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Abstract

This paper discusses the thermal modeling activities as a design and development tool for the Tracker Thermal Control System, the mechanically pumped, carbon dioxide thermal management system for the AMS-2 Silicon Tracker. Main modeling topics are: radiator sizing and condenser development, set-point control and pre-heating issues with respect to the spatial and temporal temperature gradient requirements of the Tracker.

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1 Alpha Magnetical Spectrometer

The Alpha Magnetic Spectrometer [1] is a sensitive particle detector designed to search for cosmic anti-matter, dark and missing matter, with an accuracy orders of magnitude better than was possible before. AMS-2 will operate on International Space Station (ISS) for three to five years, collecting billions of high-energy protons and nuclei.

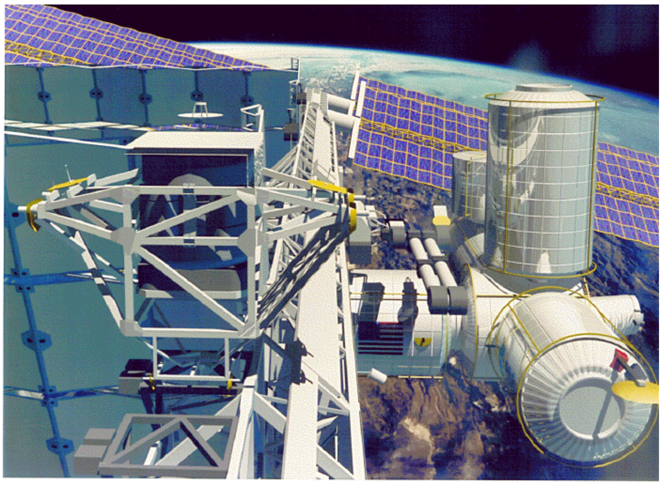

Figure 1 AMS on its location on ISS

A predecessor of AMS-2, AMS-1 flew aboard the shuttle Discovery on STS-91 in 1998. This early experiment confirmed the main concepts of the project and provided important ideas for improvement. For the AMS-02 mission a refurbished AMS, slightly different in concept, better in resolution, with a much more powerful, super-conducting magnet will be taken up to ISS.

1.1 AMS-02 layout

The AMS-2 collaboration, headed by Nobel prize laureate prof. S.C.C. Ting of the Massachusetts Institute of Technology and supported by the US Department of Energy and NASA, consists of collaborators from many academia and research institutes from all over the world.

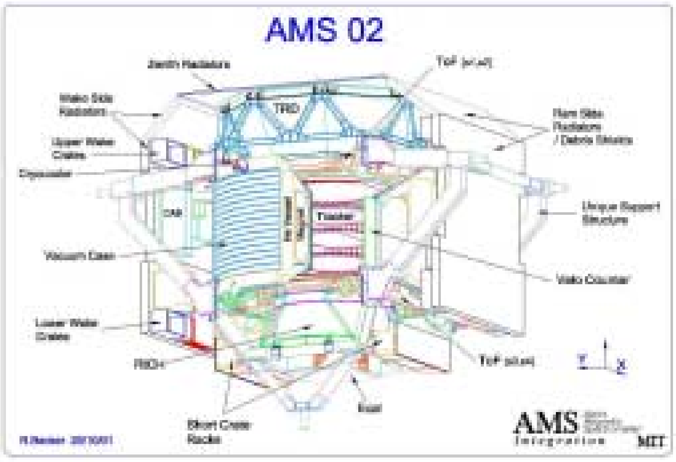

Figure 2 The AMS sub-detector layout

Each of these institutes is responsible for, or contributes to, parts of the AMS subdetectors (Figure 2):

- Transition Radiation Detector (TRD)
- Time Of Flight (TOF)
- Silicon Tracker
- Anti-Coincidence Counter (ACC)
- Ring Imaging Cherenkov Counter (RICH)
- Electromagnetic Calorimeter (ECAL)

1.2 Silicon Tracker

The Silicon Tracker, located in the center of AMS, inside the liquid helium cooled, super-conducting magnet, determines the trajectories of the charged particles in the magnetic field by measuring the (x,y) positions in six planes (z) of silicon micro-strips. The trajectories are used to deduce the momentum and charge sign of the particles detected. The loss of energy in each plane yields the charge magnitude of the particle.

