Title: Development of a Thermal Control System with Mechanically Pumped CO2 Two-Phase Loops for the AMS-02 Tracker on the ISS

Article Type: Research Paper

Section/Category: Special Applications

Keywords: space thermal control system, two-phase loop, design, construction, performance

Corresponding Author: Prof. Zhenhui He

First Author: Zhenhui He

Order of Authors: Zhenhui He; ZHAN ZHANG

Abstract: To provide a stable thermal environment for the AMS-Tracker, a thermal control system based on mechanically pumped CO2 two-phase loops was developed. It has been operating reliably in space since May 19, 2011. In this article, we summarize the design, construction, tests, and performance of the AMS-Tracker thermal control system (AMS-TTCS).
Development of a Thermal Control System with Mechanically Pumped CO₂ Two-Phase Loops for the AMS-02 Tracker on the ISS

G.Alberti^d, A.Alvino^d, G. Ambrosi^d, M. Bardet^d, R.Battiston^d, S. Borsini^d, J.F. Cao^b, Y. Chen^a,b, J. van Es^e, C.Gargiulo^i, K.H.Guo^b, L.Guo^b, Z.H.He^a,b, Z.C.Huang^b, V. Koutsenko^g, E. Laudi^d, A. Lebedev^g, S.C. Lee^k, T.X.Li^b, Y.L. Lin^i, S.S.Lv^b, M. Menichelli^d, J.Y. Miao^b, D.C.Mo^b, J.Q.Ni^b, A. Pauw^c, X.M.Qi^b, G.M. Shue^l, D.J. Sun^i, X.H.Sun^b, C.P.Tang^b, B. Verlaat^c, Z.X.Wang^b, Z.L.Weng^b, W.J. Xiao^b, N.S.Xu^a,b, F.K. Yang^i, C.C. Yeh^i, Z.Zhang^b, T. Zwartbol^c

\(^a\). State Key Laboratory of Optoelectronic Materials and Technologies, School of Physics and Engineering, Sun Yat-sen University, 510275 Guangzhou, People’s Republic of China

\(^b\). Center for Space Technology, Sun Yat-sen University, 519082 Zhuhai, People’s Republic of China

\(^c\). National Aerospace Laboratory NLR, Voorsterweg 31, 8316 PR Marknesse, the Netherlands

\(^d\). Università and Sezione INFN di Perugia, Laboratorio per lo Studio degli Effetti delle Radiazioni Ionizzanti (SERMS), Via Pentima Bassa 21, 05100 Terni, Italy

\(^e\). National Institute for Subatomic Physics Mechanical Engineering, Science Park 105, 1098 XG Amsterdam, the Netherlands

\(^f\). Istituto Nazionale Fisica Nucleare sez.Roma, Italy

\(^g\). Massachusetts Institute of Technology, Cambridge, MA 02139, USA

\(^h\). System Engineering Department, Chinese Academy of Space and Technology, 100094 Beijing, People’s Republic of China

\(^i\). Electronic Systems Research Division, Chung Shan Institute of Science and Technology, Lung-Tan, Taoyuan, Taiwan
j. Aerospace Industrial Development Corporation, Taichung city 40760, Taiwan

k. Institute of Physics, Academia Sinica, Taipei 11529, Taiwan

Key words: space thermal control system, two-phase loop, design, construction, performance

✉: stshzh@mail.sysu.edu.cn Fax: +86 20 84113398
Abstract

To provide a stable thermal environment for the AMS-Tracker, a thermal control system based on mechanically pumped CO$_2$ two-phase loops was developed. It has been operating reliably in space since May 19, 2011. In this article, we summarize the design, construction, tests, and performance of the AMS-Tracker thermal control system (AMS-TTCS).
Introduction

Alpha Magnetic Spectrometer AMS-02([1] [2] [3] [4]) is an astroparticle physics experiment that has been running on the International Space Station (ISS, see Fig.1) since May 19, 2011. The AMS Silicon Tracker is a sub-detector of the AMS. It is inside a Magnet, to detect charge particles, which can distinguish antiparticle from particle.

To achieve stability with a superconducting magnet providing a magnetic field of 0.87 Tesla, temperature stability of 3 °C per orbital period for the Tracker silicon wafers and their front-end electronics, with a temperature difference less than 10 °C between any of the silicon wafers. The operation temperature of the Tracker is between −10 °C to 25 °C, and the survival temperature is between −20°C to 40°C. Total dissipated heat to be carried away was about 156W, including 144 W (±10%) out of the Tracker’s 192 front-end electronics hybrids, 2W from the silicon wafer, and 10W from the Star Tracker. The life time was required to be 3 to 5 years. To meet such requirement, a mechanically pumped CO₂ two-phase-loop thermal control system (called TTCS) had been developed [5], to provide the required thermal boundaries to the Tracker to be working in a superconducting magnet. The design was verified [6].

After NASA announced to extend the life of the ISS to 2020, AMS-02 was upgraded [7] by replacing the superconducting magnet with the permanent magnet that was developed for the AMS-01, in order to extend the life. To maintain the Tracker’s resolution in the lower magnetic field of the permanent magnet, the Tracker’s configuration as well as the TTCS evaporator was rearranged [7].

In this paper, we present the design, the construction, the tests, and the performance of the TTCS.

2 Tracker thermal control system concept design

2.1 Analysis of the basic requirement

Two-phase technologies, such as heat pipes and loop heat pipes, are widely used in space thermal control. For the AMS Tracker, however, there are 166 (192 in the original design) heat-dissipating
front-end hybrids distributed around the Tracker. To collect all the heat from the hybrids, the total heat path is tens of meters long. Neither heat pipes, which are limited for high heat fluxes and long distance cooling applications, nor loop heat pipes, which are not suitable for distributed heat sources cooling applications, is applicable for the requirement. Moreover, complicate thermal environment on the ISS requires an active control system. A mechanically pumped two-phase loop system was thus proposed to meet the unique set of requirements [5].

There are strict budget mass and power for space applications. The Tracker thermal control system has 72kg and 120W for the mass and power budget respective. In addition, the evaporators, the heat collectors locate close to the detector, must be small enough to minimize secondary particles. (Such particles would mislead the detector to take them as cosmic particles.) For a certain fluid in a given flow rate, smaller tube leads to much higher frictional pressure drop \( h_f =8fLQ^2/\pi D^5 \), where \( h_f \) is the frictional head loss; \( L \) is the length of the pipe; \( D \) is the hydraulic diameter of the pipe; \( Q \) is the volumetric flow rate; \( g \) is the local acceleration due to gravity; \( f \) is a dimensionless coefficient called the Darcy friction factor, respectively). Such pressure drop must be controlled within a certain range, so that the two-phase saturated temperature in the evaporators, which is a function of the pressure, is less than 3 °C in order to provide a uniform temperature boundary. Among the common used refrigerants applicable in the required operation temperature range, carbon dioxide (CO\(_2\)) has the lowest viscosity. Calculation showed that, CO\(_2\) provides lower frictional pressure-drop as compared with ammonia and propylene, which have even wider working window, and are commonly used in space. In addition, the strict safety requirement (no release of harmful materials) for instruments on the manned space station also makes the CO\(_2\) the most suitable working fluid for the two-phase loop application.

