PERFORMANCE PREDICTION OF THE PLANCK SORPTION COOLER AND INITIAL VALIDATION

M. Prina[1], P. Bhandari[1], R.C. Bowman[1], L.A. Wade[1], and D.P. Pearson[1], and G. Morgante[2]

[1]Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

[2]C.N.R.-Te.S.R.E.
Via P. Gobetti 101
Bologna, 40129 Italy

ABSTRACT

Two continuous operation 18 K/20 K sorption coolers are being developed by JPL for the ESA Planck mission to provide about 200 mW of cooling at 18 K and 1.4 W at 20 K. A detailed performance prediction model has been developed to support the design process and to evaluate the results of a prototype testing.

The performance of these coolers depends on many synergistically related operating parameters (such as the temperatures of precooling thermal shield and the warm radiator) and they can only be assessed through a detailed modeling of each component coupling. This model predicts the time varying temperature, pressure and H_2 concentration gradients within the metal hydride beds, the H_2 flow rate, cooling power produced in the coldhead, and the oscillations of the coldhead temperature. Each component model has been parametrically described to allow trade off evaluation and the possibility to use it for different environmental and cooling requirements and for other sorption coolers.

The full validation of the model will be obtained by comparison of the performance predictions to the experimental data for the engineering prototype cooler being built at JPL.

INTRODUCTION

The sorption cooler is a cooling machine that performs a J-T cycle using hydrogen as working fluid. The key element of the 20 K sorption cooler is the compressor, an absorption machine that pumps hydrogen by thermally cycling several sorbent compressor units and whose only moving parts are the check valve's diaphragm. The principle of operation of the sorption compressor is based on a unique sorption material ($La_{1.0}Ni_{4.78}Sn_{0.22}$) [1,2] which can absorb large amounts of hydrogen at relatively low pressures, and which will desorb to produce high-pressure hydrogen when heated in a limited volume. Heating of the sorbent is accomplished by electrical resistance heaters while the cooling is achieved by thermally connecting the compressor element to a radiator at 270 K. The system is periodically cycled between heating and cooling cycles, producing high-pressure gas intermittently. In order not to loose excessive amounts of heat during the heating cycle, a heat switch is provided to alternately isolate the sorbent bed from the radiator during the heating cycle, and to connect it to the radiator thermally during the cooling cycle [3].

As a sorption compressor element (i.e. sorbent bed) is taken through four steps (heat up, desorption, cool down, absorption) in a cycle, it will intake low pressure hydrogen and output high-pressure hydrogen on an intermittent basis. If the high-pressure hydrogen is pre-cooled with radiators to below the inversion temperature and then expanded through a Joule-Thomson expansion orifice (J-T) the high-pressure gas will partially liquefy, producing liquid refrigerant at low pressure for sensor systems. Heat from the sensors evaporates liquid hydrogen, and the low-pressure gaseous hydrogen is re-circulated back to the sorbent for compression. In order to produce a continuous stream of liquid refrigerant several such sorption beds are needed to stagger their phases so that at any given time, one is desorbing while the others are either heating, cooling, or re-absorbing low pressure gas. In such a system, there is a basic clock time period over which each step of the process is conducted.

