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National Aerospace Laboratory NLR

NLR-TP-2013-313

AMS02 Tracker Thermal Control Cooling System commissioning and operational results

J. van Es, A. Pauw, H.J. van Gerner, Zh. He, B. Verlaat, C. Gargiulo and E. Laudi

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Executive summary

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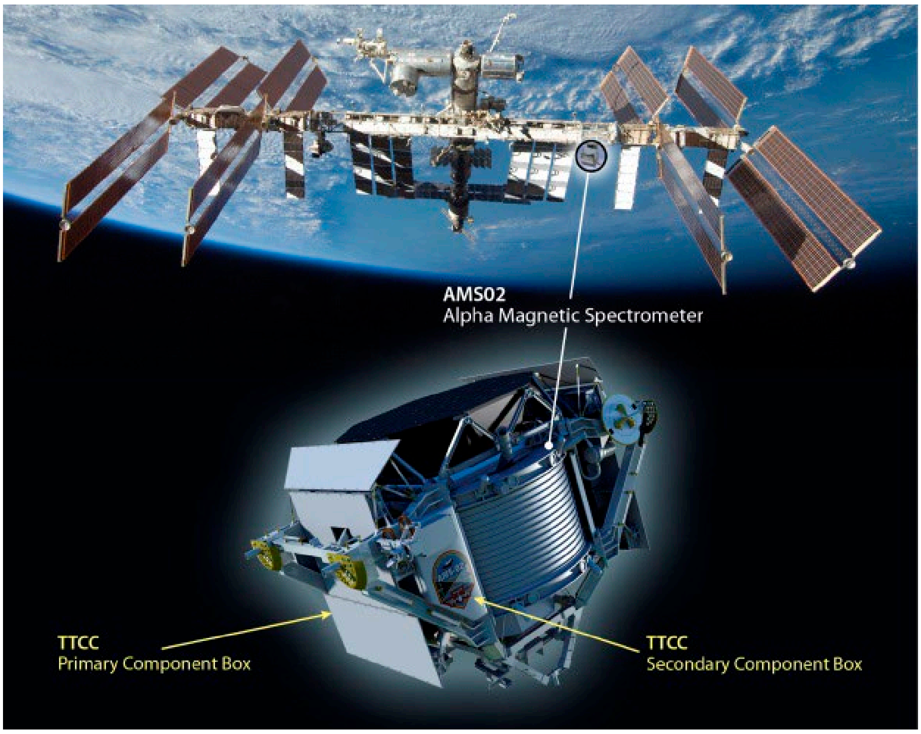

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Knowledge area(s)
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Satellite Thermal Control
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Problem area
The AMS02 Tracker Thermal Control System (TTCS) is a two-phase cooling system developed by NLR (The Netherlands), INFN Perugia (Italy), Sun Yat Sen University, Zhuhai (China), Aerospace Industrial Development Company (Taiwan) and NIKHEF (The Netherlands). The TTCS is a mechanically pumped two-phase CO_2 cooling loop used for accurate (< 3 K) thermal control of the AMS02 Tracker instrument. The TTCS is part of the Alpha Magnetic Spectrometer (AMS-02) experiment a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station launched with space shuttle STS-134 on 16 May 2011. The TTCS basically consists of a mechanically pumped two-phase loop, where 140 Watt heat is collected at two evaporators routed along the Tracker front-end electronics deep inside the AMS02 detector. The heat is transported to two radiators where it is rejected to deep space.

This report is based on a paper presented at the International Conference on Environmental Systems (ICES2013) inVail Colorado, July 14-18, 2013.

Description of work
The paper first briefly describes the loop with emphasis on the TTCS adaptations after the AMS02 TV-test. Subsequently the in-flight start-up sequence and commissioning results are presented. Also some operational features like hot switch between primary and secondary TTCS are presented.

Results and conclusions
Results show that TTCS operates flawlessly in space. The paper ends with a short summary of advantages and drawbacks of two-phase pumped technology for space applications

Applicability
Two-phase cooling systems are applicable for aerospace and industrial electronics cooling requiring accurate temperature control.

ICES Conference
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Summary

The AMS02 Tracker Thermal Control System (TTCS) is a two-phase cooling system developed by NLR (The Netherlands), INFN Perugia (Italy), Sun Yat Sen University, Zhuhai (China), Aerospace Industrial Development Company (Taiwan) and NIKHEF (The Netherlands). The TTCS is a mechanically pumped two-phase CO_2 cooling loop used for accurate (< 3 K) thermal control of the AMS02 Tracker instrument. The TTCS is part of the Alpha Magnetic Spectrometer (AMS-02) experiment a state-of-the-art particle physics detector designed to operate as an external module on the International Space Station launched with space shuttle STS-134 on 16 May 2011. The TTCS basically consists of a mechanically pumped two-phase loop, where 140 Watt heat is collected at two evaporators routed along the Tracker front-end electronics deep inside the AMS02 detector. The heat is transported to two radiators where it is rejected to deep space. The paper first briefly describes the loop with emphasis on the TTCS adaptations after the AMS02 TV-test. Subsequently the in-flight start-up sequence and commissioning results are presented. Also some operational features like hot switch between primary and secondary TTCS are presented. Results show that TTCS operates flawlessly in space. The paper ends with a short summary of advantages and drawbacks of two-phase pumped technology for space applications.

Contents

Nomenclature

AIDC	=	Aerospace Industrial Development Company, Taiwan
AMS	=	Alpha Magnetic Spectrometer
APS	=	Absolute Pressure Sensor
DPS	=	Differential Pressure Sensor
ESA	=	European Space Agency
HX	=	Heat Exchanger
INFN	=	Instituto Nazionale di Fisica Nucleare, Italy
LSS	=	Large Space Simulator at ESTEC in Noordwijk, The Netherlands
MIT	=	Massachusets Institute of Technology
NIKHEF	=	National Institute for Subatomic Physics, The Netherlands
NLR	=	National Aerospace Laboratory, The Netherlands
P	=	Primary
S	=	Secondary
SERMS	=	Laboratory Study of Radiation Effect on Materials for Space application, Italy
SYSU	=	Sun Yat Sen University, Peoples Replubic of China
TTCB	=	Tracker Thermal Control Box
TTCS	=	Tracker Thermal Control System
T	=	Thermostat
TV	=	Thermal Vacuum
USS	=	Unique Support Structure

1 Introduction

The Tracker Thermal Control System (TTCS) is part of the Alpha Magnetic Spectrometer (AMS02), a spaceborne detector for cosmic rays built by an international collaboration, lead by Nobel prize laureate S.C. Ting. AMS02 has been launched on May 16 2011 with the STS-134 mission of the Space Shuttle Endeavour for a 10 year mission on aboard the truss of the International Space Station (ISS), collecting several billions of high-energy protons and nuclei[1]. The main goal is to search for cosmic antimatter, for dark matter and lost matter. The heart of the AMS02 experiment is the Silicon Tracker. It measures particle trajectories through AMS's strong magnetic field. In a magnetic field, charged particles do not move in straight lines, but rather in arcs. A particle with positive charge will bend in opposite direction than a particle with negative charge. The higher the particle's momentum, the smaller the deflection.

