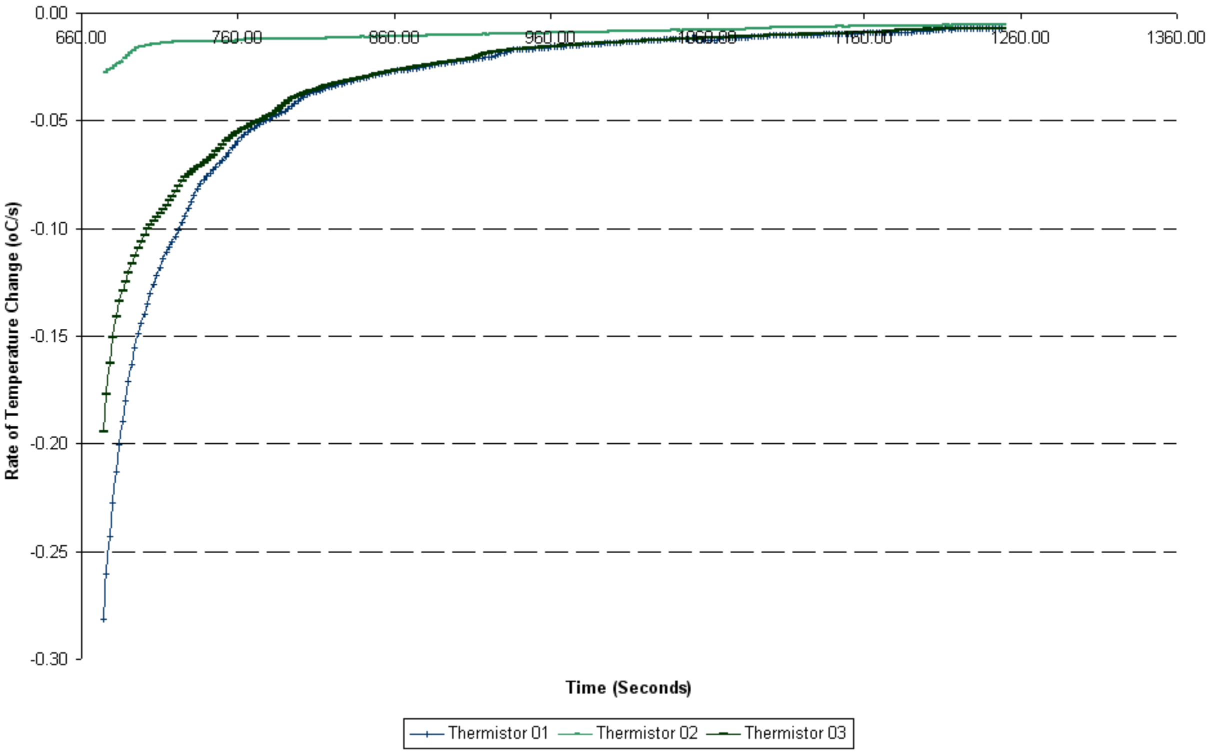

Figure 17. Rate of evaporator temperature change at HP shut-down (heater switched-off) (°C/sec).