2.2 Configuration and working principle

The Tracker Thermal Control System (TTCS) has two mutual redundant fluid-loops. Each loop contains a component box (TTCB)[8], two evaporators (top and bottom) in parallel, and two condensers (RAM and WAKE) in parallel, which are thermally contacted to the two radiators. (see
Fig. 2, with the radiators hidden for clearness). Assembled in one TTCB are one accumulator, one heat exchanger with redundant start-up heater, two redundant pumps, four redundant pre-heaters, two redundant cold-orbit heater, and pressure sensors. The basic functions of the components of the thermal control system are summarized in Table 1. The CO$_2$ driven by the pump cycles around the loop, collecting the waste heat from the evaporators by partial evaporation (converting into latent heat of evaporation), and releasing the heat in the condensers by condensing the vapor CO$_2$ into sub-cooled liquid CO$_2$. About 5 K sub-cooling is required at the pump to prevent cavitation. The condensation heat is transferred to the radiators, and then to the space. The accumulator is a fluid reservoir to compensate for the required liquid charge in the system at different heat loads as well as during transients of the thermal environments. The other function of the accumulator is to control the loop temperature. The CO$_2$ in the accumulator is in vapor-liquid two-phase state. The accumulator is connected to the loop that has low pressure drop, the pressure in the accumulator is almost the same as that in the evaporators. Therefore, controlling the saturated pressure of the accumulator is equivalent to controlling the saturated temperature of the evaporators, provided that the fluid in the evaporators is in two-phase. To insure that the fluid flowing into the evaporators is in two-phase, preheaters are used to heat the sub-cool liquid to the saturated temperature. To save heating power of the preheaters, a heat exchanger is employed between the fluid paths, in which CO$_2$ flowing in and out of the evaporators. The heat exchanger uses the two-phase CO$_2$ flown out of the evaporators to warm up the sub-cooled liquid flowing in the evaporators. It also uses the sub-cooled liquid to reduce the vapor quality of the out-flowing CO$_2$ to reduce the flow resistance in the transportation tubes (see the schematic in Fig. 3).

2.3 Design challenges and solutions

There are design challenges in extremely cold conditions, such as to prevent the CO$_2$ from freezing inside the condensers, and the Tracker from being cooled below −20°C.

Keep the Tracker above −20°C as required. The loop must be running before the Tracker is switched on. In an extremely cold condition, cold fluid below −40°C from the condensers would flow
into the evaporator, and the low power of the preheaters could not heat the in-flowing liquid above
–20°C. To prevent this from happening, a start-up heater was designed to heat the sub-cooled liquid
during start-up when the Tracker is not switched on. It can also help to ensure the CO₂ flowing in the
evaporators is in the saturated state when in an extremely cold condition during the TTCS operation.

The power of the pre-heaters and start-up heater is high enough to keep the Tracker electronics in
the required temperature range, but not enough to keep CO₂ inside the condensers above its triple
point (–56°C), below which CO₂ freezes. Increase the power of pre-heater and start-up heater could
prevent this from happening, but increase the pressure drop along the evaporators by increasing the
vapor quality of CO₂ in the evaporators. Putting the heat just before the inlet of the condensers is
much more effective for the anti-freezing. A heater with this function is implemented in the design
and called cold orbit heater.

Another driving requirement is the high pressure of CO₂. The maximum storage temperature is
+65°C resulting in a maximum designed pressure of 16 MPa. In addition, to keep the mechanical
pumps in a health condition, MIL-STD-1246 C class 100 is applied as the cleanliness requirement for
the loop. Strict leak tightness is required lower than 1×10⁻⁷ Pa·m³/s for CO₂ at 16MPa to guarantee
enough fluid in the required life time.

Special design that ensures the condensers to withstand possible high pressure in uncontrollable
melting of frozen CO₂ is given in section 4.2

3 Simulation and Detailed Design

To verify the feasibility of the designed loop, and to obtain the specifications of the TTCS
components, both static and dynamic simulations are required. A combined model with thermal sub
model and fluid models based on the SINDA/FLUINT was built up.
3.1 Space Model description

The TTCS space model consists of one fluid model and 18 thermal sub-models. The fluid model is to simulate the mass and heat transfer along the loop. The thermal sub-models are built for the Tracker, the Tracker radiators, and the TTCB, to simulate their thermal status. Seventeen heat-exchange macros and four tie links are used to calculate the heat exchange between the thermal models and the fluid model (see Fig.4). Besides, eight line macros are used to simulate the long pipe without heat exchange, such as the evaporator or condenser feed line and the return line.

Homogeneous assumption was chosen for lumps and paths calculation. The correlation of Lockhart-Martinelli was chosen for pressure drop calculation. The heat transfer correlation of Dittus-Boelter was selected for single-phase flow; while that of Rohsenow for condensing, and that of Chen for boiling of two-phase flows.

The TTCS/AMS-02 thermal environment is influenced by the following parameters:

- Impinging solar, albedo and Earth radiative fluxes
- Radiation toward deep space
- Radiative heat exchange with other ISS surfaces
- Temperature of the conductive interfaces

In addition to these factors, AMS-02 internal dissipation, geometry, surface coatings, and materials have their own influences on the Tracker and TTCS temperatures. Deeply influenced by the beta angle of the ISS and the Euler angles (that determine the ISS attitude) as well as by the resulting motion of surfaces (e.g. solar arrays and radiators), the impinging radiative fluxes and the heat exchange keep changing in the orbit. See Table 2 for the ranges of the beta angle and the Euler angles of the ISS.

Then a series of temperature boundaries and heat sources is generated with the overall AMS model according to the hottest and the coldest cases. There are 258 thermal boundaries in the TTCS model. They are distributed in the TTCB, the Tracker, and the Tracker radiators. All the thermal boundaries are orbit dependent.
The pressure of the TTCS loop is controlled by an accumulator, the temperature of which is controlled by the accumulator heater and Peltier elements with PI algorithm. It was modelled as a tank with heated shell, the heat leak to the TTCB base plate. The pump was assumed as an ideal one which provided the loop with a constant mass flow rate. In the model, the mass flow rate along the main loop was set constant. However the flow rate distribution between the branches in evaporators and condensers depended on the geometry of the tubes and the fluid state, which would be calculated by the model.

3.2 Simulation results

3.2.1 System performance

Simulation results show that the designed TTCS performs well in both the cold case and the hot case. Shown in Fig.5 are two cases: (a) in a cold case with a mass flow rate of 2g/s, and (b) in a hot case hot case with a mass flow rate of 3g/s. Because the fluid of the hot inlet comes from the evaporators, while the cold inlet affected by the cold CO$_2$ is from the condensers, the TL symbols related to TL labeled reveal the temperatures’ variation from the evaporators and the condensers. The Rad temperature is the result of the balance between the fluid, the orbital heat flux, and the radiation to the environment. It implies the overall impact of the radiator boundaries.

More simulation results showed that the design parameters of the TTCS meet the requirement.

3.2.2 Sizing the radiators and the cold-orbit heater

To define the size of the radiators, a rough model without fluid loop, in which the integrated ISS was taken into account, was built to calculate the balance temperature of the radiator in the orbital environment by CGS. Two radiators, each with area of 1.22m$^2$, are big enough to radiate the waste heat to the space in the extremely hot case, and not too big to minimize the power budget of the cold orbit heater.
In a hot case (+75,-15,-20,-15), the dynamic simulation result (see Fig.6) shows that, the mass flow rate of 4g/s can provide required sub cooling of CO₂ liquid at the pump inlet, (though that of 2g/s cannot). This means the radiator size is just enough with high mass flow rate in the hot case.