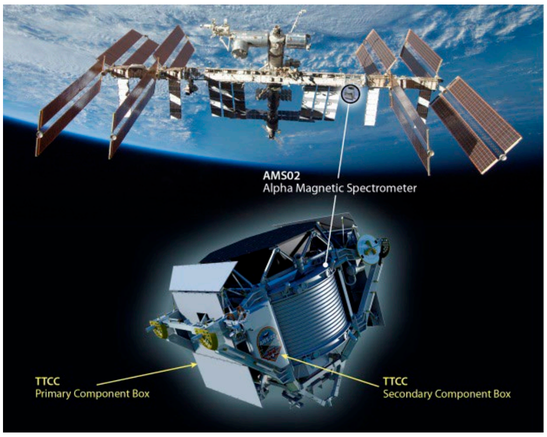


Figure 1: AMS02 Location on ISS (picture by NASA)

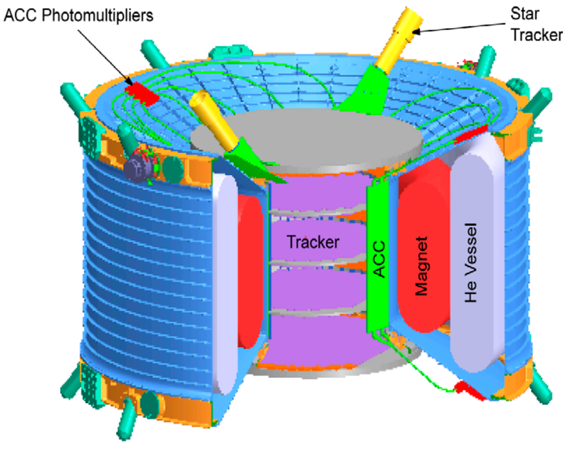


Figure 2: The heart of AMS02 with Silicon Tracker (picture by R. Becker MIT)

The tracker consists of eight large, thin sheets of silicon. The silicon sheets have millions of tiny aluminum stripes on them; each stripe generates an electrical signal when struck by a particle. By looking at the hits on all eight planes, it is possible to follow the track of the particle by combining the hits on the several planes.

Around the 8 silicon planes detecting front-end electronics are located. These dedicated electronics provide the accurate measurements (10 microns) needed. To achieve this accuracy the electronics need to be stable in temperature (< 3 K) while dissipating 144 Watt of heat. This temperature stability combined with the stringent requirement to use a minimum of metal inside the magnet lead to the development a dedicated mechanically pumped two-phase CO_2 cooling loop. Conventional space thermal hardware and working fluids would lead to large metal structures inside the magnet which is detrimental to the AMS02 experiment[5].

2 Tracker Thermal Control System

The TTCS is a mechanically pumped two-phase carbon dioxide cooling loop collecting the heat from the inside of the Tracker and transporting it to two dedicated Tracker radiators on top of the AMS02 experiment as schematically shown in figure 3. The layout of the TTCS-loop is shown in Figure 4. In Figure 5 the schematic is shown with pictures of the main hardware. By following the loop routing the loop operation is explained. At the pre-heaters stage the working fluid temperature is lifted to the saturation temperature. The working fluid enters the evaporator therefore with a quality slightly above zero, ensuring a uniform temperature along the complete evaporator. Due to the widely distributed front-end electronics the evaporator consists of two parallel branches collecting the heat at the bottom and top side of the Tracker planes. The bottom branch is first routed along additional Tracker plane 6 implemented after TV testing at ESTEC[6]. Both branches collect similar amounts of heat. With an overall mass flow of 2 g/s the mean vapor quality at the outlet of the evaporators is approximately 30%. The two-phase flow of both branches is mixed and led through the heat exchanger where heat is exchanged with the incoming sub-cooled liquid. In this way the Tracker waste heat is re-used and therefore the pre-heater power could be reduced by 80%[5]. Behind the heat exchanger the two-phase line (red) is split. One branch leads to the condenser at the RAM heat pipe radiator and the other is lead to the condenser at the Wake heat pipe radiator, where the heat is rejected to space. The sub-cooled liquid of both liquid lines is mixed. In principal this flow distribution is self-adjusting[5]. The flow to the branch with the highest quality will induce the largest pressure drop.