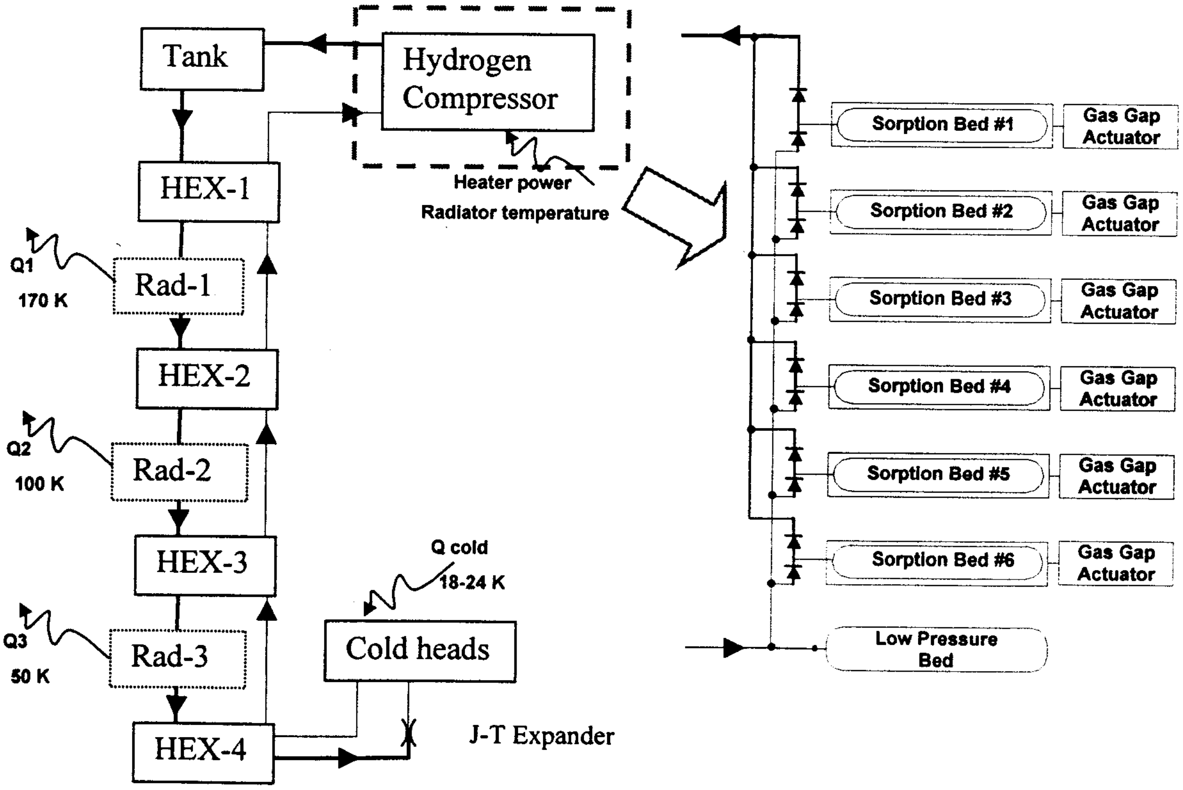

FIGURE 1. Planck sorption cooler schematic, with the three pre-cooling radiators, four heat exchangers, the cold heads and the compressor. The arrows in front of each bed sorption bed are check valves, allowing flow only in the arrow direction.

The compressor assembly shown in Figure 1 is composed of six identical sorption compressor elements, each filled with metal hydride and provided with independent heating and cooling. Each compressor element is connected to both the high pressure and low pressure sides of the plumbing system through check valves, which allow gas flow in a single direction only. The check valves are indicated on the schematic as single arrows, which indicate the direction of gas flow through them. Each compressor element has a peculiar desorbing flow characteristic depending on its hydride powder distribution in the element. The hydride material is grinded and the poured into the element before the element is sealed and the powder is distributed by sequences of shaking and analysis with the goal of uniform distribution. In Figure 2 a particular flow characteristic, measured on one of the prototype compressor elements is reported with the modeled flow prediction. The cooler modeling is based on a complex heat-mass transfer model of each component solved by a finite difference method program (SINDA/FLUINT). The detailed description of how the compressor element has been modeled can be found in Bhandari et al. [3] where the full heat/mass transfer modeling is reported.

As reported in Figure 2 and predicted by the model, the hydrogen flow out of the compressor element varies between 4 and 7.8 mg/s of hydrogen. To damp out oscillations on the high pressure side of the compressor a five liter high-pressure stabilization tank is introduced. On the low pressure side a low pressure stabilization sorbent bed is adopted to reduce the low pressure fluctuations. Refrigerant travels from the compressors through a series of heat exchangers and radiators, which provide pre-cooling to approximately 50 K, through the J-T expander. The compressor assembly is comprised of the six compressor elements, high-pressure stabilization tanks, the low pressure stabilization bed, check valves, and manifolding. The compressor assembly mounts directly onto the heat rejection radiator. This radiator is sized to reject the cooler input power at 270 K +10 K/-10 K. A single compressor element is comprised of two concentric cylinders closed with end caps. The inner of these tubes contains 626 g of $La_{1.0}Ni_{4.78}Sn_{0.22}$ hydride material and the outer forms a vacuum jacket around the inner cylinder. This vacuum jacket is used as a gas-gap heat switch [4].