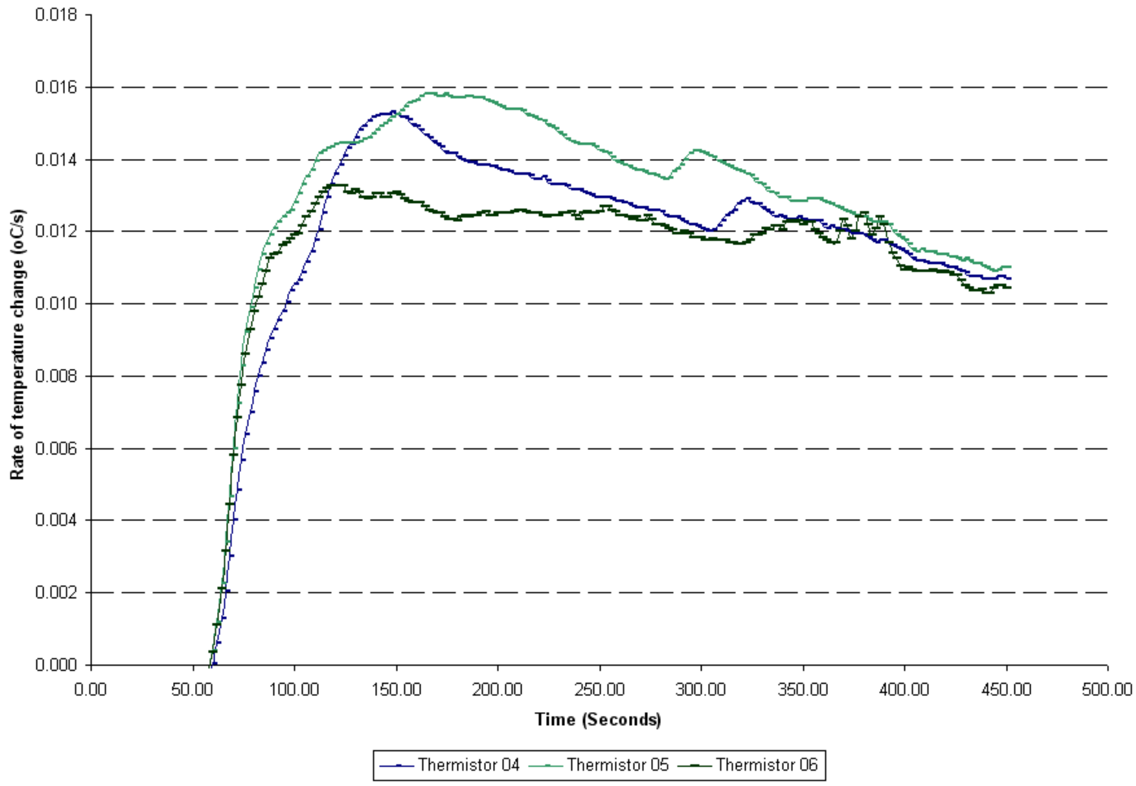

Figure 18. Rate of condenser temperature change at the HP start - up (°C/sec).

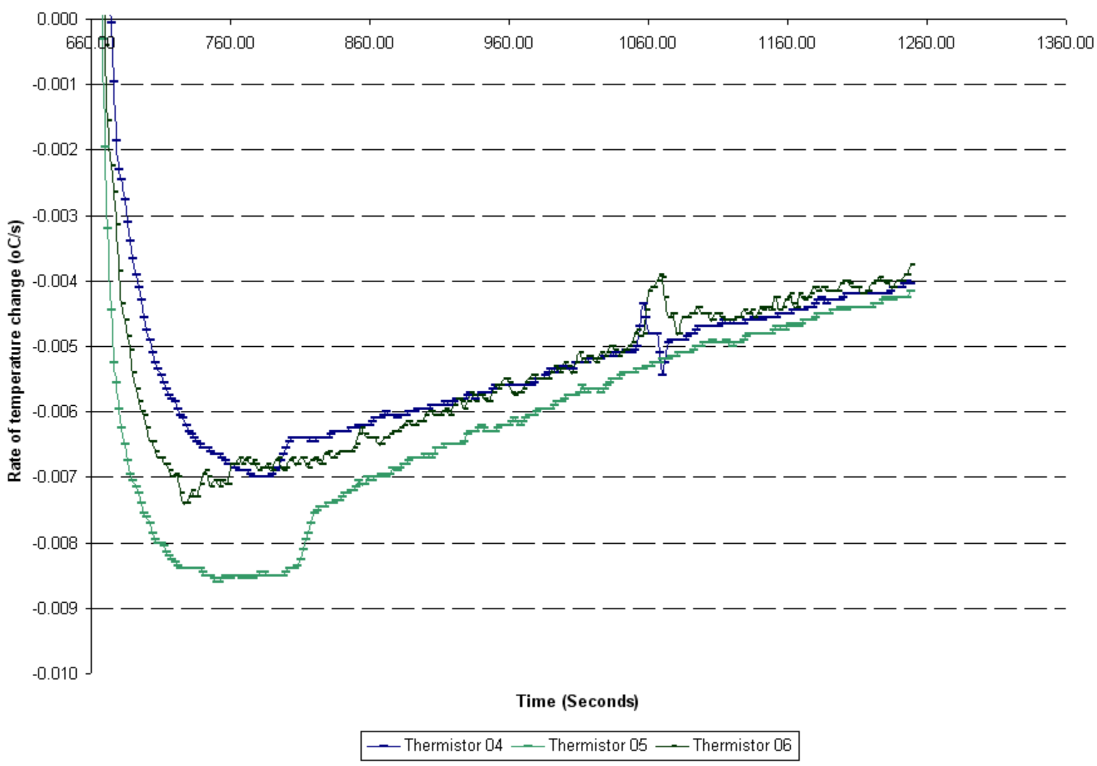

Figure 19. Rate of condenser temperature change at HP shut-down (heater switched-off) (°C/sec).