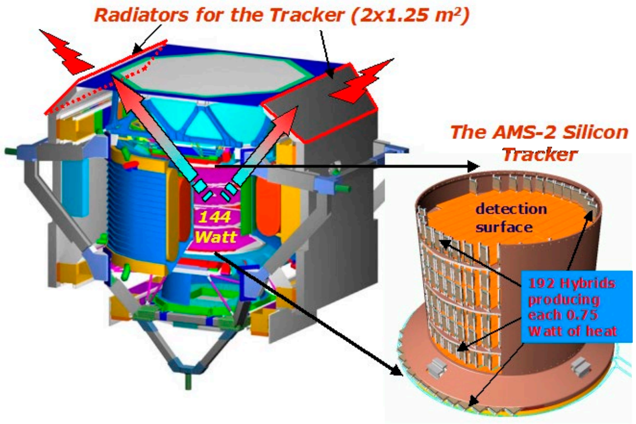


Figure 3: Schematic of the Tracker and TTCS

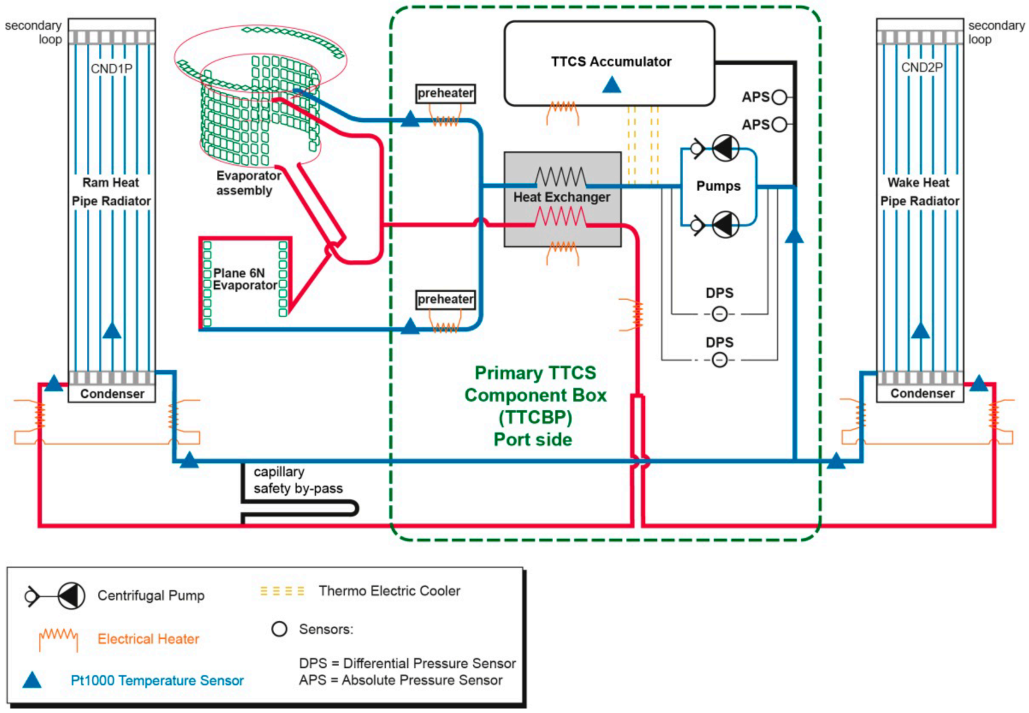


Figure 4: Simplified Tracker Thermal Control System Loop Schematic

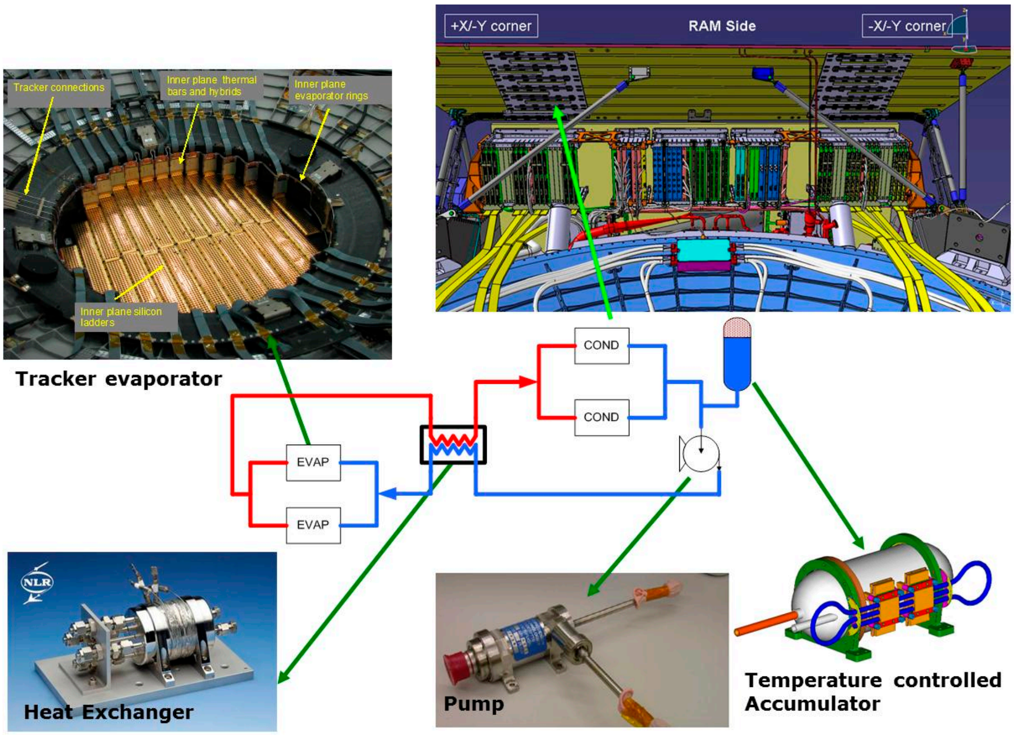


Figure 5: TTCS simplified schematic with pictures of the main components

Hence a larger part of the condenser flow will be directed to the opposite condenser branch. At the end of the condensers the fluid is sub-cooled well below the saturation point so it arrives in liquid phase back at the pump.

Downstream the pump the sub cooled liquid is pre-heated again by exchanging heat with the returned two-phase flow from the evaporator. In most cases the heat exchanger lifts the sub cooled liquid to saturation. Only in extreme cold orbits additional 8 W pre-heater power per branch is needed to create saturation.

The set-point control of the TTCS is done by the accumulator. The accumulator is the largest two-phase volume in the loop and it therefore dictates the saturation (and thus evaporation) temperature in the loop. The accumulator is controlled by heaters and thermo-electric cooling. Breadboard and TV test results showed that a stability <1K can easily be met[5,6].

2.1 TTCS Hardware

The TTCS hardware is widely distributed over the AMS02 experiment. This is illustrated in Figure 6 where the location of the TTCS hardware on AMS02 is shown. Two complete redundant systems are integrated. The primary loop is located on the port side and the secondary loop is located on the starboard side. Both systems use the same radiators to radiate the heat to deep space located on top of AMS02.

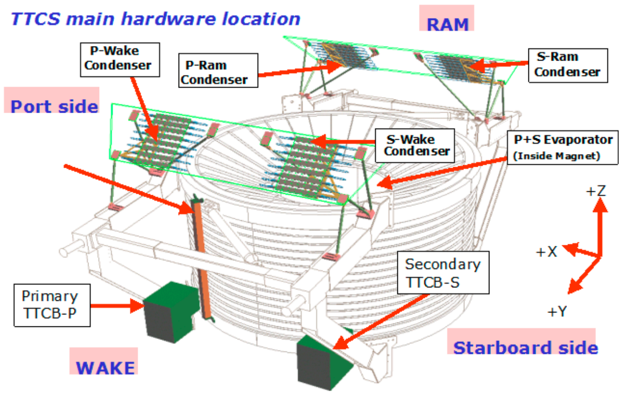


Figure 6: TTCS Hardware locations on AMS02

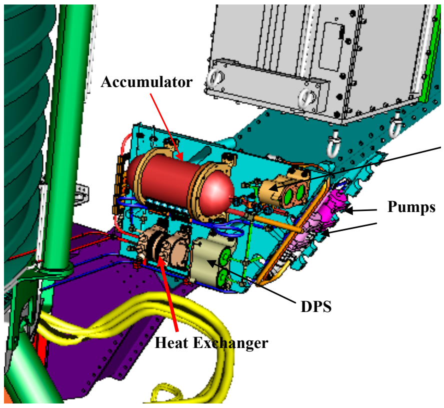


Figure 7: TTCS box on starboard side ofAMS (Picture by C. Gargiulo INFN)

2.1.1 Thermal Tracker Control Boxes

The main component boxes, called the Thermal Tracker Control Boxes (TTCB), are connected to the Unique Support Structure (USS) of AMS02. The boxes are covered in Multi-Layer Insulation (MLI) and thermally decoupled from the USS by titanium washers. A box without cover and MLI is shown in Figure 7. The main box components are indicated. Apart from the accumulator and pumps the box contains the Differential (DPS) and Absolute Pressure Sensors (APS) to monitor respectively pump health and system health. Further the TTCB contains the Heat eXchanger (HX), the pre-heaters (PR1 and PR2), start-up heater (SUP) and cold-orbit heater (COH).

During TTCS operation the temperature of the TTCB is mainly defined by the sub-cooled liquid from the condensers. In non-operational periods the TTCB slowly follows the stable temperature of the large aluminum USS structure, which always stays above -40°C to avoid CO_2-freezing. In extreme hot cases however the USS temperature can increase above the CO_2 critical temperature of +33°C. In such cases the TTCS start-up will become time consuming as the pump has to suck cold CO_2 from the condensers to the TTCB by pumping low-density vapor. To reduce the chance to end-up in such situations the pumps are located on special start-up radiators at the side of the TTCB radiating to the inside of the AMS02 Wake radiator. This ensures that the pumps have the lowest possible temperature. For the few hot cases in which the pumps will still reach supercritical temperatures a vapor start-up is possible[6].