Thermal requirements

For the AMS-Tracker it is of importance that the silicon strips of the several planes are within the specified temperature gradient (Table 1 and Table 2). The silicon strips do not dissipate heat, the AMS-Tracker heat is dissipated in the read-out electronics, which are called hybrids. In AMS-1 the hybrids were thermally well-connected with aluminum-TPG conductors (TPG=Thermal Pyrolytic Graphite) to the 2000 kg permanent magnet.

Table 1 Silicon wafer thermal requirements

Operating temperature	-10 °C < T < +25°C
Nominal operating temperature	0°C
Survival temperature	-20°C < T < + 40 °C
Temperature stability	φT< 3°C per orbit
Max. gradient between any to silicons	φT< 10°C

For AMS-2 it was decided to continue with a similar approach, only replacing the connections to the magnet with connections to a dedicated cooling loop. The hybrids cover the outer periphery of the AMS-Tracker and the silicon strips are within this enclosure. It was assumed that the thermal gradient between the silicons could not exceed the gradient over the dissipating hybrids, since they are more or less within the hybrid enclosure.

Table 2 Hybrid circuit thermal requirements

Operating temperature	-10 °C < T < +45°C
Survival temperature	-20°C < T < + 60 °C
Dissipated heat	192 W, 1 W per hybrid

2 Thermal design and thermal control

The thermal control of each of the sub-detectors of AMS-2 is handled by the sub-detector team concerned. The co-ordination, integration and interfacing between sub-detector (thermal) hardware and the development of common thermal facilities are carried out by the overall thermal design team, headed by Carlo Gavazzi Space, Italy.

2.1 AMS-02 overall thermal control

The interfacing between the Tracker and Tracker Thermal Control System (TTCS) on one side and the overall thermal system (mainly the AMS-2 radiators, Figure 3) and neighboring sub-detectors on the other, determines the thermal environment of the Tracker-TTCS combination and drives the thermal management efficiency of the TTCS.

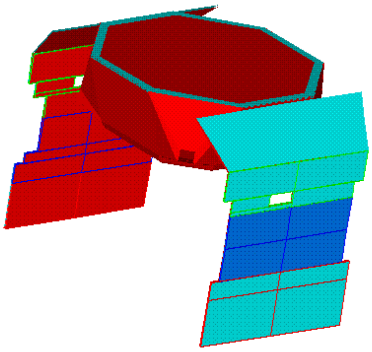

Figure 3 AMS radiators. The Tracker trapezoidal radiators are located on both Ram and Wake side, viewing outward partly in Zenith.

2.2 Tracker Thermal Control System (TTCS)

In co-operation with NIKHEF, University of Geneva and INFN Perugia, NLR is developing a mechanically pumped two-phase carbon dioxide loop for the thermal control of the Tracker. The main reason for this loop is to limit the heat rate from the Silicon Tracker towards the super-conducting magnet and save liquid helium coolant.

The cryogenic magnet surrounds the Tracker, which has rather severe spatial and temporal temperature gradient requirement (Table 1). Moreover the AMS environment is continuously changing because of orbital motion, sun, changing ISS configuration etc.