In extremely cold cases, the CO₂ in the condenser will get frozen if no extra heat is applied (see Fig.7). It means that the radiator is too large in the extremely cold cases. In order to meet requirement in both hot and cold cases, radiators are optimized with proper size and with extra loop heating capacity by employing the cold-orbit heater.

In combination of the special design of the condenser (see 4.2 for the condenser structure), where thermal contact between the inlet tubes of the condenser and the second heat pipe of the radiator in the entrance could provide the lowest anti-freezing power [9]. By choosing the right flow direction of the condenser, the power of the cold-orbit heater can be optimized to an acceptable budget of 60W [10]. Based on the analysis of the simulation, the condenser’s configuration is also finalized.

Similarly, the powers of the preheaters, the start-up heater, and the accumulator heater were also determined, within the power budget.

The final design keeps the Tracker temperatures within a band of less than 1ºC over the complete operation temperature window (see Fig.5 for the system performance).

3.3 Safety and structure analysis

The TTCB assembly and its components such as the accumulator and the heat exchanger must be safe in terms of displacement, stresses, natural frequency, reactions, and constraint locations at interfaces under critical load conditions in launching, landing, and in-orbit operation according to the NASA’s requirements. We analyzed the TTCB assembly and the main components using finite element analysis to verify that the Yield and the Ultimate Margins of Safety are positive:

- Static structural analysis;
- Connection safety analysis such as bolt-insert-washer, bolt-nut-washer, with or without thermal washers;
- Fail-Safe structural analysis
Fail-safe connection safety analysis;

In addition, Modal analysis was performed to ensure that the first significant structure natural frequency is above 50 Hz.

The TTCB is an overall assembly that holds the TTCS components except for the evaporators and the condensers. The accumulator is an important component mount in the TTCB with high inner pressure (maximum design pressure of 16 MPa) and extreme temperature range, thus the safety issue is very important. We only present the analyses of the TTCB assembly and the accumulator; without including those of other components.

3.3.1 The Accumulator

The structure of the accumulator is described in 4.4.2. The accumulator was modeled as an assembly. Most of its components were meshed as 3D solid elements and some were modeled as beam element if they are long and thin. Those masses that were not embodied in the FEM mesh model, such as that of the fluid, were added to the model as allotted mass. Connections between different parts were modeled as common nodes, connecting elements, coupled Degrees of Freedom, or bolt connections, depending on the corresponding characteristics, or if the reaction forces at those locations were needed.

Two essential load cases were analyzed for the structural verification of the accumulator.

In the Launching and Landing load case, only the pressure load and the acceleration load were applied in the calculation, because separate analysis showed that temperature load is ignorable. The acceleration load of ±40 g was applied in one direction with ±10 g simultaneously applied in the other two directions. The pressure loads inside the accumulator and the accumulator heat pipe (AHP) were 16 MPa and 5.7 MPa, respectively. Altogether, six acceleration load cases and one pressure load with two different pressures in two components, and their combination were considered in the calculation.

In the In-orbit load case, there are two kinds of loads: the pressure load and the thermal load related to heating. The pressure load is 16 MPa inside the accumulator (at 65°C) and 5.7 MPa inside the AHP, respectively. The pressure loads and the temperature gradient in three hot cases were
combined. The Factor of Safety for yield was 1.5 and that for ultimate was 2.5 or 4.0 depending on the tube diameter. The minimum Margins of Safety of all the components and bolt connections in all the load cases are summarized in Table 3.

A Fail-Safe analysis was performed with the highest loaded fastener removed, and all the Margins of Safety were recalculated (see Table 4). The Factor of Safety used for fail-safe analysis was 1.0 for both yield and ultimate.

From the calculation results, we found that the accumulator had smallest margin of safety, but was still acceptable for the NASA’s safety standards. All the other components and bolt connections had even larger margins of safety. In the modal analysis, the first natural frequency was 399.8 HZ, much higher than the required 50 Hz (see Fig.8), indicating no further vibration test was needed.

A pressure test was performed, which qualified all the box components, and the integrated box assembly, respectively. The vibration tests also verified the simulation.

Thermal analysis was carried out for the accumulator for the safety verification. The results showed that even in the case of double failures of the thermostats (TSs), the accumulator’s temperature, and thus its saturated pressure, is under the maximum design temperature (65ºC), and pressure (16 MPa).

3.3.2 The TTCB

The TTCB was modeled as an assembly. It consists of different mesh types such as 3D solid elements, 2D shells with certain thickness and beam elements, depending on the mechanical characteristics and dimensions of different components.

Bolt connections between different parts were modeled by coupling the nodes Degrees of Freedom (DoF) of different parts at their respective screws locations. Other components that were not modeled in the FEM model were considered as allotted masses. The connections of the TTCB with the USS were modeled as constrained translations and rotations at the corresponding locations.

The total estimated mass was 20.19 kg for one TTCB, therefore ±31 g acceleration load should be applied in one direction with ±7.75 g simultaneously applied in the other two directions. Different
load cases were considered by sweeping the direction of the acceleration vector. For bolts, 60% preload was used for connection safety analysis. For structural and connection analysis, the Factor of Safety for yield was 1.25, and that for ultimate was 2.0.

A Fail-Safe analysis was also performed with the highest loaded fastener removed and all the Margins of Safety are recalculated. Factor of Safety is 1 in the fail-safe analysis.

The calculated first mode is at 53.9 Hz (see Table 5), higher than the required 50Kz. Analysis showed that the designed TTCB met the safety requirement.

4 Construction and Verification

4.1 The Radiators

Due to the strict temperature requirement of the Tracker, dual radiators were designed for the TTCS (called Tracker radiators), which are linked in parallel, and facing to different directions: the ram side and the wake side of the ISS (see Fig.1). Such orientation design can avoid suffering from high temperature in the extremely hot cases; because, when the sun shines directly on one of the radiators for small beta angles of the ISS, it shines on the other at large incident angles, which suffer less from the environmental high heat flux, and can still radiate most of the heat from the loop to the space. To meet the requirement of radiation capability in the hottest case, the Tracker radiators are trapezoid in shape with radiation area of 1.16 m² each (see Fig.9 (a)). The thickness of the radiator is 14.2 mm, and that of the top and bottom face sheets are 0.5 mm, respectively.

Seven heat pipes (see Fig.9(b) for its cross section) are embedded in the ROHACELL foam, and they are sealed in an aluminum shell along the length direction (see Fig.10 for the photo). Condensers are mounted on the back side of the radiators; in a way that each of them thermally connects with all the seven heat pipes, so that the condensation heat from any of the condensers can spread out to the whole radiator. The surfaces of the radiators were painted with the white paint (SG 121FG) to optimize the heat rejection.
The radiators were manufactured in AIDC Taiwan, according to qualified composites manufacture procedures.

On-ground tests were performed for the manufactured radiators in both horizontal and vertical orientation. IR camera was employed to check the functioning of the heat pipe. In the horizontal orientation (to simulate the microgravity condition), all of the seven heat pipes functions normally. In the vertical orientation, simulation showed that the Tracker radiator could function normally even two out of the seven heat pipes fail to start up, depending on the heat load. The thermal vacuum test (TVT) showed that the radiators, which were in vertical orientation, could start up and had the ability of heat radiation as required. Together with the simulation results, such test were further confirmed in the integrated verification in the TVT (see [6]).