Figures 16, figure 17, figure 18 and figure 19 show temperature rate of the evaporator and condenser temperatures at HP start-up and shut down, i.e. d(TH04)/dt, d(TH05)/dt and d(TH06)/dt. It is expected that presence of NCG may affect the fast dynamic behavior of the evaporator and condenser temperatures. However, this criterion plays auxiliary role and may provide additional information to this study. Moreover, this phenomenon can not be simulated with the developed model.

The results presented don't show specific signals of degradation, although capture with clearance heat pipes embedded in honeycomb panel's performance, like is possible to see analyzing the experimental comparison presented in figure 20.

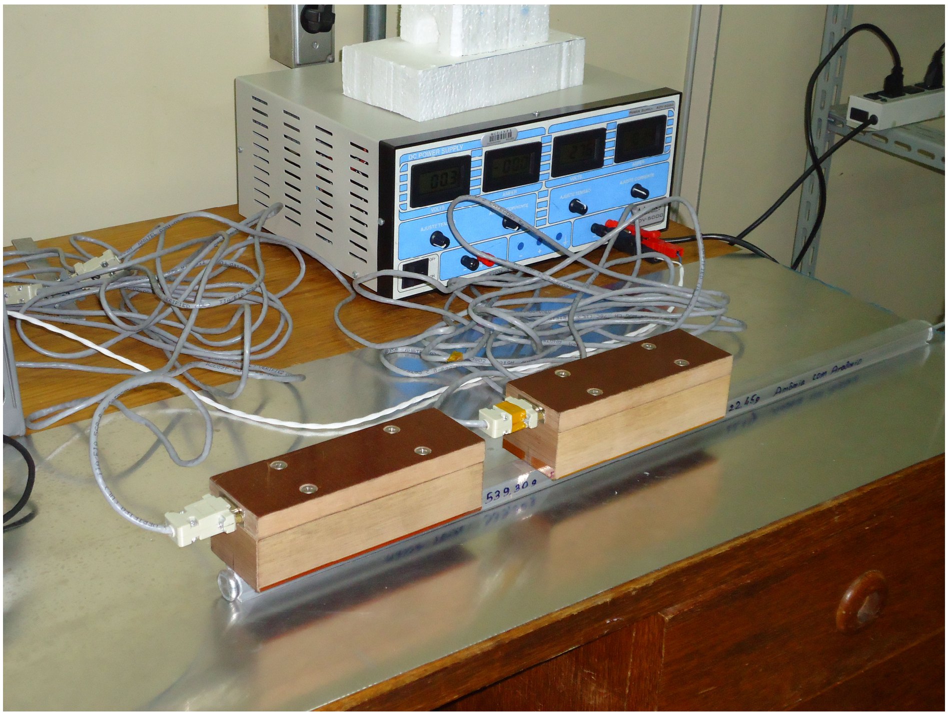

Figure 20. Measuring blocks positioned directly over heat pipes (°C/sec).

Figure 20 shows experimental setup built to compare the thermal response acquired by measuring blocks from heat pipes with and without non condensable gas. In the figures 21 and figure 22 are presented the temperature gradient of the condenser temperatures at heat pipe start - up and shut down.

