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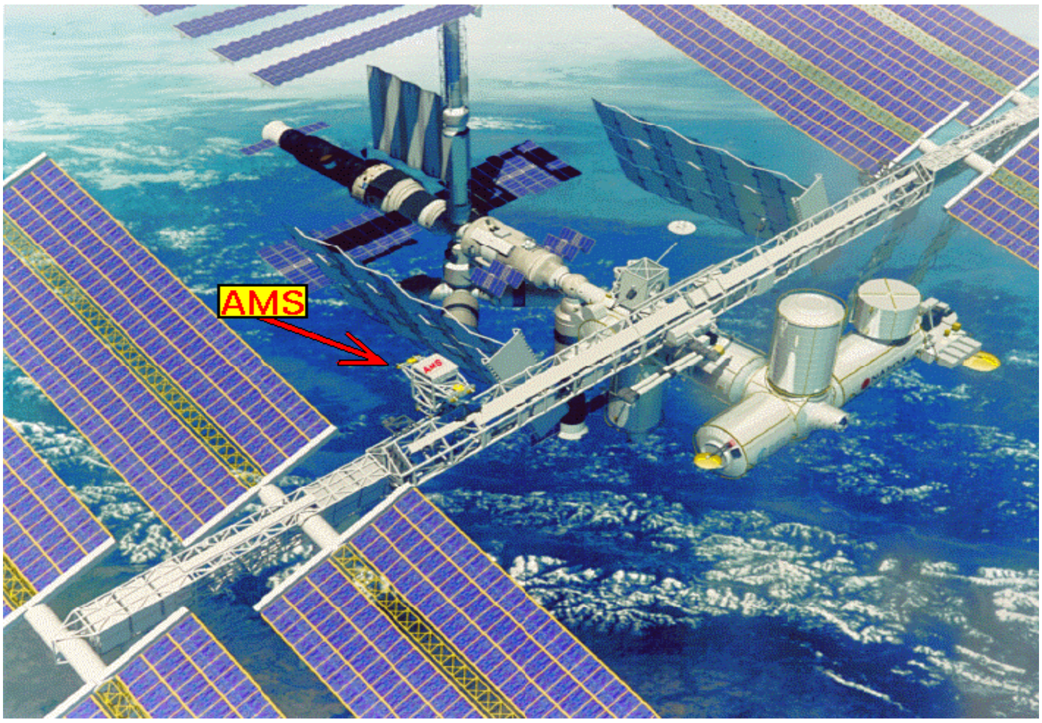

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Abstract. The Alpha Magnetic Spectrometer AMS-2, planned for a five years mission as attached payload on the International Space Station ISS, is an international experiment searching for anti-matter, dark matter, and missing matter. AMS-2, an improved version of AMS-1 flown on STS 91, consists of various particle detector systems, one of these being the (Silicon) Tracker. The trade-off based choice and the experimental feasibility demonstration of a mechanically pumped two-phase CO_2 cooling loop for the Tracker is discussed in detail. Ongoing and planned development activities are indicated.

BACKGROUND

The international Alpha Magnetic Spectrometer experiment AMS (Viertel, Capell 1998) is a particle detector for high-energy cosmic rays. It consists of several sub-detectors: The (Silicon) Tracker, the Time of Flight (ToF) system, the Veto Counters, the Transition Radiation Detector (TRD), the Synchrotron Radiation Detector (SRD), the Ring Imaging Cherenkov Counter (RICH), and the Electromagnetic Calorimeter.

The detectors operate in a magnet field generated by a super-conductive magnet, which is responsible for curving the particle tracks necessary for charge identification. Its scientific goal is to detect anti-matter, dark matter and lost matter. The project leader is Nobel Prize laureate S.C.C. Ting of the Massachusetts Institute of Technology. The collaboration, supported by the US Department of Energy and NASA, includes about 40 participants from (all over the world) academia and research institutes (Viertel, Capell, 1998). AMS-1, containing a very heavy solid permanent magnet instead a super-conductive magnet, was a demonstration flight on STS-91. Fig. 1 depicts the various experiments in the AMS-2 configuration.