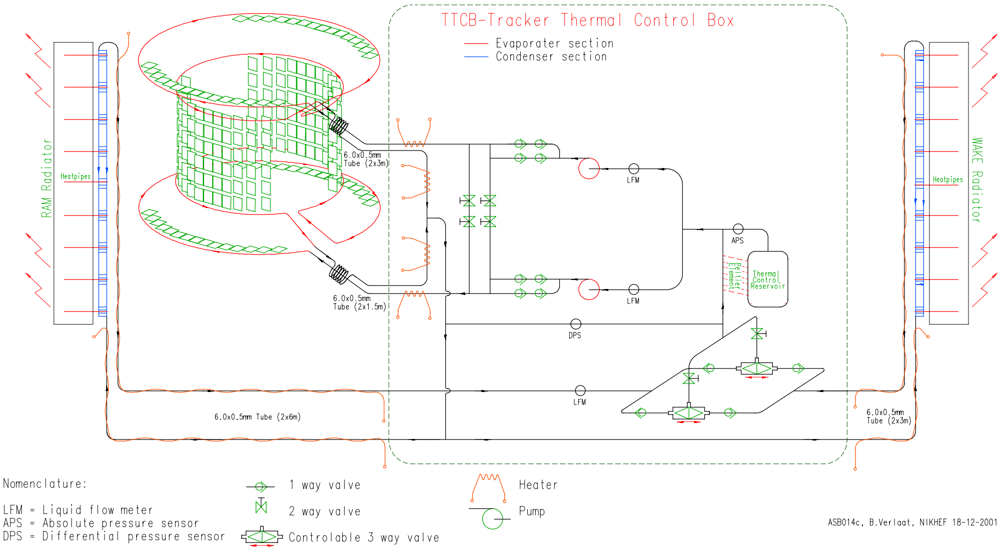

Figure 4 TTCS schematic

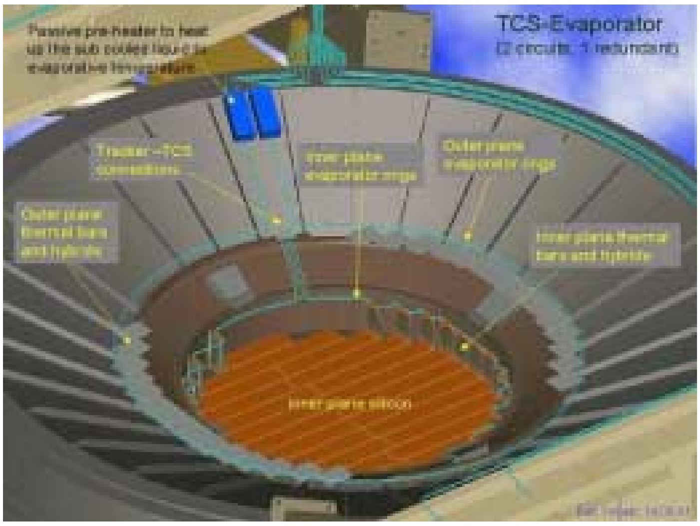

Figure 5 TTCS evaporator

Together with the existing complicated three-dimensional configuration, the severity of the specifications require the power dissipated in the Tracker (approximately 200 W) to be removed by means of an active mechanically pumped two-phase loop. The rationale behind the choice for this system is given in [2,3]. It is based on NLR's experience with two-phase heat transfer using several working fluids in various types of applications, e.g.[4,5].

Thermal bars and evaporator

As was already discussed, the hybrids are thermally connected to the TTCS evaporator (Figure 5) by means of aluminum-TPG high-conduction thermal bars

This TTCS two-phase loop incorporates two parallel long evaporators, picking up the heat from the input stations (1 or 3 Watt, depending on the number of hybrids connected) at the thermal bars distributed over the six silicon planes.

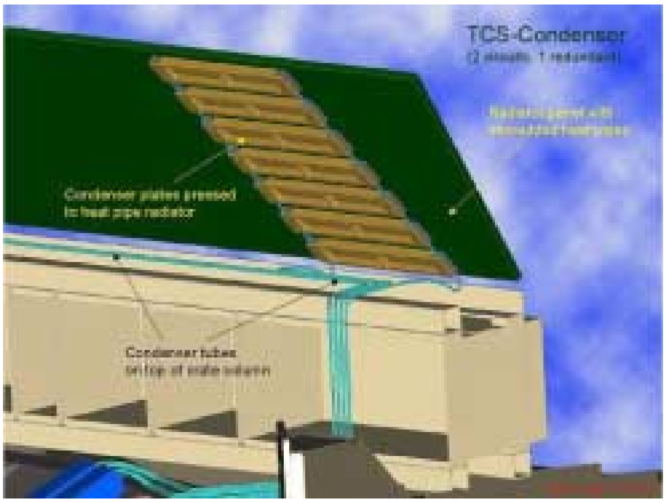

Figure 6 TTCS condensers and radiator

Condenser

After picking up the heat at the evaporators, the heat is transported to two series of parallel Multi Port Extrusion (MPE) condensers connected to a heat pipe radiator (Figure 6), either on Ram or Wake-side of AMS. Therefore the two radiators experience a different orbital environment, resulting in different temperatures and heat rejecting capabilities over time.
The liquid is transported back to the evaporator by means of mechanical pumps.