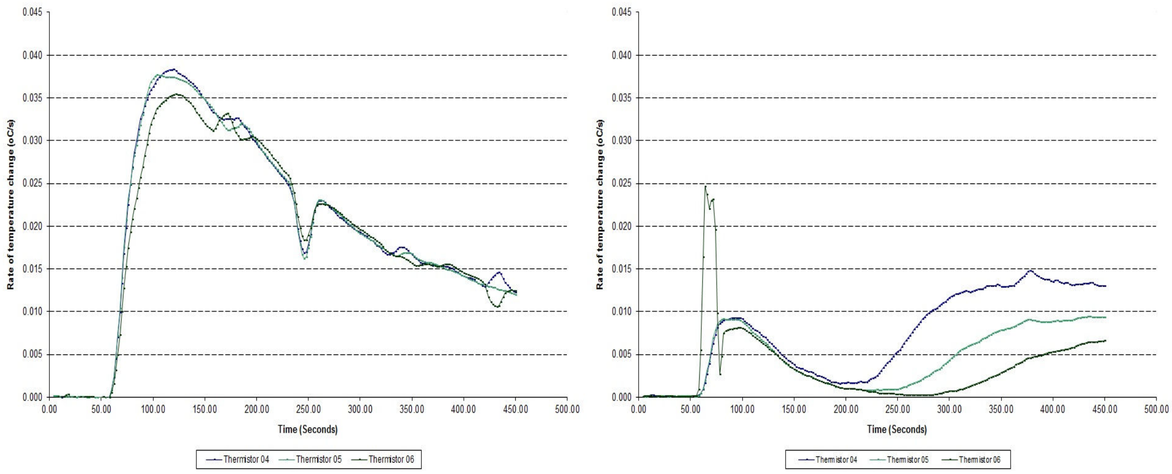

Figure 21. Rate of condenser temperature change at the HP start – up (°C/sec), without and with NCG respectively.

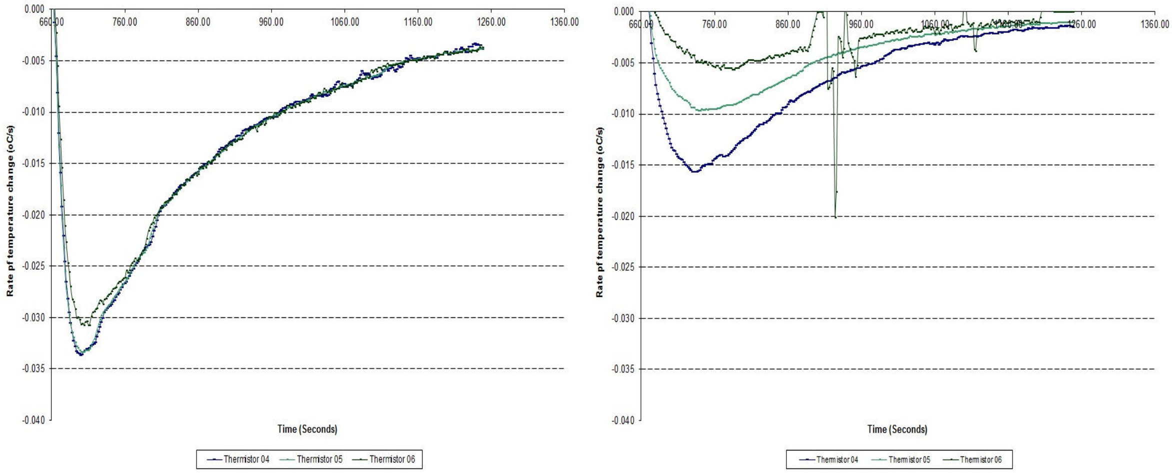

Figure 22. Rate of condenser temperature change at HP shut-down (heater switched-off) (°C/sec), without and with NCG respectively.

The results comparison provided by figure 21 and figure 22, show the direct influence over the fast dynamic behavior of the evaporator temperatures.

IV. CONCLUSION

The proposed technique for evaluating the performance of heat pipes embedded in satellites structural panels aims to verify the possible degradation or HP failure. The technique is very practically and the verification can be conducted without any invasion to the satellite structure. Proposed set-up with heating and measured blocks can guarantee repeatability of test conditions for periodic verifications. On this base a comparative analysis of periodic tests conducted with long intervals (6-months or longer) can be performed. Five characteristic criteria are chosen to evaluate possible HP degradation by periodical testing. Developed numerical model provides theoretical base to the proposed technique.

Separate tests with two HPs with and without NCG have been performed. The new experimental results based on different temperature rates (i.e. derivative dT/dt) show these transient criteria can be also used to detect the NCG presence besides the conventional steady-state criteria based on temperature differences in the condenser zone. Separate study on if these transient criteria could be useful to detect small amount of NCG is under way.

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