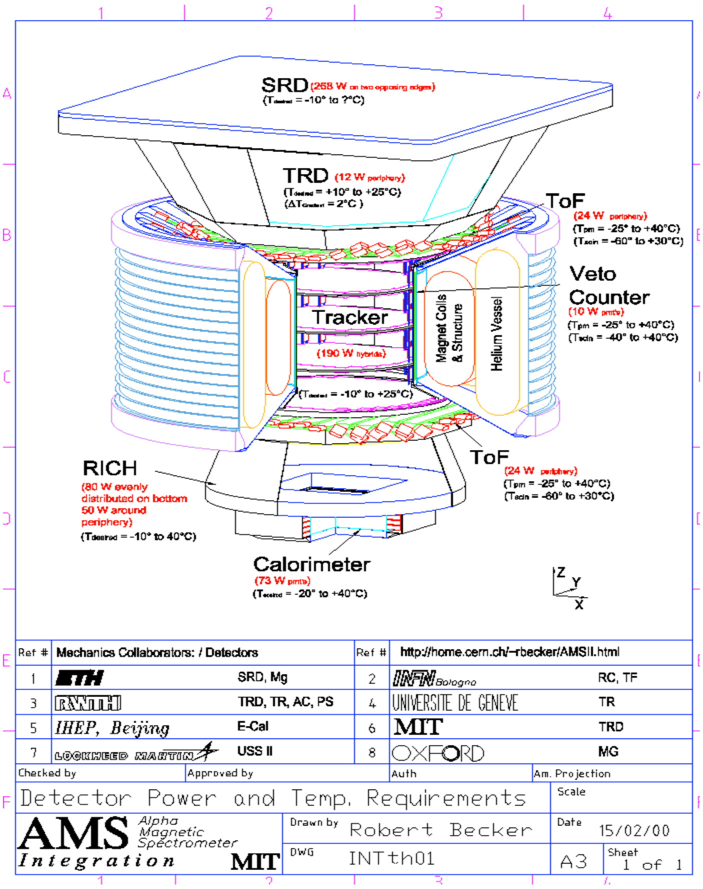


FIGURE 1. The Different AMS Experiments.

The thermal issues of AMS-2 are far more demanding and critical than in AMS-1, because of the replacement of the heavy (high thermal capacitance) magnet by a liquid Helium cooled super-conductive one, and by the very long (five years) mission duration. Therefore a team consisting of NIKHEF, NLR and the University of Geneva started early 2000 to develop a cooling system for the most critical part, the Tracker, the so-called TTCS (Tracker Thermal Control System).

This paper presents the requirements and discusses the trade-off between different cooling options, which led to the choice of a mechanically pumped two-phase thermal control loop concept, and its working fluid Carbon Dioxide. It describes the results of feasibility and some performance tests carried out in test loops at NIKHEF. These tests focused on the waste heat collection part of the TTCS (the evaporator sections), and the heat exchanger used for the system stabilisation and power optimisation.

INTRODUCTION AND TRADE-OFF

The Tracker, located inside the vacuum case, is surrounded by the cryogenic magnet, which is not allowed to receive any heat from inside. Moreover the Tracker has rather severe requirements regarding spatial and temporal temperature gradients. This and the existing complicated three-dimensional configuration, requires that the power dissipated in the Tracker (192 W) has to be removed to two thermally speaking out of phase radiators (one in RAM, one in Wake direction) to be dumped into space. This could be done by a mechanically pumped two-phase loop system (Fig. 2), by a mechanically pumped single-phase (liquid) loop system, and by a capillary pumped loop system (Fig. 3). The latter system requires heat collecting heat pipes to transport the dissipations from the silicon front-end electronics to the capillary system, since a capillary system is not capable to handle evaporators (heat sources) in series. But a parallel capillary configuration (Delil, 2000) leads to unacceptable tubing sizes (length and mass), which certainly cannot be accommodated by the existing 3-dimensional Tracker configuration. Finally it is remarked that the chosen system has to be installed two-fold to guarantee the full redundancy required.

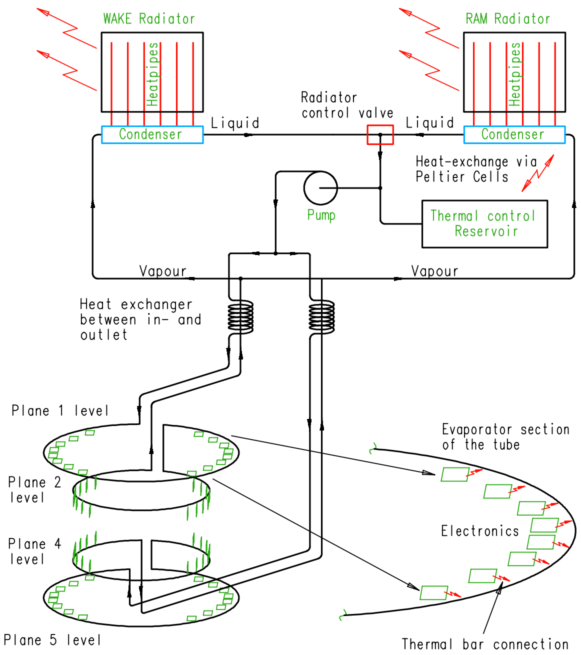


FIGURE 2. MPL Concept for Tracker Thermal Control.