2.1.2 Evaporator

The evaporators are located inside the AMS02 magnet and along an additional Tracker plane at the bottom of AMS02. This plane has been added after the TV-test at ESTEC and is shown in Figure 16. The evaporators of the primary and secondary TTCS run exact the same route one just above the other. In Figure 8 an overview of the inner evaporator lay-out is shown (without Plane 6). Each evaporator has a top and bottom ring which are parallel branches. The inner diameter of the evaporator is 2.6 mm and the total length is 9 m. Heat collected at the inner tracker planes is transported by thermal bars to the top and bottom evaporator ring. In Figure 9 the inner ring of the top evaporator is presented, showing the widely distribution of the tracker front-end electronics. The temperature along the evaporator should stay within a 3 °C band and the temperature difference between the inner Tracker planes and the evaporator should be smaller than 10 °C. The stability of each individual front end electronics should be better than ±3°C. The stability has been verified during the thermal vacuum test[6] and in-orbit verification results are presented in section III next page.

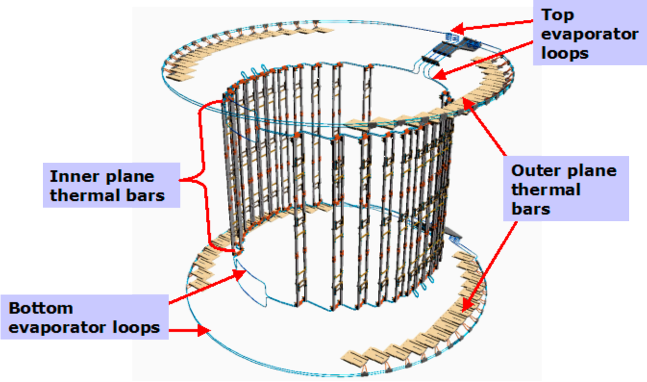


Figure 8: Evaporator lay-out with thermal bars

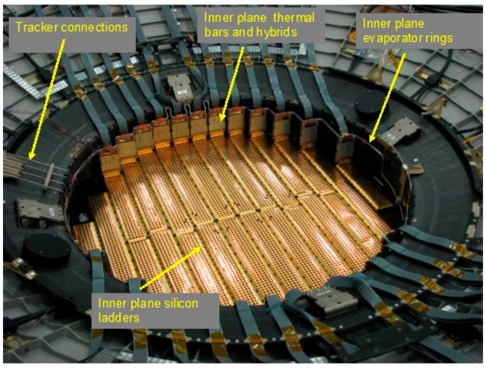


Figure 9: Top evaporator (Picture by NIKHEF)

2.1.3 Condensers

Each TTCS loop has two parallel condensers, one located on the WAKE Tracker radiator and one on the RAM Tracker radiator. The location of the condensers on the RAM heat-pipe radiators is shown in figure 10. The condensers are the only TTCS parts which can freeze. The rest of the TTCS is connected to the USS or the magnet flange which will stay above -40 °C, well above the -55°C CO_2 freezing temperature. The condenser design is shown in figure 10 and consists of 7 parallel tubes of Inconel 718 which allowing freezing and uncontrolled thawing up to -5°C with inner pressures up to 300 MPa[2]. The design can withstand 1200 MPa by design and is tested up to 1000 MPa.

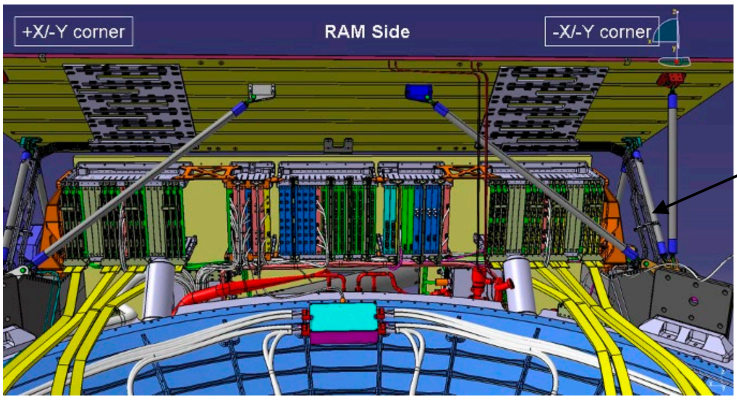


Figure 10: Condenser location on the heat pipe radiators (Picture by F. Cadoux, University of Geneva)

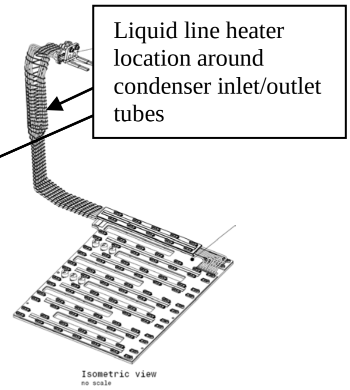


Figure 11: Condenser design (Picture by NLR)

To recover from a frozen situation, in case of a complete AMS02 power down the condenser inlet and outlet are equipped with so-called liquid line health heaters which de-frost the condensers inlet tubes from the manifolds connected to the USS until the radiator. This is to be sure that the inlet and outlet are liquid before the radiators will be de-frosted. When the liquid inlet lines reach temperatures above -40°C the radiator heaters can be switched on to also defrost the condensers attached to the radiator. The heater design is inherent safe as the radiator heaters are switched by thermostats with a set-point of -15 °C well below the maximum design temperature of -5°C. The design was verified during the TV-test at ESA ESTEC[6] including a condenser freeze/thaw cycle.

3 TTCS Commissioning in Space

The commissioning of the TTCS in space was performed in three main steps. First four functional checks were performed on 17 and 18 May 2011 during the Space Shuttle Endeavour STS-134 flight to ISS and when docked to ISS with AMS in the Shuttle bay. This was to assure that both TTCS Primary and Secondary loop were operating according to specification commanded via the A-side or the redundant B-side of the electronics illustrated in Figure 12. The second step was the AMS transfer from the Endeavour to its final destination on ISS.

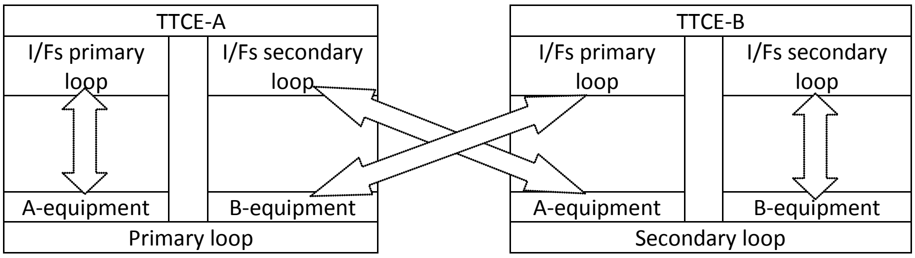


Figure 12: Operation of Primary or Secondary Loop using A or B equipment

During the transfer preparation TTCS was used to heat up the inner Tracker before AMS shutdown. From that moment on until the handover of the shuttle arm to the space station arm AMS02 cooled down. After handover to the space station arm AMS immediately got power via the space station arm. Vital AMS components were heated by a heater network to keep them above their temperature limits. The TTCS radiators were not part of this network and could therefore drop below the CO_2 freezing point. The TTCS condenser design is freeze-proof but defrosting is a time-consuming issue and therefore immediate TTCS action after AMS switch-on was required. After defrosting and heating the Tracker radiators TTCS start-up and Tracker start-up took place concluding step two of commissioning. The third and last step of the commissioning consisted of four quick functional checks to verify TTCS system health after AMS transfer and a TTCS characterization programme to verify the proper working of the TTCS set-point control and stability during induced power and pump variations. All functional checks were successful and TTCS operates without interruption since May 19, 2011.