Temperature Control

The main advantages of a two-phase loop over a single-phase loop are the energy transport per pumping power and the ability to control the loop temperature accurately and approximately constant over the whole loop. The latter is necessary to meet the temporal and spatial temperature specifications (Table 1, Table 2) for the Tracker during the large orbital radiator temperature changes. The pump characteristics of available space qualified pumps demand low system pressure drops. This is the main reason that carbon dioxide is chosen as the working fluid [2,3].

Subcooling and preheating

In addition to the aforementioned basic ingredients of a two-phase loop, the TTCS also incorporates control mechanisms for sub-cooling and pre-heating.

An important pump requirement is that only sub-cooled liquid is allowed to enter the pump, to prevent it from cavitating. Therefore the radiator capacity or the loop set-point should allow some degrees of sub-cooling at the radiator/condenser exit.

On the other hand, the temporal and spatial Tracker specifications demand the fluid to enter at saturation temperature and thus the liquid needs to be pre-heated somewhere in between the pump and the Tracker. Two options are considered. The first, an electrical heater is the easiest to apply, but consumes scarce power during colder periods. Another option is a counterflow heat exchanger between the line entering and exiting the Tracker evaporator, assisted by an electrical heater. The latter also lowers the average liquid temperature and thus increases the level of sub-cooling of which an example given in this paper.

Loop set-point philosophy

The loop reservoir is equipped with a Peltier thermo-electric cell for control of the loop set-point temperature. The nominal TTCS set-point is 0°C, but if necessary the set-point will be adjusted in steps of 5°C in the range from –10 to + 15 °C. This prevents frequent, disturbances of the Tracker operating set-point temperature.

Radiator shape, size and mass

The behavior of the TTCS is largely dependent on the radiators, their location, orientation, shape, size and mass. Currently the choice for a radiator is determined by the orbital debris penetration risk, the AMS mass budget, the safety classification of the TTCS and the thermal performance. The three radiator candidates are, the ordinary heat pipe radiator, a flat radiator with heat pipes sticking out of the debris shielding on the inside and a curved radiator. The later two are depicted in Figure 7.

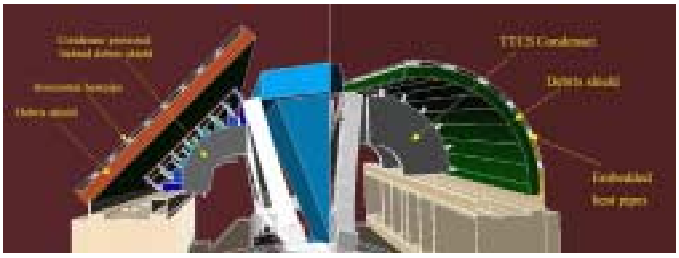

Figure 7 Flat and curved condenser concept

2.3 Thermal experiments

Apart from high-energy physics experiments, AMS serves as a platform for two-phase heat transfer experiments with the TTCS. The TTCS will be designed and prepared for in-orbit thermal research issues such as:

- Evaporator unbalance experiments
- Condenser unbalance experiments
- Control exercises
- Three-way valve control experiments
- Start up test
- Operational limits test

3 Experimental set-up

An important addition to the numerical modeling reported next is laboratory experiments. First on a small-scale test-rig both at NIKHEF and NLR [3], and now on a full scale breadboard at NLR (Figure 8).