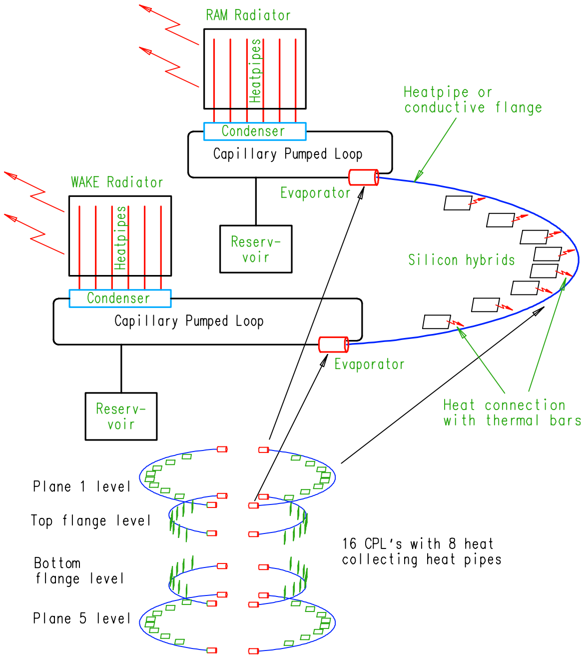


FIGURE 3. CPL/Heat Pipes Concept.

Silicon wafer thermal requirements:
- Operating temperature: -10 to +25 ºC (263 to 298 K)
- Survival temperature: -20 to +40 ºC (253 to 313 K)
- Temperature stability: 3 K per orbit
- Maximum accepted gradient between any silicon: 10 K
- Dissipated heat: 2.0 W End Of Life

Hybrid circuit thermal requirements:
- Operating temperature: -10 to +40 ºC (263 to 313 K)
- Survival temperature: -20 to +60 ºC (253 to 333 K)
- Dissipated heat: 192 W total, 1 W per hybrid pair

Keeping in mind the above requirements specifications, it can be said that:

- The series configuration two-phase Mechanically Pumped Loop (MPL) is compatible with existing Tracker hardware. It is characterised by minimal material inside or near the tracker field of view. It is directly connected to the thermal bars, hence no additional heat collector needed. Multiple source heat input is possible, with minimum temperature gradients (< 1 K). It has the possibility of implementing a fully redundant system. The costs and mass are relatively low. The only drawback is the presence of a mechanical pump in a two-phase system.
- The Single-Phase Mechanically Pumped Loop (SPL) has more or less the same layout as the MPL option, so it is relatively easy to fall back on the SPL solution, in case of unforeseen (serious) problems with the MPL development. It has the possibility of parallel and counter-current flow system set-up. It is a low-risk design, as there is sufficient experience in space with SPL's. The main drawbacks are the far larger temperature gradients (say 10 K), as compared to the nearly isothermal MPL, and the larger hardware dimension.
- Any parallel two-phase system (MPL, LHP or CPL) is not capable to accommodate the existing Tracker hardware (multiple location heat input), by it self in one stage, because of the huge mass and (not available) space needed, especially in case of redundancy. In a two-stage approach, an additional heat collector is needed: A heat pipe or a high conductivity TPG-flange. But this induces significant mass increase and also serious integration problems.

The above makes obvious that by far the best solution is the series two-phase MPL. The SPL is a possible back-up solution. The parallel concepts are non-recommendable or even impossible solutions.

Carbon Dioxide was chosen to be the working fluid because of:

- It is considered to replace Freon-like refrigerants, as it is environment friendly and non-toxic. It is used for nuclear power plant cooling, as it is inert for radioactive radiation. For AMS-2 this means no ISS safety-related problems.
- CO_2 has a very low liquid/vapour density ratio, Order (1-10), being profitable for a series 2-phase system. Its alternative, Ammonia: Order (100-1000).
- CO_2 experience was gained at NIKHEF, where tests have proven the concept feasibility of CO_2 cooling for the LHCb Vertex detector (Boer Rookhuizen, 2001). For the Tracker application, this implies small tube dimensions (3 mm OD) in case of 2 loops, very low temperature differences (< 1 K), low pumping power (< 10 W).