In the next subsections a selected number of commissioning data is presented:

- Tracker radiator and TTCS condenser defrost and warm-up after AMS02 installation on ISS
- First TTCS and Tracker start-up on ISS including start of two-phase operation
- Hot switch from Primary Loop to Secondary loop
- TTCS evaporator stability during power switches

3.1 TTCS condensers de-frosting and Tracker radiator heating

The temperatures right after the AMS02 installation on the ISS truss and the locations of the Pt1000 temperature sensors are shown in Figure 13. A schematic of the TTCS-loop with temperature sensor indication is shown in Figure 15.

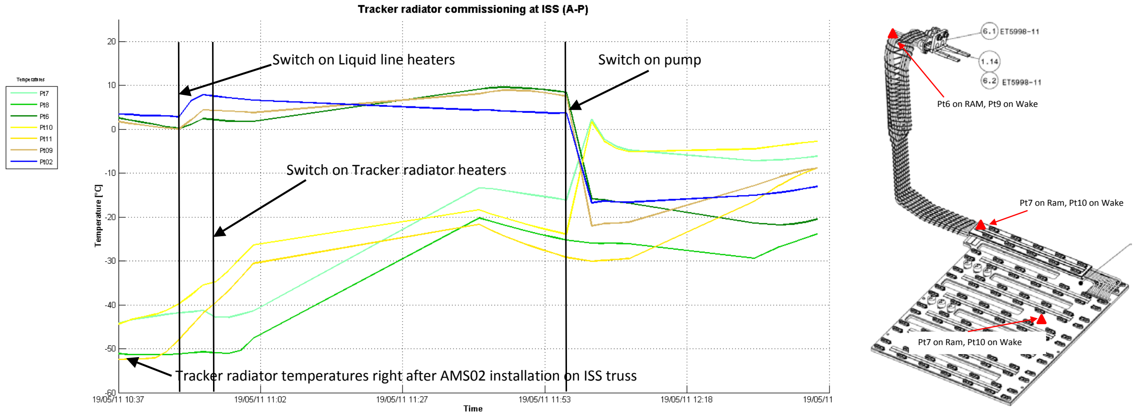


Figure 13: Left: TTCS Condenser and Tracker radiator start-up after ISS installation
Pt6, Pt7, Pt8: RAM condenser and Tracker radiator temperatures, green colors
Pt9, Pt10, Pt11: Wake condenser and Tracker radiator temperatures, yellow-brown colors
Pt2: Pump inlet temperature, blue
Right: Location of the PT1000's on the condensers

The right of Figure 13 show that the first temperatures of the Tracker radiators (Pt8 Ram, Pt11 Wake) are below -50 °C and close to CO_2 freezing (-55 °C). Therefore it was decided to start first with the liquid line health heaters to defrost any possible ice in the inlet and return lines of the condensers. Subsequently the Tracker radiator heaters were enabled raising also the RAM condenser above -40 °C into the TTCS start-up range.

3.2 TTCS and Tracker start-up on ISS

After the heating up of the condensers and the Tracker radiators the TTCS start-up sequence was started. The start-up consisted of the following steps:

1. Raise accumulator temperature to a set-point of +15 °C
2. Warm-up TTCS HX and pre-heater
3. Pump start-up
4. Tracker radiator heaters switch off and Tracker start-up
5. Lower accumulator set-point to start two-phase operation

To understand the results presented in Figure 14 the detailed loop schematic and exact temperature sensor locations on the TTCS evaporators inside the Tracker are presented in Figure 15 and Figure 16. The accumulator temperature (Pt01) is already raised to +15 °C as can be seen at the blue dotted line on the left. This is to assure that the accumulator is hotter than all parts the loop and is in a liquid state. A margin is required to avoid cavitation at the pump inlet. The last step before pump start-up is pre-heating the heat exchanger and the pre-heater sections to avoid cold liquid from the radiators enters the Tracker. During nominal operation the start-up heater automatically switches on when the liquid flow to the evaporator (pt04) drops below -20 °C. The start-up preparation is then finished and the pump is started. TTCS is then running without heat load and with the Tracker radiators switched on. The Tracker inlet temperatures (Pt04 and Pt05) are at +2 °C and the TTCS operates in stable operation. Next the Tracker radiator heaters are switched off immediately followed by Tracker switch on.

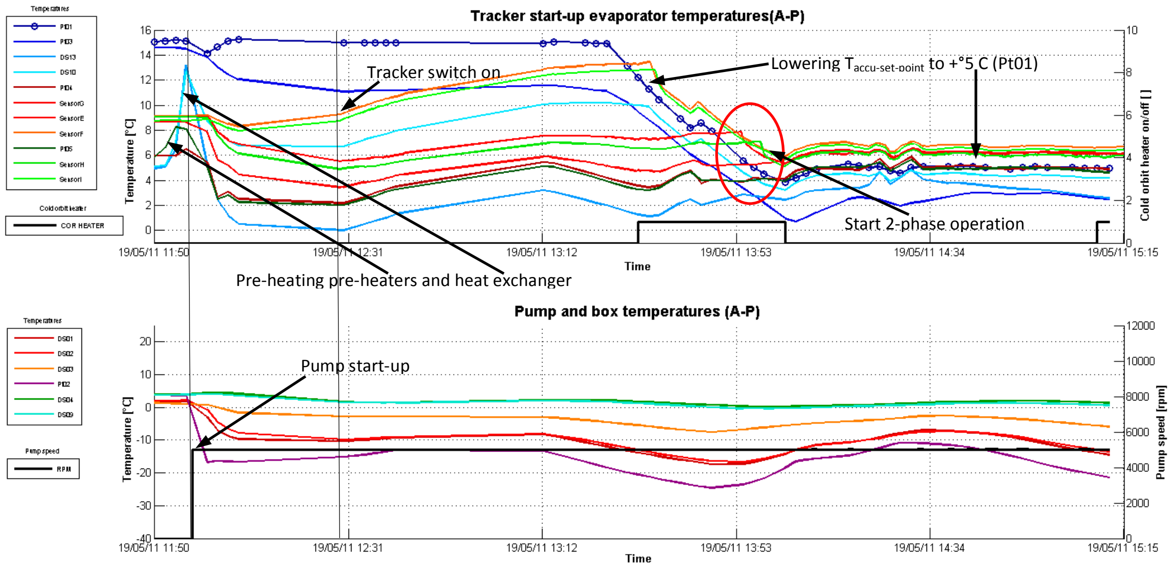


Figure 14: TTCS start-up, Tracker switch on until two-phase operation
Top graph: Bottom evaporator branch: green lines, Top evaporator branch: red lines
Accumulator temperatures blue lines, (Pt01 is accu control temperature)
Pt04 and Pt05, pre-heater temperatures, DS13, DS10 loop temperatures close to HX
Bottom graph: Pump speed and TTCS component box temperatures (see also Figure 15)
Pt02 pump inlet: Purple line