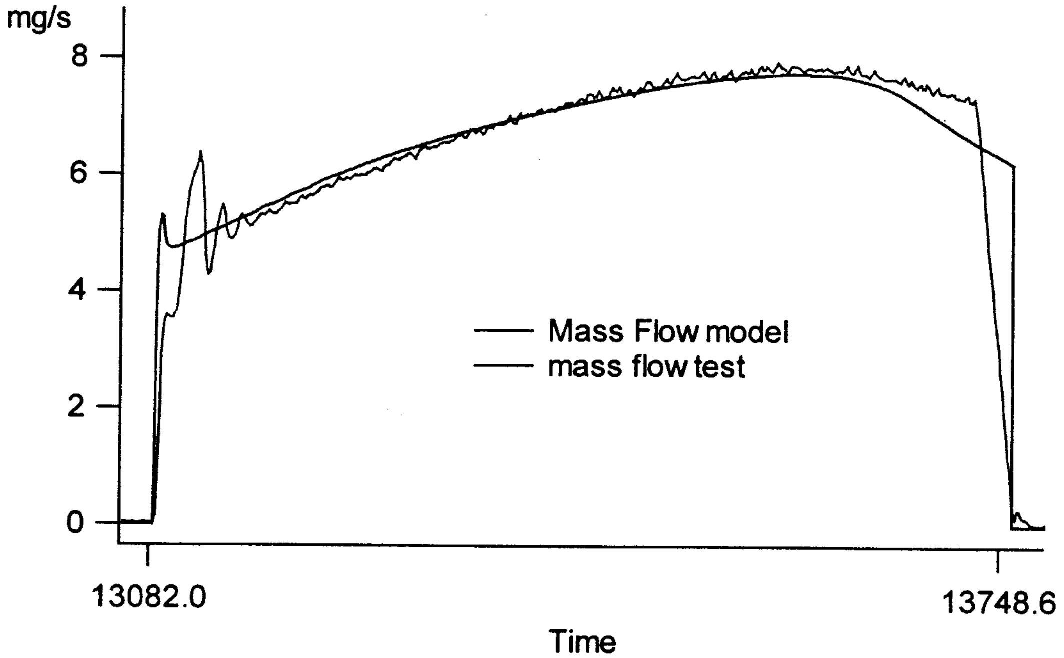

FIGURE 2. Desorption Flow measured on a compressor element prototype and what has been predicted. The non-linearity is related to the fact the hydride properties are highly non-linear and the power supplied during the desorption is constant and not adjusted consequently.

Each component of the system has been characterized to validate their performance and their model is used to predict and eventually control the cooler operations. We used the cooler model to anticipate and predict how to start up the cooler, how to operate it and how to optimize its performance in terms of cold-head temperature fluctuations and cooling capacity stability.

COOLER STEADY-STATE PERFORMANCE PREDICTION

The cooler performance has been predicted in terms of cooler input power, cooling produced, cold head temperature average and cold-head temperature fluctuations. The compressor power and the coldhead temperature predictions have been verified on the sub-component level (compressor element test). The cooling power has been verified by A. Sirbi [5] whereas the fully integrated system has not been tested yet.

Cold Head Temperature and Cooling Power

The coldhead temperature is primarily determined by the temperature at which the hydride is absorbing. In fact, the temperature at which the hydride alloy in the compressor element is absorbing the low pressure hydrogen flow determines the pressure of absorption (gas-solid phase transition) and therefore the temperature of the cold-head (liquid-vapor phase transition). The hydride temperature is determined by the temperature of the radiator on which the compressor is mounted as reported in figure 3a. The cold-head temperature has been derived based on the measured absorption pressure characteristic of the compressor elements and on the estimated pressure drops in the lines between the compressor and the coldhead. The measurement of the pressure drop will be performed on the prototype cooler at JPL in the next months.