TTCS BASELINE CONCEPT: A REDUNDANT MECHANICALLY PUMPED CO_2 LOOP SYSTEM

The proposed TTCS is a closed two-phase system (Fig. 4). The heat is absorbed in the evaporators and rejected to space by the radiator panels at the condensers. Since the mechanical (liquid) pump provides the CO_2 flow rate needed, it has to be located after the condensers, as it needs pure liquid to operate properly. Hence the condensers/radiators need not only to condense all vapour, but also to provide at least a few degrees of sub-cooling. The blue boxes on top are heat exchangers. They connect thermally the in- and outlet of the evaporator together. In this way the absorbed heat can be used to heat the entering sub-cooled liquid from the pump so it gets close to the evaporative temperature needed in the Tracker.

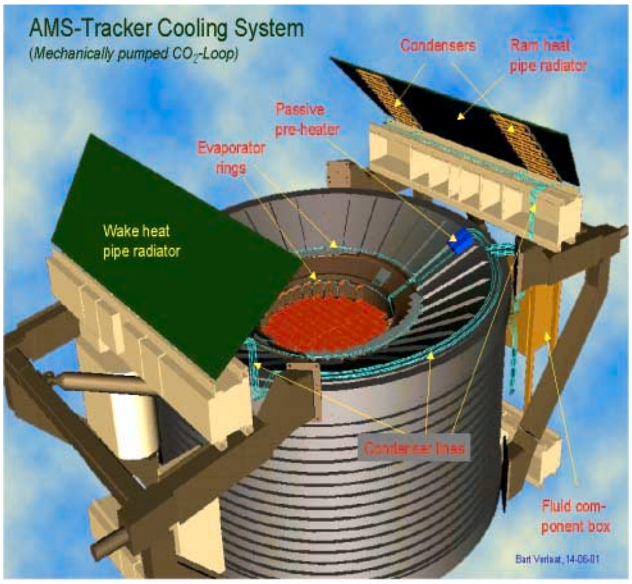


FIGURE 4. Artist's Impression of the Integrated TTCS.

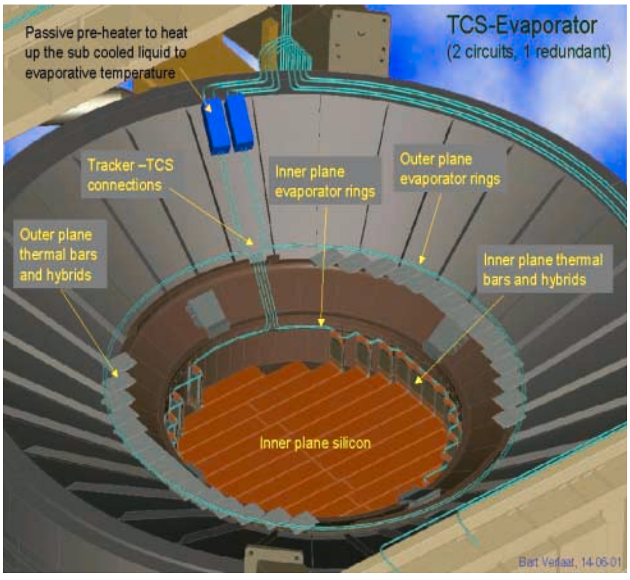


FIGURE 5. Artist's Impression of the TTCS Evaporator.

The evaporators consist of two parallel tubes each having an inner diameter of 2.6 mm and a length of 10 metres. These two tubes are serially cooling the hybrid circuits, located on the outer periphery of the Tracker. Fig. 5 shows one of the parallel evaporator branches, routed as two rings following the widely distributed Tracker hybrids. The second branch is located similarly at the bottom of the Tracker. The evaporator tube is mounted with a copper connection bridge to the hybrid thermal support structure named thermal bars. Fig. 6 shows the thermal connection from the inner thermal bars to the evaporator. Clearly visible is the bent configuration of the evaporator tube; which is needed to follow the stepped orientation of the tracker hybrid boxes. This stepped orientation is one of the reasons that a small diameter evaporator tube was selected as the baseline, because it seemed to be the only design that was compatible with the already existing tracker hardware. There are two tubes, one acts as the redundant line in the case of a failure.