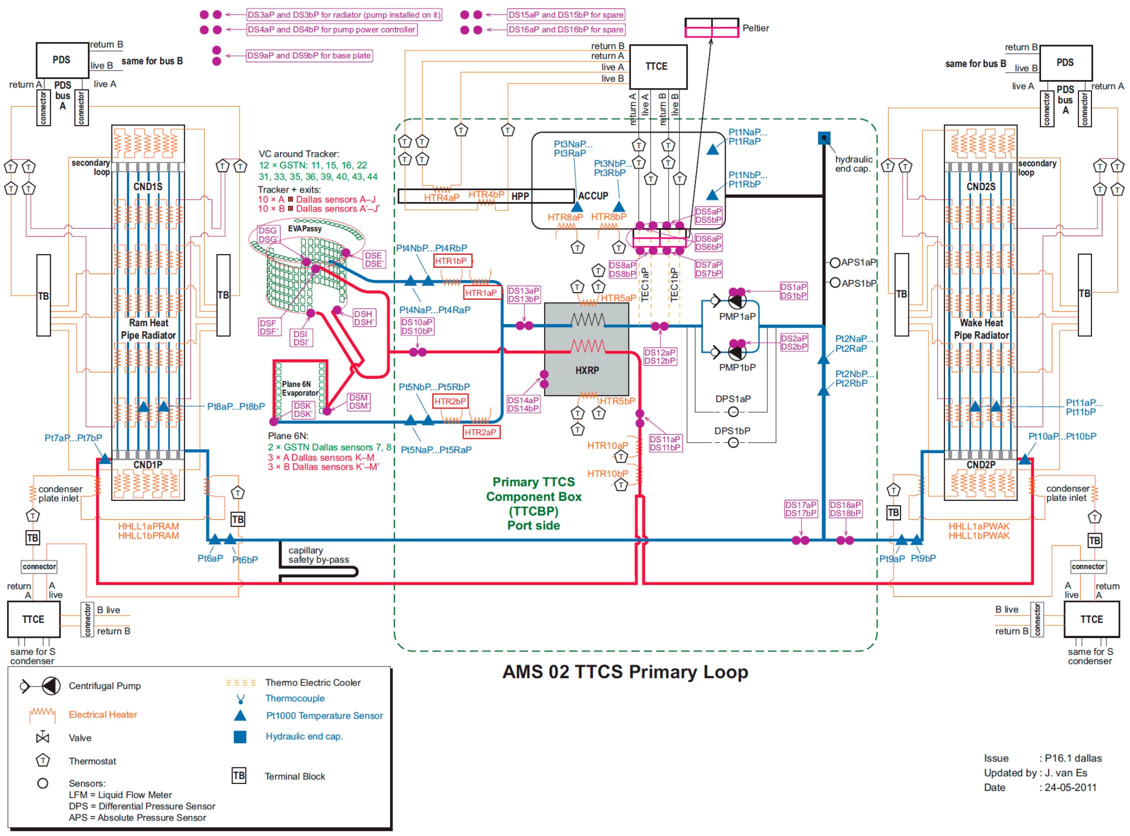


Figure 15: TTCS Schematic with temperature sensor locations

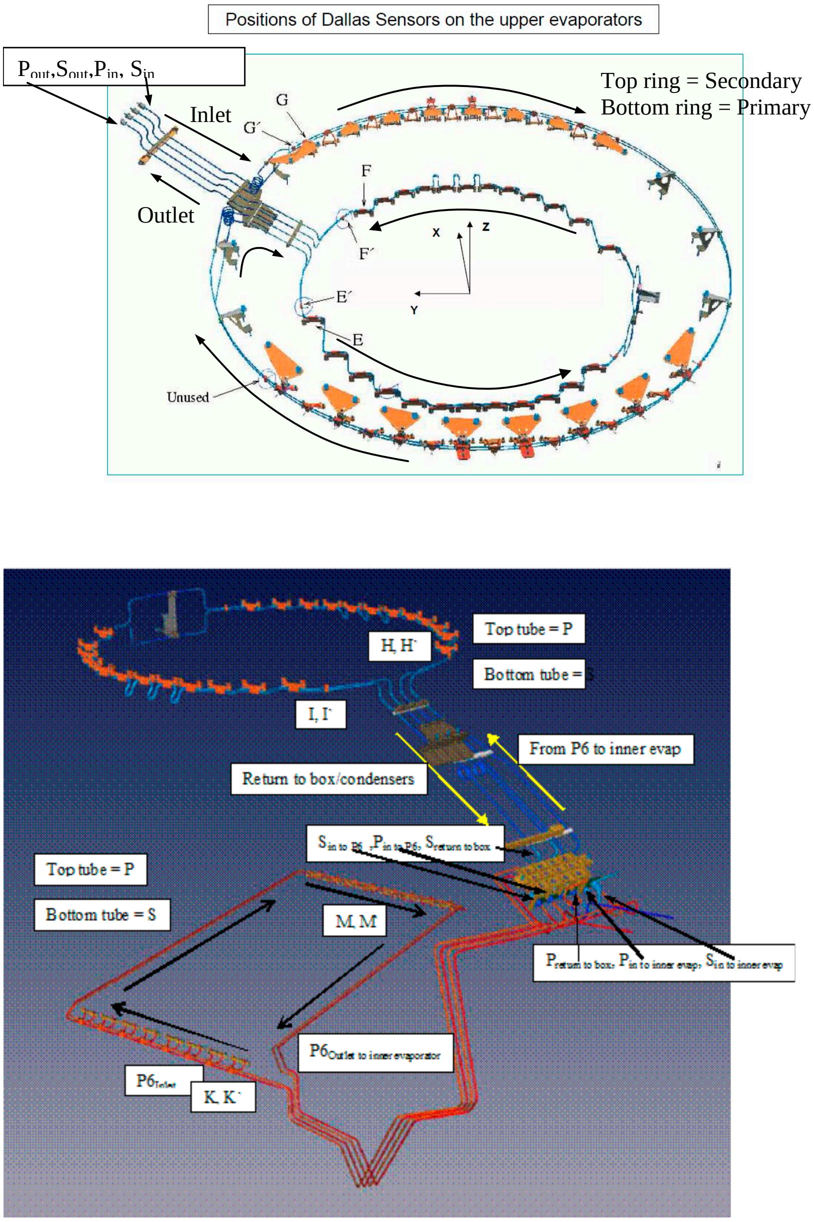


Figure 16: Physical location of temperature sensors inside the Tracker evaporators

TTCS shows typical single phase operation with the coldest temperatures at the evaporator inlets (Pt04, Pt05) and the hottest temperatures at the evaporator branches outlets (Sensor F, Sensor I). To get the TTCS in two-phase operation the accumulator set-point is lowered to +10 °C and +5 °C. Around 14:00 the Tracker temperature lines converge and two-phase operation starts. The Tracker temperatures show a small off-set to the set-point. This is because the sensors are located on copper blocks connected to the evaporator and not directly on the loop like Pt04 and Pt05. Three hours after pump start-up TTCS was in stable operation and it operates since then without interruption

3.3 Hot switch from Primary Loop to Secondary loop

Two redundant TTCS loops are integrated and both loops have redundant components (see Figure 12), therefore a total of four pumps is available of which only one is needed for operation. To equally load the pumps, the pumps are operating in shifts of three months. To not interfere with AMS Tracker science a hot switch between loops is possible this is shown in Figure 17 where a hot switch is presented from Primary-A to Secondary A.