The cooling power is primarily determined by the temperature of the radiative precooling shield nominally at 50 K and the flow produced by the sorption compressor. The current compressor design can produce an average of 6.5 mg/s of hydrogen (see Figure 2) determining the cooling power profile summarized in Figure 3b as a function of the coldest precooling shield temperature.

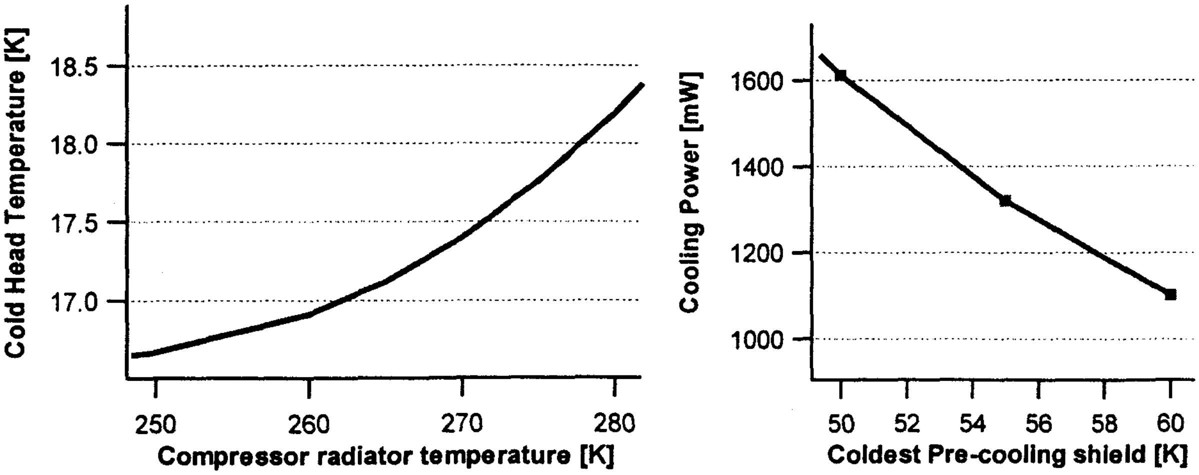

FIGURE 3. Cold head temperature and power predictions.

Low Temperature Fluctuations

The verification of the low temperature fluctuation is one of the main purposes of the engineering breadboard cooler complete system test that JPL is currently preparing for. All the components strongly affect the cold-head temperature oscillations: the hydride non-linear characteristic, the timing of the gas gap actuator, the interaction of three absorbing compressor elements and of the low pressure stabilizing bed, the differences between the various compressor elements, check valves hysterisis, etc. The sorption cooler is required to produce a temperature fluctuation of the cold-head less than 100 mK/cycle. In the cold-head temperature fluctuations analysis, the cold-end has been modeled simply as a single phase ullage volume, neglecting the effect of the liquid thermal capacity and of the gas/liquid interactions (evaporation - condensation). This simplification represents a worst case analysis, to estimate the cold-head temperature fluctuations induced by the sorption compressor. The fluctuations, as reported on Figure 4, are generated by the variations in time of the pumping speed and pressure characteristics of the compressor. Both of the simplifying assumptions are intended to be overestimates and will be soon removed when a full cold head fluid-thermal model using FLUINT is incorporated.