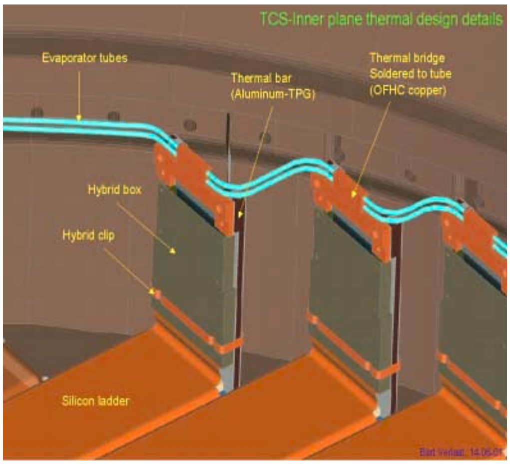


FIGURE 6. TTCS Connection to Hybrids.

The AMS radiator panels are outside the experiment (Fig. 4). They are covered with high emissivity and low solar absorptivity coatings/paints. The two opposite radiator panels are out of phase, meaning that there is always one radiator shaded from the sun, hence able to radiate waste heat to space. The evaporation temperature is set by the system pressure. This pressure is controlled via the accumulator, a small reservoir with a mixture of vapour and liquid. A Peltier element controls the reservoir temperature, hence the system pressure by condenser flooding. Most of the TTCS hardware is located in a box outside on the support structure. Only the evaporators, heat exchangers and condensers are outside this box.

TEST SET-UPS & TEST RESULTS

An open simulation test set-up (Figs. 7, 8) was built to prove the feasibility of the TTCS-evaporator with CO_2 as working fluid. The evaporator tube was connected to a liquid CO_2 filled bottle. The CO_2 flow was regulated by a needle valve, the pressure in the test tube by a spring-relieve valve (at the exit). In the TTCS all thermal bridges are individually connected to evaporator tubes. In the feasibility test heat is applied over the test section tube wall using the tube electrical resistance as heater. The pressure drop was measured by comparing the readings of the gauges P1 and P2. The temperature distribution along the tube was measured with thermocouples glued to the outside of tube. The flow was measured using a household-type gas meter, normally measuring flow in atmospheric environment. The CO_2 had to be superheated before the spring-relieve valve to prevent freezing by the expansion of the mixture.

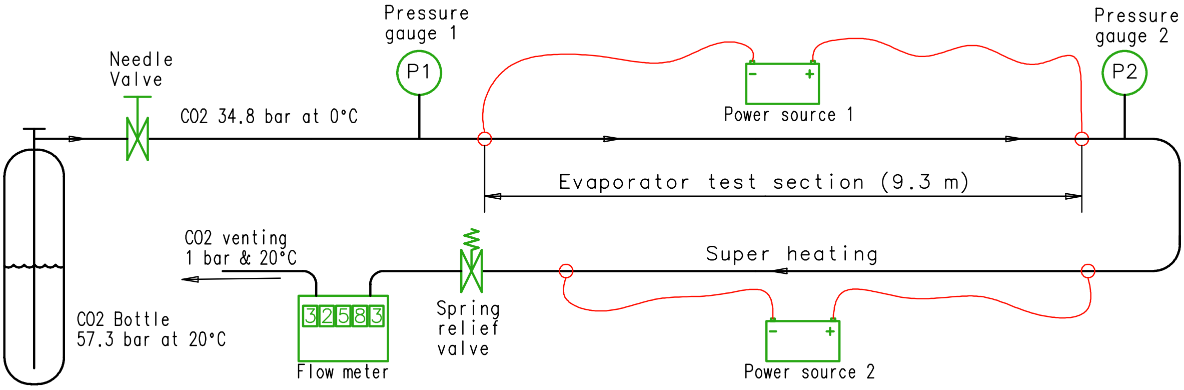


FIGURE 7. Test Set-Up at NIKHEF to Prove the Feasibility of CO_2 Cooling for the TTCS.

Fig. 9 shows the test results: The temperature drop profile dT (K, °C) along the line, for different heat inputs and flow rates. The nominal case for one evaporator branch in the Tracker is roughly 100 W at evaporation temperature 273 K. A gradient of 1 K over the tube length is allowed. In Fig. 9 it can be seen that in the measurement close to the nominal case (A1), a gradient of 0.6 K was observed. This is within the specifications. An extreme case is when all the heat produced in the Tracker has to be removed by one evaporator; which means that 200 W need to be removed. Measurement C4 shows that, even with 200 W heat input, the specifications of the Tracker are met. In reality the gradients will be less, as the fluid enters the evaporator with a vapour quality marginally above 0. Due to the adiabatic expansion, from 57.3 bar at room temperature to 34.8 bar at 273 K, the two-phase mixture in the test tube starts at quality 0.24, which yields larger pressure and temperature drops over the evaporators.