4.2 The Condensers

The two condensers of the primary loop were mounted onto the RAM and WAKE radiators on the port side; and those of the secondary loop onto the starboard side, respectively.

The high triple-point of the CO\(_2\) (\(-56.6 \, ^\circ\)C) makes the CO\(_2\) freezing highly possible in the TTCS condenser, for example, in the case of a full AMS power shutdown or in the phase of transferring AMS from the shuttle to the ISS, where CO\(_2\) in the condenser might drop down to \(-120 \, ^\circ\)C. The expansion of CO\(_2\) during the melting creates a high inner pressure. Therefore, if the de-freezing heating of the condenser by environmental heating is out of control, the in-homogenous heating on the solid CO\(_2\) could induce a local high pressure up to 300 MPa for enclosed liquid CO\(_2\) between the still frozen parts [9]. This is quite a challenge to the condenser design. To withstand such a high pressure, Inconel mini-tubes (outer diameter D\(_{\text{out}}\) = 3.15 ±0.05 mm and wall thickness t=1.1 ± 0.1 mm) were used, which can survive up to 1200 MPa by test (see Fig.11 for the structure of the condenser) [11].

To construct the condenser, seven small and smooth Inconel tubes were meanderingly imbedded between two aluminum plates, glued with thermal conductive adhesive (Master Bond Polymer System EP21TDC-2LO) to transfer heat from tube to bottom plate and to release possible stress between the
tubes and the condenser plates because of the different thermal expansion coefficients between inconel alloy and aluminum, together with the large magnitude changes of the condenser temperature. The inlet and outlet of the seven tubes were brazed into an inlet and an outlet manifold, respectively. The tube length embedded in the condenser plate was 2.49 m and that from the manifold to the base plate inlet and the outlet were 0.45 m, respectively. The length and the width of the plate were 460 mm and 340 mm, respectively the effective area was about 0.07 m² (see Fig.11 (a) and (b) for the configuration of the condenser). The thermal conductance of a single condenser two-phase flow state is about 85 W/K at the working temperature of −5°C, which is from the measured heat transfer coefficients [12].

Based on the condenser EM test results, the contact thermal conductance between the condensers and the cold plates were about 30 to 60 W/K, depending on the cold plate temperature and the mounting procedure.

The manufactured QM condenser (see Fig.12 for the photo) was mounted on a cold plate that simulated the Tracker radiator. It passed the CO₂ freezing and de-freezing tests (thermal cycling test) and performance test performed at SYSU.

4.3 The Evaporators

There are two evaporators (the top and the bottom) in parallel connected to the loop. The two evaporators are stainless steel tubes with outer diameter of 3 mm and thickness of 0.2 mm. For the first design, both evaporators have two rings in series, along which, and thermally connected with are the front-end electronics of the AMS Tracker. The inner ring with many bends connects with 24 pieces of copper brands that thermally connect to the front-end electronics through carbon fiber bars; the outer ring to 30 through copper braids. (see Fig.13 and Fig.14)

For the upgraded Tracker, the original layer 8 was removed. Part of it was put on the top of the transition radiation detector (named as new layer 1). This layer is no longer thermally controlled by the TTCS but by passive radiation cooling and an additional heater circuit. The rest of layer 8 formed a new bottom Tracker layer between RICH and the electromagnetic calorimeter, (named layer 9, see
Fig. 3 in [4] for more details). Correspondingly, the TTCS bottom evaporator was also rearranged to collect waste from the front-end electronics of the layer 9 (see Fig.15). The outer ring of the bottom evaporator was replaced by a rectangular ring, with total length of the tube unchanged. About 19.5 W of waste heat shifted correspondingly with the new layer 1 to the top of the AMS, indicating that the bottom evaporator has 19.5W less heat load. Compared to the original design, the upgraded TTCS now has asymmetric evaporators in terms of both heat load and tube routing geometry. It faces more challenges from the cold environment because the radiators become over-designed now; and the asymmetric evaporators may result in unequal flow distribution between the two evaporators, and thus risk of dry-out for the evaporator at low flow-rate. The in-orbit results below showed that the concept is robust for the late design upgrade.

4.4 The Component boxes

The component box (TTCB) is an assembly that integrates the core components of the TTCS, except for the evaporators and the condensers. They are two pumps, one accumulator, one heat exchanger, two absolute pressure sensors, two differential pressure sensors, four preheaters, two start-up heaters, and two cold orbit heaters. The mechanical concept box was designed by INFN Italy and the detailed by NLR, the Netherlands. TTCBs were manufactured in AIDC Taiwan.

The two pumps are mounted on a start-up radiator, aluminum (7075) plate painted with white paint, and facing the outer space as much as possible. This keeps the pumps the coldest components in the TTCB before any of the pumps is switched on. This could prevent the pump from cavitation. The accumulator, the heat exchanger, and the pressure sensors are mounted on aluminum (7075) plate that is the base of the TTCB, and also the mechanical interface of the box to be mounted on the USS. In the front edge of the TTCB base plate, a cold orbit heater is mounted (see Fig.16, the rectangular copper plate, into which armored heater-wires were soldered). Armored heater-wires were soldered onto the shell of the heat exchanger, to operate as the start-up heaters. Armored heater-wires were soldered onto the tubes connected to the inlets of the evaporators.
Performance tests were carried out for the integrated TTCB QM (see Fig.17) at SYSU, China, by making use of the experimental setup for the TTCS EM tests. Thermal vacuum test and EMI/EMC test were performed at SERMS, Italy, for the TTCB FMs.

4.4.1 The Pumps

The pumps to cycle the working fluid are the hearts of the two-phase loops. The rotation speed of the centrifugal pump can be adjusted independently to change the flow rate of the cycling CO$_2$. Therefore, it has the advantage of decoupling the driving force of the pump from the heat load, as compared to those capillary force pumps, and thus provides much higher systematic stability and reliability. Because the pumps contain moving parts that always limit its life time. Centrifugal pumps were chosen because they are good at long life-time among mechanical pumps.

Pacific Design Technology (PDT) developed small and light centrifugal pumps for the path-finder to Mars, which could be used to guarantee the life-time design requirement. The continuous test time of 12 months indicated that the life time of such a pump could be three to five years. PDT modified the pumps to adapt to the CO$_2$ for the TTCS application (see Fig.18). Two mutual redundant pumps are employed in one loop, i.e., four for two redundant loops. The possible total life time including redundancy is 12 years.

The rotation speed of the pumps can be adjusted to provide from a normal flow rate of 4 ml/sec at 460 mbar pressure head, to a maximum flow rate of 7 ml/sec at 1400 mbar pressure head. Since the life time of the pumps is very much related to their rotation speed in operation, the rotation speed is always kept as low as possible, yet just enough to support a stable and normal operation of the TTCS.

The pump rotation speed is set and changed by ground command.

4.4.2 The Accumulator

The accumulator is made of stainless steel to withstand an inner pressure of 24 MPa, the designed yield pressure of the accumulator. Wick materials with special design structure were applied in the inner accumulator to manage the CO$_2$ liquid in microgravity. A heat pipe (AHP) extending from
the inside to the outside of the accumulator was welded to and through the accumulator shell. On the outer part of the heat pipe, armored heater wires (THERMOCAAX) were soldered to heat the accumulator more uniformly. On the heater wires, six thermostats (Comepa) were mounted to physically switch off the heaters at a set-point temperature of 55°C, to meet the safety requirement for pressure vessels. To cool the accumulator, Peltier elements were mounted between the accumulator wall and the loop tube in which sub-cooled liquid is flowing through (see Fig.3 for the schematic, and Fig.19 for the 3D drawing of the accumulator, and Fig.20 for the outcome product of a FM). Three thermostats (with set temperature 45 ºC) were mounted on the Peltier saddle to meet the safety requirement.