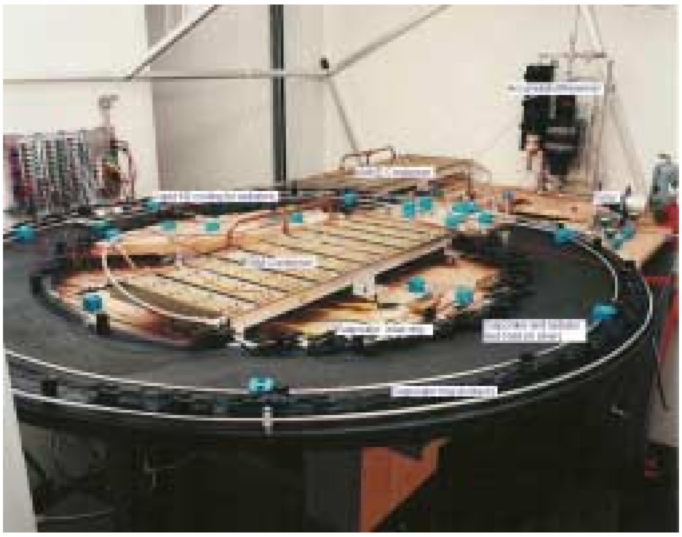

Figure 8 TTCS breadboard set-up

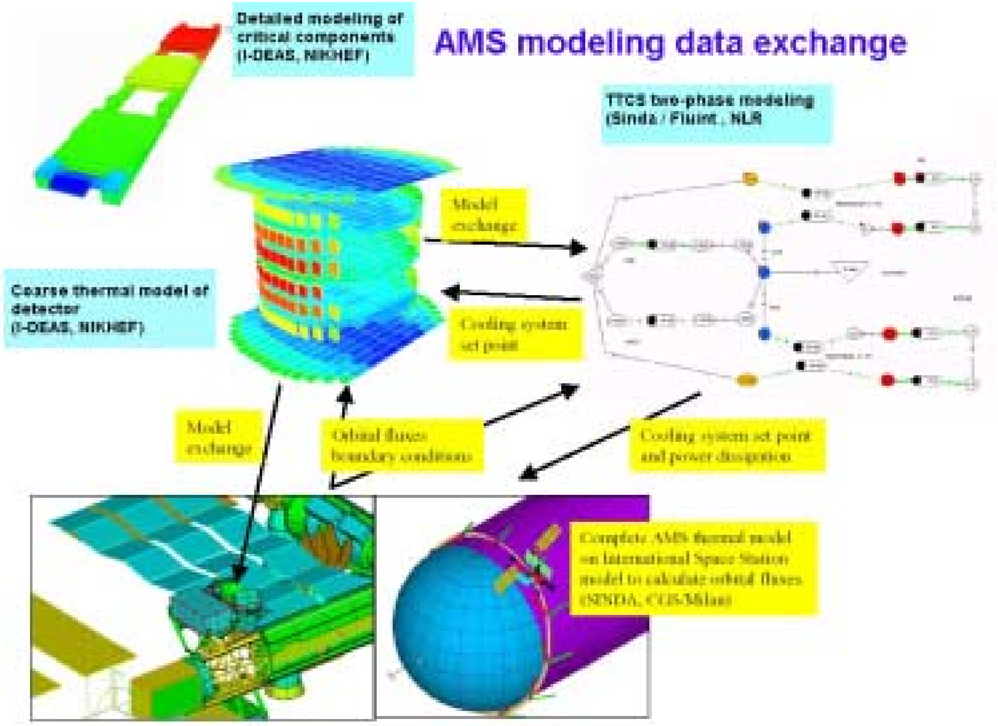

Figure 9 AMS modelling data exchange diagram

4 Numerical modelling

For the TTCS development the numerical modeling is used as design tool for sizing of the components, such as radiators, condensers and evaporators, implications of mechanical fixations, and interfaces and in combination with the different orbital cases and influence of surrounding subsystems.

In future development phases, numerical modeling will be used as a simulation tool, predicting the in-orbit operation of the Tracker and TTCS. Furthermore, simulations will be used to define Thermal Vacuum test cases and predict the Tracker and TTCS behavior during TV tests. Subsequently the TV test results will be used to validate the Tracker and TTCS numerical models.

4.1 Exchange of interface data

The thermal modeling of each of the sub-detector teams and of the overall thermal design team is brought together by thermal interface data (e.g. temperatures, thermal links and heat fluxes). The flow of these data is given in Figure 9.

4.2 Internal tracker modeling

To stay within the specified maximum gradient of 10°C for the silicons, it should be a good start to design the aluminum/TPG thermal conductors such that the hybrids will already meet this requirement. This approach should bring thermal modeling of the entire AMS-Tracker to a minimum.