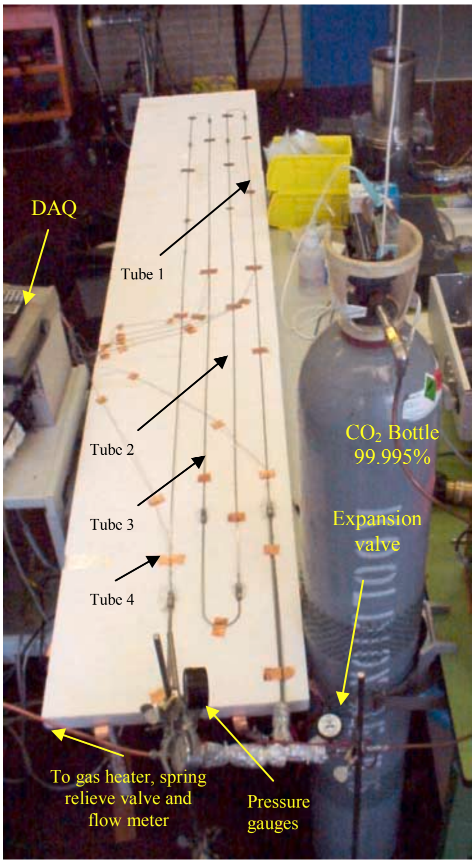
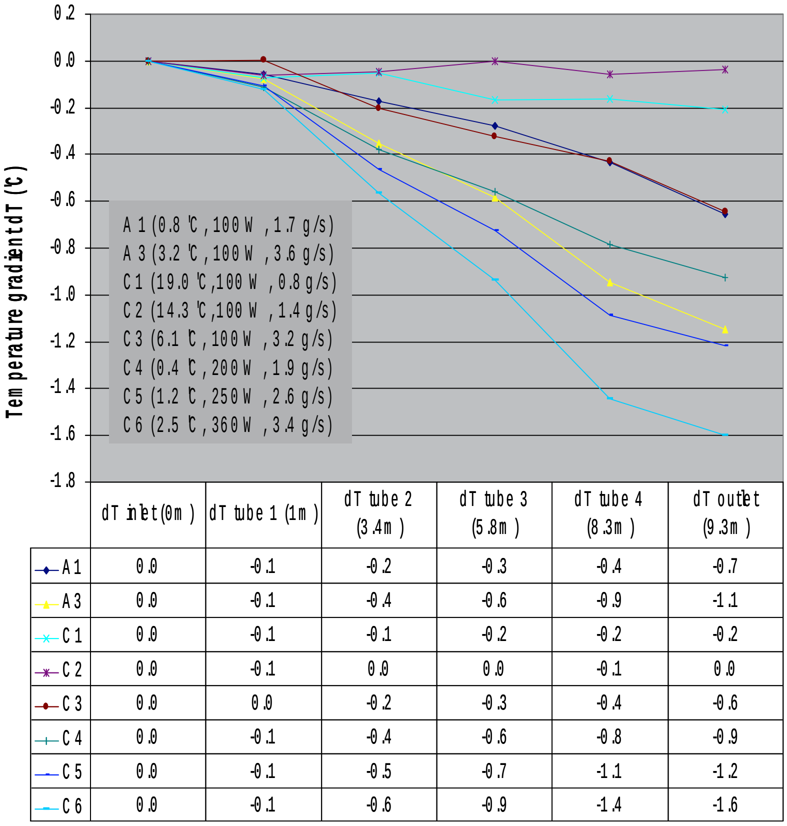


FIGURE 8. CO_2 Feasibility Test Set-Up.



	dT inlet (0m)	dT tube 1 (1m)	dT tube 2 (3.4m)	dT tube 3 (5.8m)	dT tube 4 (8.3m)	dT outlet (9.3m)
◆ A1	0.0	-0.1	-0.2	-0.3	-0.4	-0.7
▲ A3	0.0	-0.1	-0.4	-0.6	-0.9	-1.1
× C1	0.0	-0.1	-0.1	-0.2	-0.2	-0.2
✱ C2	0.0	-0.1	0.0	0.0	-0.1	0.0
● C3	0.0	0.0	-0.2	-0.3	-0.4	-0.6
+ C4	0.0	-0.1	-0.4	-0.6	-0.8	-0.9
- C5	0.0	-0.1	-0.5	-0.7	-1.1	-1.2
- C6	0.0	-0.1	-0.6	-0.9	-1.4	-1.6

FIGURE 9. Feasibility Test Results.