The Pt-1000 sensors that used to measure the accumulator temperature for the temperature control were glued on the outer surface of the accumulator shell. Inside the corresponding position of the accumulator, the CO₂ is in where two-phase state (see Fig.16 for the Pt-1000s’ position).

4.4.3 The Heat Exchanger

The TTCS heat exchanger is a cross-flow plate heat exchanger. In the normal operation condition, two-phase CO₂ flows in the hot side; while the sub-cooled CO₂ liquid in the cold side. To withstand the high pressure, the heat exchanger is made of Inconel alloy.

Two armored wire heaters were soldered onto the shell of the heat exchanger, which are used as the mutual-redundant start-up heaters (50W each). Fig.21 shows a heat exchanger flight model. Six thermostats (3 in series per heater, with a set-point temperature of +80°C) were mounted on the heat exchanger shell.

4.4.4 Integration

The whole TTCS loops were integrated onto the AMS. The evaporators were first mounted on the Tracker, with good thermal contacts to the Tracker front-end electronics. The condensers were then mounted onto the Tracker radiators respectively. The component boxes were mounted on the USSs correspondingly; and the TTCE crate was mounted on the main radiator. Finally, transportation
tubes and cables were connected to the corresponding components, respectively. After integration, carbon dioxide was filled into the loops.

4.4.5 Verification

Except verifications at component level and box level, the two TTCS loops were verified at system level, together with the AMS. They pass all the tests, including Helium leak tests, proof pressure tests, functional test. The TTCS loops were also thoroughly tested during the AMS02 thermal vacuum test and EMC test at ESA ESTEC in the Netherlands. Please refer to [6] for details of the thermal vacuum test of the TTCS.

5 Control electronics and control scenarios

5.1 Control electronics

TTCS thermal control electronics (TTCE) is a combined unit of engineering data acquisition and thermal control. Orientated to the redundant TTCS loops, TTCE adopts cross redundant design: each loop is mounted with two sets of sensors and actuators (A and B), which, together with the TTCE board A and B, are correspondingly composed of the redundant TTCE control loops (see Fig.22).

Dual CAN buses (CAN A and CAN B) connect the TTCE with the four JMDCs. The (dual redundant) TTCE acts as four (2×2) slaves. Dual redundant power (+28 VDC / 10A) will be offered by the PDS (power distribution system) to the Tracker thermal electronic power board (TTEP) inside the TTCE crate (see Fig.22).

Inside the TTCE crate, there are three kinds of electronic boards; the TTEC, the TTEP, and the TTPP (see Fig.23). TTEC board is a core electronic control board. It communicates with JMDC (mission computer) through dual redundant CAN buses; collects temperature signals from three-fold Pt1000s at each sensing point, and DS1820 sensors; interpreters control commands; runs control algorithm and implements low-level control by outputting control signals. TTEP board is a power supply for TTCE. More precisely, it provides +5V and +15V DC power to TTEC, and electrically
isolated control output powers for: 1) PWM (pulse width modulation) power control for the accumulator Peltier elements; 2) PWM power control for the accumulator heaters; 3) on-off power output for the preheaters, cold-orbit heaters, and the start-up heaters, respectively. TTPP is a pump control board, and at the same time, it collects pressure information from the absolute pressure sensors (APSs) and differential pressure sensors (DPSs) of the loops.

The design, the manufacture, and the tests of the TTEC boards were given in more details in [13].

5.2 Control scenarios

A TTCS control loop controls temperature at a given set-point with the temperature-control sensors’ values as inputs. Three sensors are used to implement a voting mechanism for reliable determination of the true value. Once on power, the TTCE reads the state parameters, such as temperatures, pressures, and sends those values to JMDC (red arrows in Fig.24), which are then sent to ground through the ISS. Those temperature-control sensors’ values are used for the TTCS operation control at TTCE (see Fig.24). Control parameters, such as set-point temperatures, PI parameters, pump rotation speed, and control modes and ground commands are sent through the TM/TC interface and CAN bus interface in JMDC to the TTCE (see Fig.25).

Three health-guards are implemented in the JMDC. They are: (1) Overall Tracker Electronics high and low temperature health-guard, which is to provide an overall independent protection of the Tracker Electronics for too high and too low temperatures; (2) Radiator freezing health-guard, which is to warn for freezing of the radiators, which may occur during periods when the PDS does not supply power to the Tracker radiators (120V) when the Tracker is switched off; (3) JMDC-TTCE communication outage health-guard (in TTCE-Manager), which is to protect the Tracker Electronics for possibly hazardous malfunctioning of the TTCS during a TTCE-JMDC communication outage.

5.2.1 TTCE low level controls

There are five low level controls: 1) Pump set point control; 2) Accumulator temperature set...
point control; 3) Evaporator inlet heating control; 4) Start-up heating control; 5) Cold-orbit heating control; two of them are close-loop controls: 1) accumulator temperature PI control, and 2) cold orbit heater on-off control (see Fig.24).

5.2.2 Communication

The TTCE communicates with JMDC through CAN bus, and the JMDC communicates with ground through the tele-monitor or tele-control (TM/TC) interface (see Fig.25).

6 In-orbit performance

AMS02 was launched to Space on 16th, May 2011 and transferred from shuttle to International Space Station on 19th, May 2011.

6.1 Communication check

Communication was checked before the other tests with the shuttle and the ISS respectively, by sending request of ‘READ ALL’ to TTCE and getting feedback to verify the entire critical information of temperature, pressure, and so on, all over the cooling system. Ever since the up-and-down data flow was confirmed, which indicating normal communication were established, the following tests were ready to proceed.

6.2 Functional check

Before servicing to AMS Tracker, TTCS conducted a serial of functional tests for each component from May 17th to 18th while shuttle STS-134 entered the space orbit. All the TTCS components and sensors passed the tests and performed as they did on the ground.
6.3 Performance tests

6.3.1 Start-up test

The start-up of the TTCS and the Tracker were successfully completed and the process is depicted in Fig.26. To prevent cavitation to the pump, the accumulator temperature was increased to 15°C in advanced to expel liquid CO₂ from the accumulator to the loop, and to liquidize CO₂ vapor in the loop. As soon as the sub-cooling, the temperature difference between the accumulator and the pump inlet liquid, was over 5°C, the pump was switched on with rotation speed of 5000RPM. Due to the cooled liquid coming from the condensers, the temperature of the pump inlet dropped; those of the evaporators and the Tracker planes dropped as well. When the Tracker was powered on, the liquid CO₂ started to evaporate and smoothly turned to stable two-phase state in half an hour without super-heating. To prevent the Tracker planes’ temperatures from rising over the limit of 30°C, the set-point temperature was tuned down to 5°C. The evaporators’ temperature decreased with the accumulator’s temperature correspondingly. In the end, the TTCS was running at the saturation temperature of 5°C.