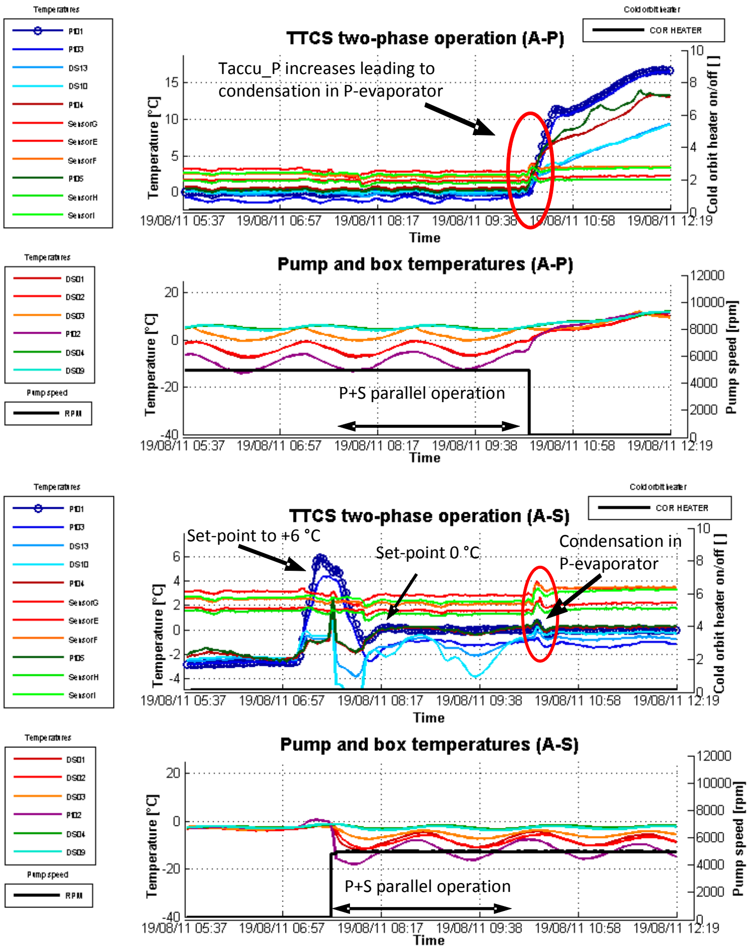


Figure 17: Hot switch from Primary loop-A to Secondary loop-A

Before switching over to the redundant (Secondary) loop the accumulator of the loop is set above all temperatures in the loop and box to +6 °C to avoid pump cavitation at start-up. When this set-point is reached the pump of the secondary loop is switched on and both loops are running in parallel. This has no impact on the Tracker evaporator stability. After all Secondary loop settings are checked the Primary pump is switched off and the operation is taken over by the Secondary loop. Right after pump switch off a 1 °C temperature spike is seen in the evaporator. This is because of CO_2 -condensation in the Primary evaporator. After this spike the stable operation is continued. The slightly different and higher evaporator temperatures are caused by the position of the temperature sensors which are closer to the primary evaporator then to the secondary evaporator resulting in a temperature off-set.

3.4 TTCS stability during power changes and pump speed changes

One of the main advantages of two-phase pumped systems is temperature stability[7] making TTCS-like systems interesting for an increasing number of applications[4]. Therefore it is interesting to see how TTCS responds to sudden power changes. TTCS nominal power is 150 W without any variation. However in cold cases additional heat is needed to keep the TTCS condensers well above freezing point. Hereto a 60 Watt cold orbit heater switches on and off. The additional heat load causes the condenser front in the condenser to shift and liquid is pushed into the accumulator. This results in an accumulator temperature increase and therefore an ±0.2 °C temperature increase in the evaporator. This is shown in Figure 18. During switch-off the effect is opposite.

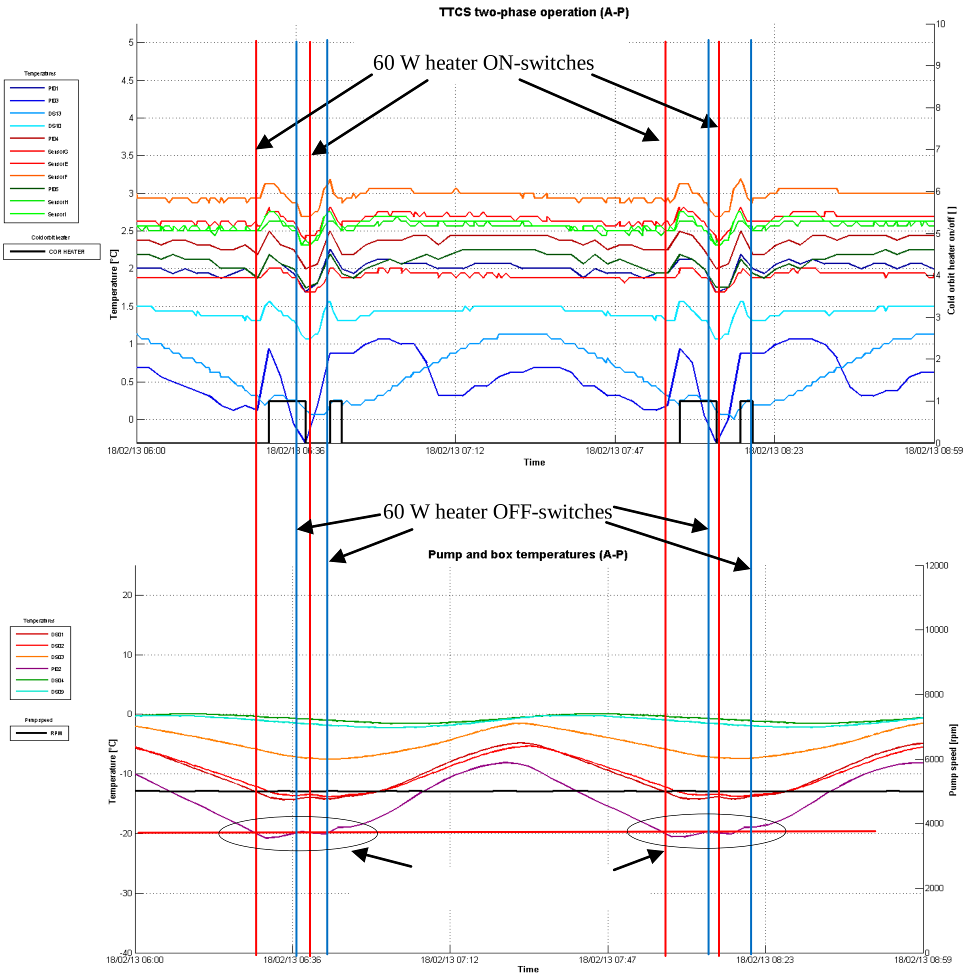
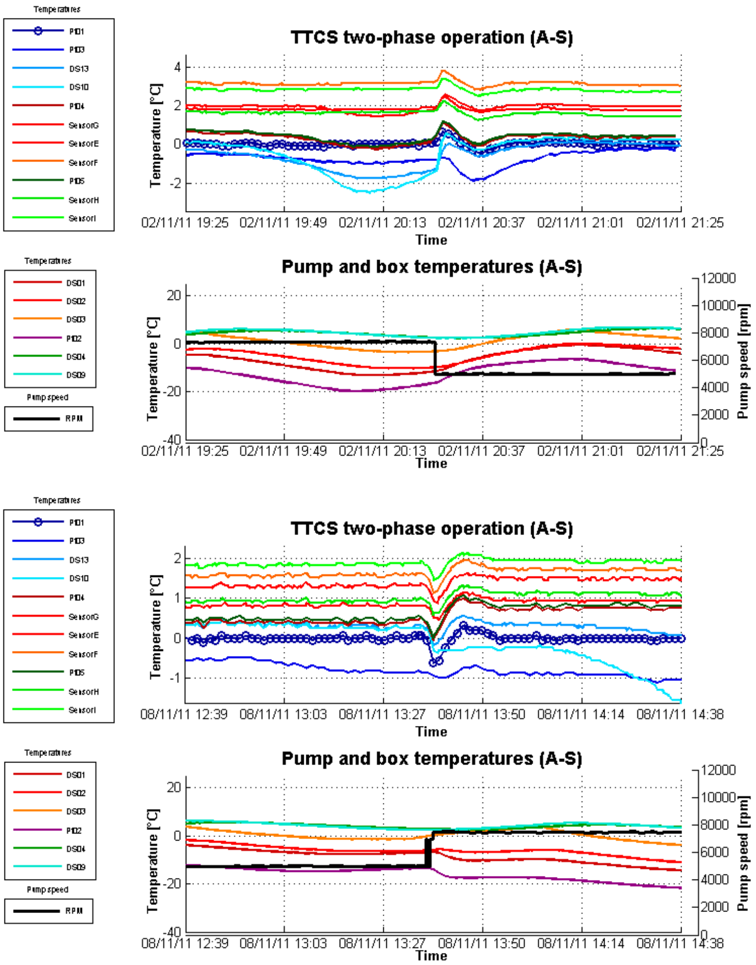