The results of the feasibility testing suggest that CO_2 is a good candidate refrigerant. Detailed research is being done to prove this by a built closed system simulating the real TTCS (Fig. 10). The objectives of this research are:

- To measure the pressure drop characteristics and heat transfer coefficients of CO_2 at different flow rates, heat input and evaporation temperatures, using the 10 m long, 2.5 mm ID test evaporator. Helical sections were added between the long sections to simulate the multiple bends in the real Tracker evaporator.
- To compare the test outcomes to theoretical predictions and experimental data, published by SINTEF Energy Research (Pettersen, 2000) and being produced in a recently built NIKHEF/SINTEF test set-up.
- To demonstrate the feasibility of a heat exchanger as pre-heater between in- and outlet of the evaporator.
- To yield recommendations for further TTCS development, on pumping rates and parallel evaporators.

Anticipating the started reporting of the results of the many experiments (Verlaat, Krijger, 2001), a few preliminary results on the TTCS-evaporator can be given. Fig. 11 shows pressure and temperature drops, as a function of the mass flow, at 273 K. Fig. 12 depicts the heat transfer coefficients and observed flow patterns, as a function of the vapour quality and heat flux, at 278 K and a nominal flow rate of 2.7 g/s.

Finally it is remarked that preliminary test results confirm the usefulness of the presence of a heat exchanger as pre-heater between the in- and outlet of the evaporator. It was observed that up to say 90% of the heat collected in the evaporator could be reused for pre-heating the sub-cooled liquid coming from the cold radiators. Because this amount of heat replaces part of the power to be added to the electric pre-heater that has to condition the liquid such that the fluid entering the evaporator is a pure liquid, close to saturation temperature as desired. It is obvious that the above yields a substantial power saving. Apart from this power saving impact, it can be said that the presence of the heat exchanger has also a stabilising effect on the temperature excursions of the evaporator during orbital radiator temperature variations.

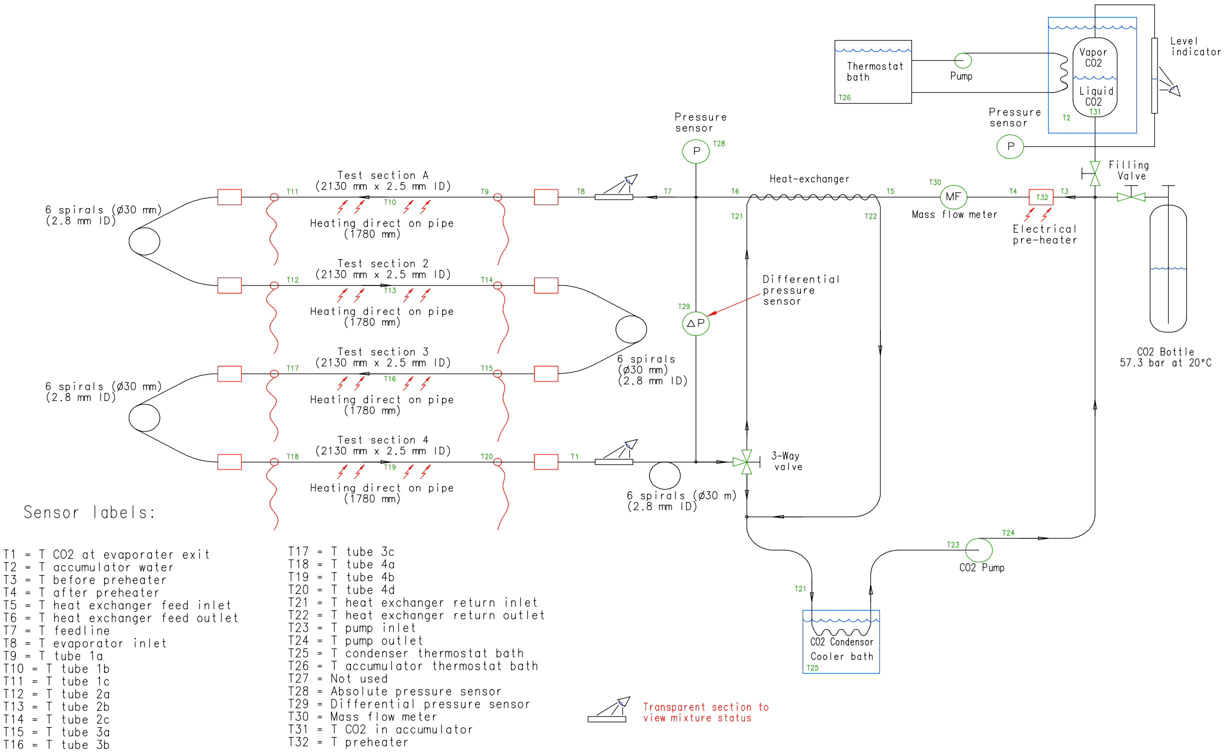
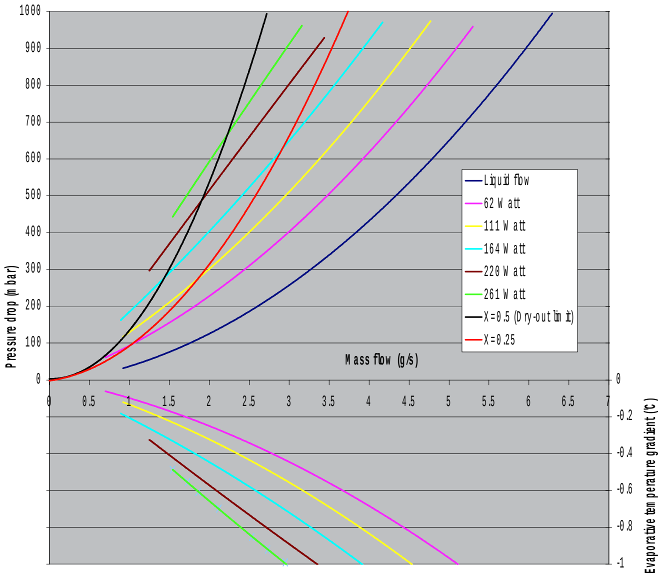