6.3.2 Nominal operation

Having been tested in space, we found the proper working condition for the normal operation of the TTCS, with the operation temperature of 0 °C and the pump rotation speed of 6000RPM. The temperatures of the evaporators and the Tracker planes stay stable even the radiators temperatures vary from −35 °C to −10 °C (see Fig.27). The thermal boundaries of the TTCS, reflected by the two radiator temperatures, are mainly affected by the beta angle in general. If the beta angle stays in the range of −45 to 45 degrees, the temperature of the pump inlet is between −20 °C and −5.6 °C. Thus the TTCS could smoothly run at the saturation temperature of 0 °C and the pump rotation speed of 6000RPM, without any operation interrupt, nor extra heating power consumption. When the beta angle is higher than 45 degrees, or lower than −45 degrees, the cold-orbit heater would be activated automatically. We will discuss the cold-orbit heater’s performance in the next section.
6.3.3 Automatic control for the cold-orbit operation

To maintain the TTCS running automatically, most of the heaters are in auto-control mode, monitored by Pt1000’s and controlled by heaters such as the cold-orbit heater (60W) that is used to prevent the CO₂ from freezing inside the condensers or being too cold to initiate the CO₂ to two-phase in the evaporators. Its switching set-point was set at −20 °C, which is adjustable by the ground command. The control scenario is to take the temperature of the pump inlet as the reference, once it goes below −20 °C, the cold-orbit heater would automatically switch on; otherwise, it stays off. As shown in Fig.28, every time when the pump-inlet temperature drops to −20 °C during the ISS orbit variation, the cold-orbit heater functions automatically as designed. Only 1 °C of temperature oscillation on the evaporator is seen and it comes back to the previous state (above −20 °C) within a few minutes, there is no visible temperature variation to the Tracker temperature at all (neither that of Plane_4 nor that of Plane_9).

6.3.4 Hot switching from the primary loop to the secondary loop

The centrifugal pumps are the only moving components of the TTCS. To sustain its proper performance, the pumps are used alternatively: each pump operations for three months on average. Thus, the hot switching, without powering down the Tracker, from a running loop to a stand-by loop is scheduled every three months. To verify the temperature stability of the Tracker during the hot switching, a loop was switched from the primary to the secondary loop with operation temperature of −5 °C, pump speed of 5000RPM (see Fig.29). When CO₂ sub-cooling of over 5°C was guaranteed in the secondary loop, one of the pumps of the secondary loop was switched on. As a result, the temperature of the pump-inlet of the secondary loop started to drop from −5 °C to −20 °C, and then varied with time in an orbital period. After running the two loops simultaneously for a while, the pump of the primary loop was switched off. The temperature of the pump-inlet of the primary loop went up steeply because there was no more sub-cooling liquid flowing through. The Tracker plane4’s temperature increased by 2 °C, which is explained by the thermal resistance between the evaporator of
the primary and the secondary, leading to the difference of resistances of the two loop to the Tracker hybrids. As shown in the Fig.13, the evaporator of the secondary is above that of the primary, the thermal resistance of tubes and liquid would have an impact on the heat transfer efficiency from the Tracker to the TTCS evaporators. As a result, the Tracker plane 4’s temperature increased.

6.3.5 Performance during the Soyuz undocking.

Working on the ISS, the TTCS is indirectly impact by the shuttle’s docking and undocking, because the space station must adjust its attitudes. For example, during the Soyuz (42P) undocking on 29th, October, 2011, from 07:45 to 09:32, the ISS attitude shifted from (+356.000, +355.500, +0.700) to (0.000, +90.000, 0.000), and back afterward, where the (Yaw, Roll, Pitch) are the three Euler angles that define the ISS attitude. This means that the ISS rotated by 90° in the horizontal. The Tracker’s temperature was hardly affected. However, the sub-cooling was not sufficient anymore, because the temperature of the wake radiator increased. The cavitation-prevention alarm was triggered. This alarm was a health-guard in the control electronics to prevent the pump from cavitation. The operation temperature increased automatically by heating up the accumulator until enough sub-cooling was reached. In the case shown in Fig.30, the sub-cooling is set at 5 °C. The evaporator temperatures show a ripple, while those of the Tracker planes are hardly affected. Implicitly it is shown that the health-guard was working properly.

7 Conclusion

The AMS-TTCS has been developed for the thermal control of the AMS Tracker. It has been operating reliably since May 19, 2011. The temperature stability of the Tracker layers can be controlled within 1°C for each loop for various complex thermal environments, including spacecraft dockings and un-dockings; and within 3 °C for loop switching, which meets the Tracker operation requirement. It shows promising applications of mechanically pumped two-phase loops for space thermal controls, manned space flights and distant planets exploration.
Acknowledgements

This work was supported by the Prophase Research of National Basic Research Program of China under Grant No. 2006CB708613, the Science and Technology Program of People’s Government of Guangdong Province, China.

Supports to the thermal vacuum test of the TTCS are acknowledged, in particular from Dr. X.D. Cai (MIT), Prof. Bruna, Bertucci, (U. of Perugia). The authors would like to thank AIDC (Taiwan) for the manufacture of the Tracker radiators, the condensers and the heat exchangers, and integration of the TTCB; CSIST (Taiwan), H. Jinch, Y.J. Fanchiang, and S.H. Wang for the manufacture of the electronics; CAST (China) for the development and manufacture of the accumulators; NLR for the efforts for condenser & HX design, detailed box design and TV test; and NIKHEF for the design and manufacture of the evaporators. Supports from NASA during the development of the TTCS are appreciated. Special thanks go to ESA, ESTEC Laboratory (Noordwijk), for providing thermal vacuum test facilities.
1. Alcaraz, J., et al., The Alpha Magnetic Spectrometer (AMS). Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2002. 478(1-2): p. 119-122.

2. Lamanna, G., Astrophysics and particle physics in space with the Alpha Magnetic Spectrometer. Modern Physics Letters A, 2003. 18(28): p. 1951-1966.

3. Borgia, B. and A.M.S. Collaborat, The alpha magnetic spectrometer on the international space station, in 2004 IEEE Nuclear Science Symposium Conference Record, Vols 1-7, J.A. Seibert, Editor. 2004. p. 166-170.

4. Battiston, R. and A.M.S. Collaboration, The anti matter spectrometer (AMS-02): a particle physics detector in space. Nuclear Physics B-Proceedings Supplements, 2007. 166: p. 19-29.

5. Delil, A.A.M., A.A. Woering, and B. Verlaat, Development status of the mechanically pumped two-phase CO2 cooling loop for the AMS-2 TTCS. Space Technology and Applications International Forum - Staif 2003, 2003. 654: p. 88-95.

6. Zhang, Z., et al., Stable and self-adaptive performance of mechanically pumped CO(2) two-phase loops for AMS-02 tracker thermal control in vacuum. Applied Thermal Engineering, 2011. 31(17-18): p. 3783-3791.

7. Luebelsmeyer, K., et al., Upgrade of the Alpha Magnetic Spectrometer (AMS-02) for long term operation on the International Space Station (ISS). Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2011. 654(1): p. 639-648.

8. Van Es, J., AMS02 Tracker Thermal Control System (TTCS) design, model and breadboard results. SAE 2004-01-2556, 2004.

9. Huang, Z.C., et al., Design optimization of condensers in a CO2 two-phase thermal control system for space detector application. Chin. J. space sci., 2008. 28(1): p. 44-48.

10. Huang, Z.C., et al., The numerical simulation of the anti-freezing design for CO2 two phase condenser in a space thermal control loop. J. Eng. Thermophysics, 2009. 30(1): p. 87-89.
11. G. van Donk, M.B., A. Pauw, J. van Es. Testing of a Freeze-proof Condenser for the Tracker Thermal Control System on AMS-02. in International Conference on Environmental Control Systems (ICES). July 2007. Chicago USA.