Figure 18: Temperature instabilities during a power increase of 60 Watt

Shifts in condenser and evaporator vapor quality can also occur by pump speed changes. This leads also to temperature instabilities in the evaporator as shown in Figure 19. During a pump decrease more vapor is generated in the evaporator and condenser leading to a mass flow to the accumulator and therefore accumulator pressure and accumulator temperature increase. The opposite effect is seen during a pump increase. This leads to a sudden decrease in the vapor amount in the loop and a flow of liquid from the accumulator to the loop. Because the pump speed changes change the vapor quality in both the evaporator and the condenser the effect is larger (±0.6°C) than for the 60 Watt heater close to the condenser.



Pump speed increase

Pump speed decrease

Figure 19: Temperature stability during pump speed changes.

4 Conclusions

4.1 Conclusions

An overview is given of the TTCS system as developed for AMS02 Tracker instrument. The TTCS was launched with space shuttle Endeavour STS-134 on May 16 2011. Functional checks inside the shuttle bay showed that both TTCS-loops functioned according to expectations. After final installation on ISS truss S3 the Tracker radiators were first heated and brought to operating range. Subsequently TTCS and the Tracker instrument were started up. Stable TTCS and Tracker operation was achieved after three hours and TTCS is working since May 19 2011 without interruption. Results are presented on a hot switch between primary and the redundant loop with negligible effect on evaporator stability. TTCS delivers exceptional stability (±0.2°C) during large (60 W) power changes and sudden pump changes (±0.6°C).

4.2 Benefits and drawbacks of two-phase pumped systems in space

The successful TTCS in-orbit commissioning and the flawless operation have led to more confidence in two-phase mechanically pumped systems for space applications. The main advantages of two-phase pumped cooling are the excellent temperature stability and flexibility to cool payloads with widely distributed electronics in confined enclosures[7]. The active loop components (e.g. pump, accumulator, heaters) and control electronics can be far away from the dissipative pay-load allowing compact and lightweight pay-load design. This is at the cost of using a pump which is a single-point-of-failure and requires additional mass. Due to the increasing temperature stability requirements, increasing payload power and increasing payload complexity the application of pumped two-phase technology becomes however attractive to more space applications. First applications are foreseen for active antennas but also telecommunication satellite developers look already into two-phase mechanically pumped systems as possible alternative to complex LHP-HP networks. NLR is involved in scaling up part of the TTCS technology in the ESA ARTES 5 programme. For terrestrial applications NLR further improved the TTCS technology for applications requiring extreme temperature stability.

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References

[1]AMS collaboration, "The Alpha Magnetic Spectrometer (AMS) on the International Space Station, Part I, Results from the test flight on the Space Shuttle", *Physics Reports*, vol. 366/6, pp.331-404, Aug. 2002.

[2]van Donk, G., Bsibsi, M., Pauw, A., and van Es, J., "Testing of a Freeze-proof Condenser for the Tracker Thermal Control System on AMS-02", 37th International Conference on Environmental Systems, Chicago, Illinois, USA, July 9-12, 2007.

[3]Verlaat, B., Van Lysebetten, A.,Van Beuzekom, M., "CO_2 Cooling for the LHCB-VELO experiment at CERN", 8th IIF/IIR Gustav Lorentzen Conference on Natural Working Fluids, Copenhagen, Denmark, 7-10 September 2008.

[4]Hugon, J., Larue de Tournemine, A., et al., "Development of a Two-Phase Mechanically Pumped Loop (2ΦMPL) for the Thermal Control of Telecommunication Satellites", International Two-Phase Thermal Control Technology Workshop, ESTEC, The Netherlands, 13-15 May 2008.

[5] Van Es, J., Van Donk, G., Pauw, A., Verlaat, B., Rens, C.A.M., Jaarsma, J., Brouwer, M.P.A.M., "AMS02 Tracker Thermal Control System (TTCS) design, model and breadboard results", 34th Int. Conf. on Environmental Systems, Colorado Springs, SAE2004-01-2556, 2004.

[6] Van Es, J, Pauw, A.,Van Donk, G.,Verlaat, B., Laudi, E., Gargiulo, C., He, Z., Ragnit, U., Van Leeuwen. P., "Test Results of the AMS02 Thermal Vacuum Test in the LSS at ESA ESTEC", 42nd Int. Conf. on Environmental Systems, San Diego, USA, AIAA 2012-3577, 2012.

[7] van Es, J., van Gerner, H.J., "Benefits and Drawbacks of Using Two-Phase Cooling Technologies in Military platforms" Electronics Cooling Spring, Issue March 2013, http://www.electronics-cooling.com