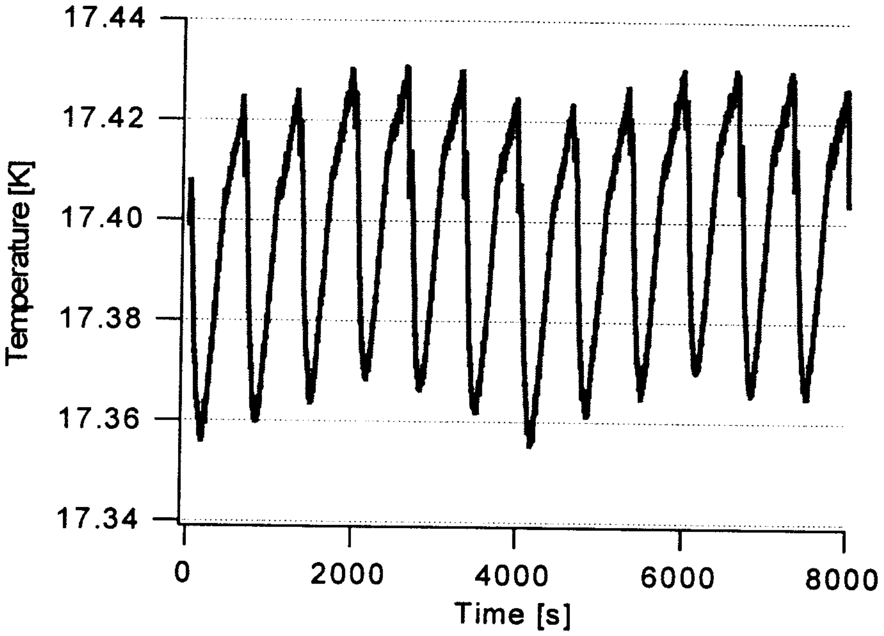

FIGURE 4. Cold head temperature fluctuations predictions derived on the variations of the pressure-pumping speed characteristic of sorption compressor.

The major contribution on the fluctuations comes from the non-linear behavior of the hydride (40 mK) and from the local fluctuations of the radiator temperature on which the compressor is mounted (as reported before, the change in temperature of absorption of one compressor element influences its pumping speed and consequently the pressure of absorption). A compressor tuning operation is needed to minimize the fluctuations derived by the gas gap actuators timing. In regular operations there are three compressor elements absorbing but, if the compressor element that is cooling time reaches the absorption temperature too soon, there will be a short period of time in which there will be four compressor elements absorbing. Conversely, if the cooling phase is longer than the cycling time, there will be a period in which there are only two compressor elements absorbing. The possibility of having more (or less) than three compressor elements absorbing for more than few seconds introduces dramatic changes in the pumping speed characteristic of the compressor and therefore larger temperature fluctuations. The low-pressure bed in fact can only take care of short term instabilities during the transition of absorbing compressor elements. The cooling phase of each compressor element need to be timed by controlling the time on which the gas gap actuator is turned on. The current design of the gas gap actuator allows a compressor cooling time of less than 450 seconds, which is less than the 667 currently chosen as the baseline cooler phase time.

Cooler Input Power

The nominal input power (excluding cooler electronics) for a heat rejection radiator temperature of 270 K is 435 W. The initial power estimate has been confirmed by the compressor element test performed at JPL. The end of life compressor power has been estimated based on the measurement of the hydride degradation due to the cycling of the compressor and an estimate of the system contaminants generated (such as water, methane, etc.). Table 1 summarized the cooler input power predictions.

TABLE 1. Cooler input power for different heat rejection radiator temperature.

POWER Load	**T-Radiator (K)**	**260**		**280**	
	BOL/EOL	***BOL***	***EOL***	***BOL***	***EOL***
Compr. Element, Heatup		201	216	179	194
Compr. Element, Desorb		150	183	154	187
Compr. Element, Gas-Gap Actuator		24	24	24	24
Low Press. Sorb. Bed		4	0	4	0
Pressure Transducers (8)		8	8	8	8
3rd Liquid Reservoir		1	1	1	1
	Total	**388**	**432**	**370**	**414**