12. Huang, Z.C. Numerical Simulation and Thermal Control Characteristic of the Space Mechanically Pumped Two-Phase CO2 Loop, PhD thesis in School of Physics and Engineering, Sun Yat-Sen University. 2008, Sun Yat-Sen University: Guangzhou. p. 166.

13. Menichelli, M., et al., The construction and space qualification of the control electronics for the tracker detector cooling system of the AMS-02 experiment. Nuclear Instruments & Methods in Physics Research Section a-Accelerators Spectrometers Detectors and Associated Equipment, 2010. 617(1-3): p. 507-508.
Figure captions

Fig. 1 The AMS-02 working on the International Space Station. The two red arrows point to the two TTCS radiators, respectively.

Fig. 2 The 3D model graph of the two redundant TTCS loops with all the other AMS parts hidden.

Fig. 3 The schematic diagram of the upgraded TTCS design, with the only change of bottom evaporator, which differs from the original design in heat load (-19.5W), outer ring’s shape (square), and position.

Fig. 4 The schematic SINDA/FLUINT model (fluid part) of the TTCS.

Fig. 5 The variation of the inlet and the outlet temperatures of the heat exchanger with the that of orbital heat flux; (a) Cold case (-75,+0,+0,-15), FR=2 g/s, Tset=-15 °C; (b) hot case (+75,-15,+0,-15), FR=3 g/s, Tset=15 °C. Label TL stands for the temperature of the fluid at the inlet and the outlet of the heat exchanger; Label Rad stands for the average temperature of the radiator out plate.

Fig. 6 The variation of the temperatures of the primary loop in the case (+75-15-20-15), 4g/s, and at 20 °C.

Fig. 7 The variation of temperatures of the condenser, indicating that the CO2 should freeze after 0.8 hour at Tset=258 K in a cold case (-75+0+0-15). Labels TL#### stand for the temperature of the condenser lumps in the SINDA model, and the numbers following TL are the lump numbers. The frozen point of CO2 is -56 °C.

Fig. 8 The modal shape of the TTCS accumulator.

Fig. 9 (a) The radiator design drawing; (b) the radiator condenser interface.

Fig. 10 A Tracker radiator, before and after the top plate was covered.

Fig. 11 3D design drawing of the condenser (a). The cross-section of the condenser plate (b).

Fig. 12 A condenser under construction.

Fig. 13 The 3D design drawing of the top evaporator. It consists of two redundant evaporators (blue lines) connected with the Tracker front-end electronics. The hybrids were thermally connected to
the evaporator outer rings by cooper braids. G, E and F are temperature sensors along the evaporator.

Fig. 14 The top evaporator inner rings that have been integrated to the AMS-Tracker. The copper soldered on the evaporator tubes (the fine metal tubes) thermally connects with the front-end electronics hybrids (vertical blocks in the photo) through carbon fiber bars (not shown in the photo).

Fig. 15 The 3D design drawing of the bottom evaporator, the only upgraded part of the TTCS.

Fig. 16 The TTCB assembly drawing.

Fig. 17 The integrated TTCB QM. ① Accumulator; ② Cold-orbit heaters.

Fig. 18 The centrifugal pump produced by PDT.

Fig. 19 3D design drawing of the accumulator; ① accumulator vessel, ② braces, ③ subcooled CO₂ tube, ④ Peltier element set, ⑤ liquid pipe (that connects the accumulator to the loop, ⑥ accumulator heater heat pipe.

Fig. 20 A flight model accumulator.

Fig. 21 The flight model heat exchanger.

Fig. 22 The TTCE block diagram

Fig. 23 The dual redundant block structure inside TTCE crate.

Fig. 24 The schematic diagram of the TTCS control loops. The liquid flow control, the start-up heater control, and the defreezing control are impletemented by the ground commends.

Fig. 25 The communication interfaces of the TTCE.

Fig. 26 TTCS start-up for operation temperature of 5 °C, at pump rotation speed of 5000RPM. The noise of the DPS is clearly associated with the appearance of the two-phase flow after the Tracker switched on.

Fig. 27 Routine performance of the TTCS at the operation temperature of 0 °C and pump rotation speed of 6000 RPM.

Fig. 28 Cold-orbit heater auto-function performance at the pump rotation speed of 6000RPM and at the saturation temperature of 0 °C.
Fig. 29 TTCS performance during hot switching from the primary to the secondary loop at the saturation temperature of –5 °C, and the pump rotation speed of 5000RPM.

Fig. 30 TTCS performance during the undocking of the Soyuz (42P) with the attitude change from (+356.000, +355.500, +0.700) to (0.000, +90.000, 0.000), and a duration of 107 minutes. The subcooling health guard functions as designed.
Fig. 1 The AMS-02 working on the International Space Station. The two red arrows point to the two TTCS radiators, respectively.

Fig. 2 The 3D model graph of the two redundant TTCS loops with all the other AMS parts hidden.
Fig. 3 The schematic diagram of the upgraded TTCS design, with the only change of bottom evaporator, which differs from the original design in heat load (-19.5W), outer ring's shape (square), and position.

Fig. 4 The schematic SINDA/FLUINT model (fluid part) of the TTCS.
Fig. 5 The variation of the inlet and the outlet temperatures of the heat exchanger with the that of orbital heat flux; (a) Cold case (-75,+0,+0,-15), FR=2 g/s, Tset=-15 °C; (b) hot case (+75,-15,+0,-15), FR=3 g/s, Tset=15 °C. Label TL stands for the temperature of the fluid at the inlet and the outlet of the heat exchanger; Label Rad stands for the average temperature of the radiator out plate.

Fig. 6 The variation of the temperatures of the primary loop in the case (+75-15-20-15), 4g/s, and at 20 °C.
Fig. 7 The variation of temperatures of the condenser, indicating that the CO2 should freeze after 0.8 hour at Tset=258 K in a cold case (-75+0+0-15). Labels TL### stand for the temperature of the condenser lumps in the SINDA model, and the numbers following TL are the lump numbers. The frozen point of CO2 is -56 °C.

Fig. 8 The modal shape of the TTCS accumulator.
Fig. 9  (a) The radiator design drawing; (b) the radiator condenser interface.
Fig. 10  A Tracker radiator, before and after the top plate was covered.

Fig. 11  3D design drawing of the condenser (a). The cross-section of the condenser plate (b).
Fig. 12 A condenser under construction.

Fig. 13 The 3D design drawing of the top evaporator. It consists of two redundant evaporators (blue lines) connected with the Tracker front-end electronics. The hybrids were thermally connected to the evaporator outer rings by cooper braids. G, E and F are temperature sensors along the evaporator.
Fig. 14 The top evaporator inner rings that have been integrated to the AMS-Tracker. The copper soldered on the evaporator tubes (the fine metal tubes) thermally connects with the front-end electronics hybrids (vertical blocks in the photo) through carbon fiber bars (not shown in the photo).

Fig. 15 The 3D design drawing of the bottom evaporator, the only upgraded part of the TTCS.

Fig. 16 The TTCB assembly drawing.
Fig. 17 The integrated TTCB QM. ① Accumulator; ② Cold-orbit heaters.

Fig. 18 The centrifugal pump produced by PDT.