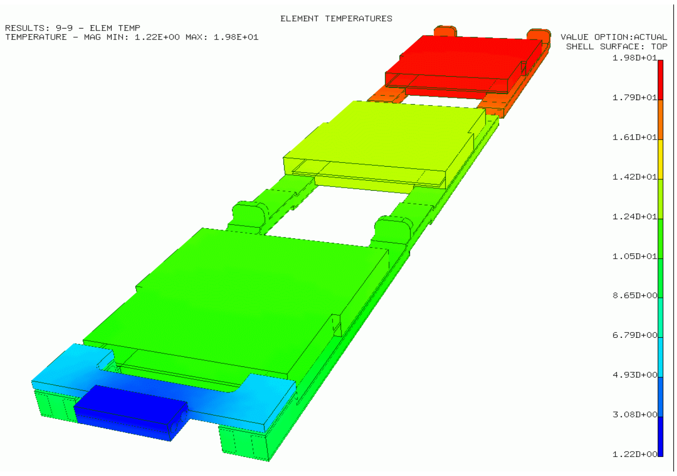

Figure 10 Thermal bar modeling result

As already remarked, the AMS-2 thermal bars are of the same configuration as the AMS-1 thermal bars. The increased power dissipation in the hybrids however needed an optimization of the thermal conductance. The thermal bars were redesigned using SDRC-Ideas11`` software. This engineering software has a thermal modeling module integrated called TMG from Maya HTT. Figure 10 shows the gradient calculation from the hybrids to the cooling loop. The calculated gradient turned out to be 8°C between the three hybrids, which is within the 10 °C requirement for the silicons.

4.3 TTCS modeling

The model consists of two coupled, separate models; a fluid and a thermal model (Fluint and Sinda). Both models use different nodal network elements, only exchanging heat. The code is a configuration of fluid and thermal submodels, which are solved simultaneously.

Flow patterns

The two-phase heat transfer coefficient is largely dependent on the type of flow. For single-phase turbulent flow, and two phase film boiling, the Dittus-Boelter correlation for the Nusselt number (Nu) is used, with different Prandtl exponents for cooling and heating (respectively 0.3 and 0.4). For laminar flow the isothermal circular Nu=3.66 and Haussen’s transition is used for a smooth connection (2000<Re<6400). For condensing two-phase flow the Rhosenow correlation is used and for nucleate boiling Chen’s correlation is used. These correlations can be found in most standard heat transfer handbooks like Rhosenow et al [6].

4.4 Simulation cases

The boundary conditions are obtained from the interface data between the TTCS and other AMS (sub) systems provided by CGS. For each representative orbit and orientation of ISS the interface data change. Whatever the orbit and ISS orientation, numerically the loop operating temperature can be, should be and were chosen such that the liquid enters the pump sub-cooled. Several cases were used to study the effects of for example the radiator area, the radiator mass and the heat exchanger to optimize the design.

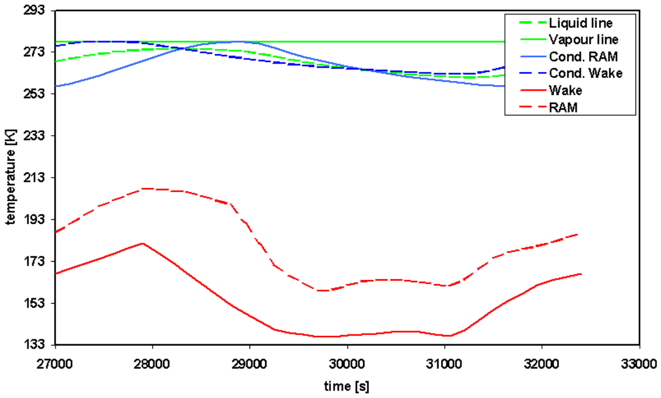

Figure 11 TTCS transient temperatures

Meeting the TTCS requirements

One of the main advantages of a two-phase loop is the extremely low spatial temperature gradient inside the evaporator. Furthermore, the temporal temperature gradient inside the evaporator is negligible even when the radiator temperatures change more than 60 K within 45 minutes periodically. This behaviour is captured within the numerical model and can be seen in Figure 11.

Effect of radiator shape, size and mass

A larger radiator area will result in more heat rejection in the colder periods and thus more preheating is necessary. Besides, in the hotter periods (radiator hotter than operating temperature) heat is added to the loop. A thermal buffer will help in these cases and of course this buffer is present in the radiator mass and the (components of) the loop.

An example of the combined effect of a larger and heavier radiator is given in Figure 12, where the liquid line temperatures for two orbits for a 13kg opposed to an 18kg radiator, are plotted.