COOLER NON-STEADY-STATE PREDICTIONS

In addition to the cold head temperature fluctuations, the other important reason for the bread board cooler test is the verification of the startup/shutdown and restart procedure. The cooler model has been very helpful also in the description and initial debugging of these procedures. During launch the hydrogen pressure in the system is designed to be below 1 atm for safety transportation reasons. When the cooler is turned on, the pressurization of the high-pressure side will be the first operation performed. Most of the hydrogen gas that will pressurize the 5 liter tank is stored in the low pressure bed that cannot directly desorb it to the high pressure levels in the tank. In fact, the low-pressure bed will desorb hydrogen in the absorbing compressor elements without compressing it. The compression is done uniquely by the compressor elements that will absorb it at 0.25 atm and desorb it in the tank. The high-pressure tank filling operation will take around three hours as shown in Figure 5. The cooler model has been useful in the determination of the low-pressure bed power profile during the startup procedure and also in the optimization of the cooler performance during the cold head (and the focal plane) cool down. The initial temperature of the J-T and the thermal mass attached to the coldhead affect the cooler startup time. Until the J-T reaches liquid temperatures the flow through it is lower than the nominal flow and therefore the cooling power produced by the cooler will be lower than its full power. This initial reduction in the flow implies that the compressor has to adjust the flow produced to avoid over-pressurization of the tanks. The flow is adjusted by gradually varying the energy supplied to the compressor element during the heat up and desorption phases. The total energy supplied to the compressor consist of the sum of the energy needed to take the hydrogen-hydride system pressure to 50 atm (sensible heat) and the energy needed to sustain the hydrogen desorption (mostly heat of reaction). If the energy supplied to the compressor is restricted to that required for heat up and pressurization, no net flow will be produced by the cooler because it would simply cool down and reject the heat inserted into it to the radiator. In other word, the compressor element simply heats up, pressurizes, cools down and depressurizes without any net flow produced.

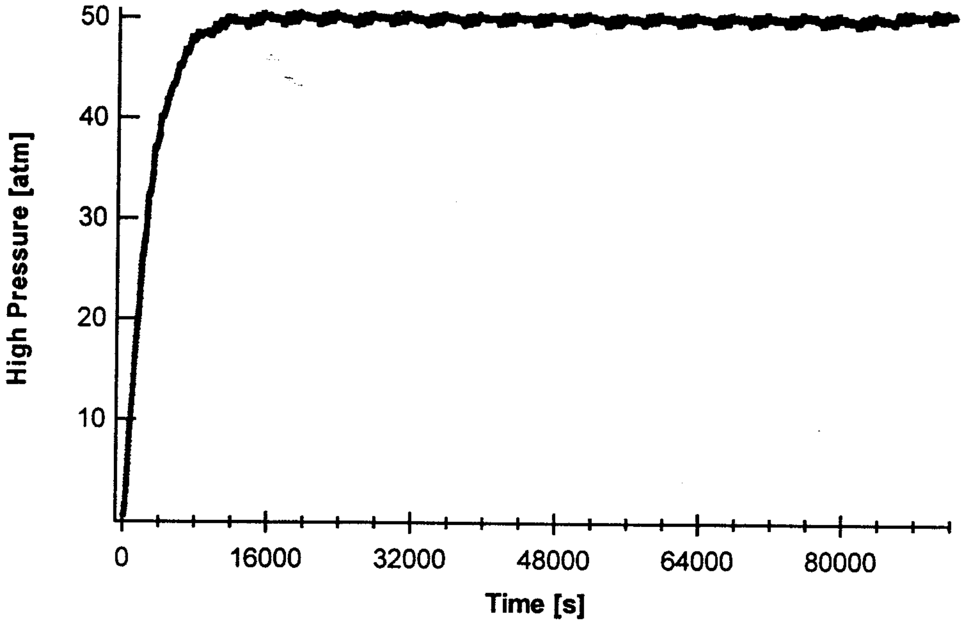

Figure 5. High pressure profile during the "cold" startup of the cooler. The prediction compressor start up time is 3 hours, while the whole cooler startup time depends on the initial temperature and on the thermal mass of the body connected to the cold-head.

This applied amount of energy can thus be restricted by appropriately shortening the phase time during which the same nominal power is applied. This cooler operation, called the "safe mode", can be compared to a neutral gear of an car, where the engine is running and ready for the command to start moving the car. This state will be introduced to let the compressor idle while troubleshooting any cooler malfunctions to restart the cooler after the problem has been resolved (i.e. defrost clogged J-T orifice, troubleshooting anomalous transducer's reading etc.).

CONCLUSIONS

The sorption cooler model presented in this paper has been demonstrated to be a powerful tool in the prediction of the cooler performance and in the understanding of the highly synergistic behavior of such coolers. Many cooler component models have been validated during the initial component test. The overall system behavior in terms of cold head temperature oscillations, start up, shutdown and restart procedures will be verified in the upcoming months during the engineering breadboard cooler tests.

ACKNOWLEDGEMENTS

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