FIGURE 10. Schematic of the TTCS Test Loop at NIKHEF.



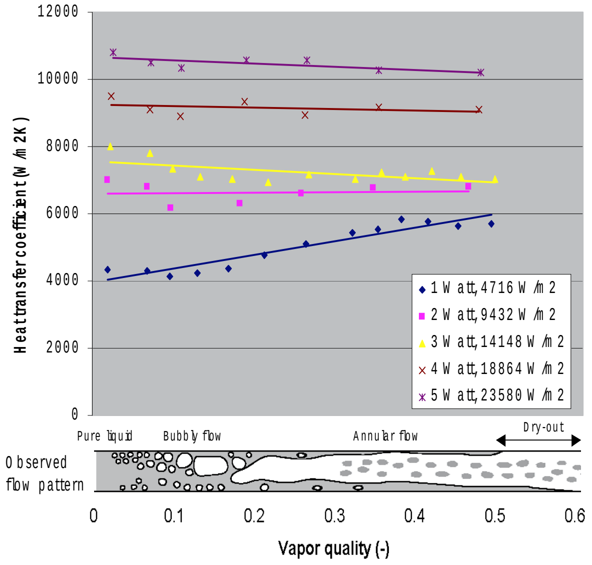


FIGURE 11. Power Dependent Pressure/Temperature Drops for a 10 m long, 2.5 mm ID Evaporator at 273 K.

FIGURE 12. Vapour Quality and Power Dependence of the Heat Transfer Coefficient and Observed Flow Patterns, for a 2.5 mm ID Tube, at a Flow Rate of 2.7 g/s and a Temperature of 278 K.

CONCLUDING REMARKS

In conclusion it can be remarked that:

- According to trade-off considerations, the better solution for the AMS-2 TTCS is the concept of a redundant mechanically pumped two-phase CO_2 thermal control loop. It consists of two parallel branches collecting the dissipated heat in serial evaporators, and transporting it to the condensers at the AMS-2 Wake and RAM radiators.
- The first test series in the NIKHEF blow-down CO_2 test set-up confirm the feasibility of the above concept.
- The results of preliminary experiments in the NIKHEF rig, that simulates the sizes and geometry of the real TTCS (focusing on evaporator parts), are in line with the envisaged pressure/temperature drop characteristics and heat transfer coefficients. They also confirm the expected positive impact of the presence of the heat exchanger between the inlet and outlet of the evaporator.

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