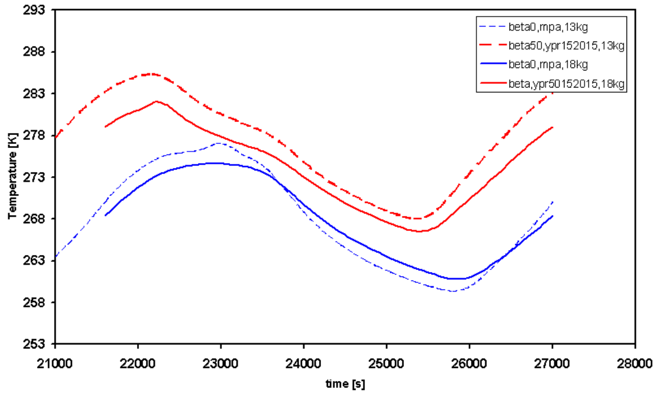

Figure 12 Liquid line temperature entering the pump: Effect of radiator mass

Heat pipe failure

As radiators are exposed to space, they run the risk, especially on the Ram-side of being penetrated by debris.

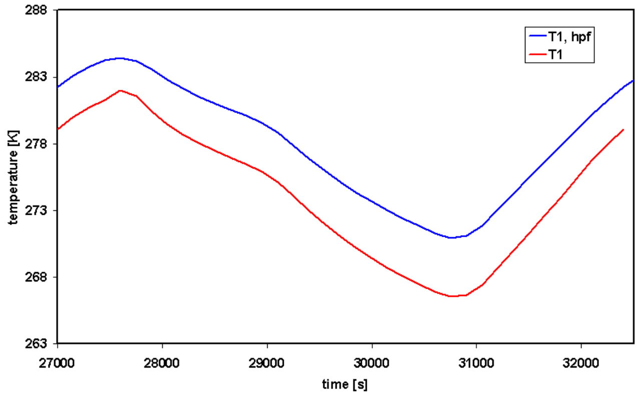

Figure 13 Typical example of the effect of heat pipe failure, because of puncture

Generally, the effect on the TTCS is that with partial functionality of a radiator, the average liquid line temperature rises and therefore the loop set-point has to be increased to prevent the pump from running dry. A typical example is given in Figure 13.

Preheating and the effect of a passive heat exchanger

As said before the effect of the HX placed between the line entering and leaving the Tracker is expected to lower the needed heater power and to lower the minimal operating temperature. This is clearly shown for б =0, MPA in Figure 14.

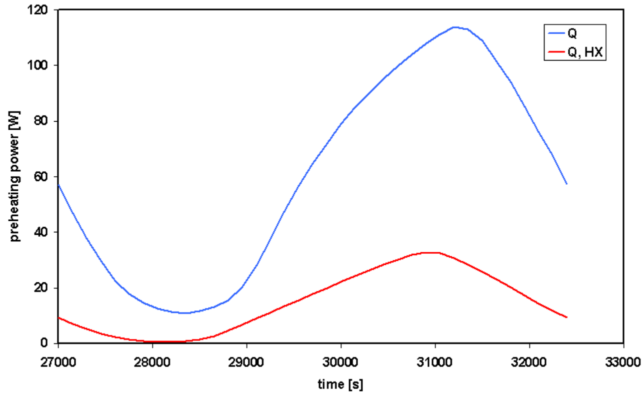

Figure 14 Influence of heat exchanger per evaporator branch

Without HX the minimum operating temperature is 278 K to ensure sub-cooled liquid to enter the pump at all times. During the coldest period a lot of heater power (approximately 110Watt, average 60 Watt) is needed.

With the HX the minimum operating temperature is 273 K and less heater power is required (max 30 Watt, average 15 Watt). Lower minimum operating temperature and less heater power are both advantages for the Tracker.

5 Conclusions

Within the AMS TTCS development, two-phase modeling has proven to be a valuable tool throughout the design process, showing the thermal effects of design options with regard to limitations in radiator space, mass and AMS power consumption, which seriously affects the operational margins of the TTCS. It supported the idea of an heat exchanger between the in-outlet of the evaporators and it helps the discussion on Tracker radiator sizes, shape and mass.

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Definitions, acronyms, abbreviations

AMS	Alpha Magnetic Spectrometer
HX	Heat eXchanger
ISS	International Space Station
NASA	National Aeronautics and Space Administration
MPA	Minimum Propulsion Attitude
MPE	Multi-Port Extrusion
NIKHEF	National Institute for Nuclear and High-Energy Physics NIKHEF
NLR	National Aerospace Laboratory NLR
TPG	Thermal Pyrolytic Graphite
TTCS	Tracker Thermal Control System