Fig. 19 3D design drawing of the accumulator; ①accumulator vessel, ②braces, ③subcooled CO₂ tube, ④Peltier element set, liquid pipe (that connects the accumulator to the loop, ⑥ accumulator heater heat pipe.
Fig. 20 A flight model accumulator.

Fig. 21 The flight model heat exchanger.

Fig. 22 The TTCE block diagram
Fig. 23 The dual redundant block structure inside TTCE crate.

Fig. 24 The schematic diagram of the TTCS control loops. The liquid flow control, the start-up heater control, and the defreezing control are implemented by the ground commands.
Fig. 25 The communication interfaces of the TTCE.

Fig. 26 TTCS start-up for operation temperature of 5 °C, at pump rotation speed of 5000RPM. The noise of the DPS is clearly associated with the appearance of the two-phase flow after the Tracker switched on.
Fig. 27 Routine performance of the TTCS at the operation temperature of 0 °C and pump rotation speed of 6000 RPM.

Fig. 28 Cold-orbit heater auto-function performance at the pump rotation speed of 6000 RPM and at the saturation temperature of 0 °C.
Fig. 29 TTCS performance during hot switching from the primary to the secondary loop at the saturation temperature of $-5 \, ^\circ C$, and the pump rotation speed of 5000 RPM.

Fig. 30 TTCS performance during the undocking of the Soyuz (42P) with the attitude change from (+356.000, +355.500, +0.700) to (0.000, +90.000, 0.000), and a duration of 107 minutes. The subcooling health guard functions as designed.
Table 1 Functions of the TTCS main components.

| Components           | Functions                                                                                           |
|----------------------|-----------------------------------------------------------------------------------------------------|
| Evaporator           | To collect and transport the heat from the Tracker to the CO\textsubscript{2} loop                   |
| Condenser            | To conduct the heat from the loop to the radiators that dissipate the heat to the space             |
| Accumulator          | To compensate the mass of CO\textsubscript{2} in the loop and to control the operation temperature of the system |
| Pump                 | To provide driving power for the loop                                                               |
| Heat-exchanger       | To exchange heat between the saturated CO\textsubscript{2} and the sub-cooled liquid CO\textsubscript{2} |
| Pre-heater           | To heat the sub-cooled liquid CO\textsubscript{2} into saturated state before flowing into the evaporator |
| Start-up heater      | To avoid sub-cooled liquid CO\textsubscript{2} flow into the Tracker to damage the electronics at extremely cold environmental condition |
| Cold orbit heater    | To prevent the CO\textsubscript{2} from being cooled to the freezing point by effectively heating the fluid |
| De-freezing heater   | To defreeze the solid CO\textsubscript{2} inside the tubes from the manifolds to the condensers       |
| Radiator heaters     | To defreeze the solid CO\textsubscript{2} inside the condensers mounted on the radiators             |
| Component box        | To assemble the components except for the evaporators and the condensers                            |
Table 2 The Beta and Euler angles range of the ISS.

| Angle                | Variation Range                     |
|----------------------|-------------------------------------|
| Beta angle           | $-75^\circ$ to $+75^\circ$          |
| Yaw (Z) attitude angle | $-15^\circ$ to $+15^\circ$        |
| Roll (X) attitude angle | $-15^\circ$ to $+15^\circ$      |
| Pitch(Y) attitude angle | $0^\circ$ to $+25^\circ$ with docked STS |
|                      |                                     |
|                      | $-20^\circ$ to $+15^\circ$ with undocked STS |

8
Table 3  Summary of the minimum MofS for all the load cases.

| Components                                           | Static:MofS | Thermal:MofS |
|------------------------------------------------------|-------------|--------------|
|                                                      | Yield       | Ultimate     | Yield       | Ultimate     |
| Accumulator                                          | 0.03        | 0.11         | 0.02        | 0.02         |
| Fixed Bracket & Clamp Collar&Wedge                   | 1.10        | 2.11         | 1.00        | 1.82         |
| Sliding Bracket                                      | 4.01        | 3.56         | 2.76        | 2.95         |
| Heat Pipe                                            | 1.05        | 2.46         | 0.92        | 1.14         |
| Peltier Fixed                                        | 2.07        | 2.26         | 0.51        | 1.20         |
| TS & Peltier Heat Exchanger & Peltier heat exchanger press &Spring Support | 0.61        | 1.13         | 0.68        | 1.22         |
| Joints                                               | Static: bolt MofS | Thermal: bolt MofS |
| Accu.Bracket Clamp&Collar Bolt                       | 0.12        | 0.09         |
| PipeFix&Clamp Bolt                                   | 0.123       | 0.122        |
| Press&Saddle Bolt                                    | 0.107       | 0.106        |
Table 4  Summary of the minimum MofS for all load cases (Fail-safe)

| Components | Static: MofS | Thermal: MofS |
|------------|--------------|---------------|
|            | Yield        | Ultimate      | Yield | Ultimate |
| Accumulator| 0.54         | 1.80          | 0.53  | 1.55     |
| Fixed Bracket & Clamp Collar&Wedge | 1.61 | 5.17 | 1.49 | 4.66 |
| Sliding Bracket | 6.91 | 8.85 | 3.68 | 6.92 |
| Heat Pipe | 1.07 | 9.19 | 1.87 | 7.31 |
| Peltier Fixed | 4.94 | 16.41 | 0.76 | 3.17 |
| TS & Peltier Heat Exchanger & Peltier heat exchanger press & Spring Support | 0.98 | 3.20 | 0.24 | 2.64 |
| Joints | Static: bolt MofS | Thermal:bolt MofS |
| Accumulator.Bracket Clamp&Collar Bolt | 0.34 | 0.30 |
| PipeFix&Clamp Bolt | 0.50 | 0.49 |
| Press&Saddle Bolt | 0.19 | 0.20 |
Table 5 Minimum Margins of Safeties and locations

| Structural  | Yield MoFS | Ultimate MoFS | Location     | Bolt MoFS | Location                      |
|-------------|------------|---------------|--------------|-----------|-------------------------------|
| Normal      | 4.97       | 3.35          | Side-plate   | 0.047     | Cover/Base-plate              |
| Fail-safe   | 5.28       | 6.21          | Side-plate   | 0.22      | Pump Bracket/Start up radiator |
| Abbreviation | Meaning                                      |
|--------------|----------------------------------------------|
| AHP          | Accumulator heat pipe                       |
| AMS          | Alpha Magnetic Spectrometer                 |
| APS          | Absolute pressure sensor                    |
| CAN (bus)    | Controller Area Network                     |
| DoF          | Degree of Freedom                           |
| DPS          | Differential pressure sensor                |
| EM           | Engineering Model                            |
| EMC          | Electro Magnetic compactibility             |
| ESTEC        | European Space Technology Centre            |
| FEM          | Finite element method                       |
| FM           | Flight Model                                 |
| HX           | heat exchanger                              |
| ISS          | International Space Station                 |
| JMDC         | Mission Computers                            |
| MofS         | Margin of Safety                            |
| Abbreviation | Full Form |
|--------------|-----------|
| PDS          | Power Distribution System |
| PWM          | Pulse width modulation |
| QM           | Qualification Model |
| RICH         | Ring-imaging Cherenkov (detector) |
| RPM          | Revolutions Per Minute |
| STS          | Space Shuttle Mission |
| TC           | Tele-control |
| TM           | Tele-monitor |
| TS           | Thermostat |
| TTBP         | Tracker Thermal Back Plane |
| TTCB         | Tracker Thermal Component Box |
| TTCE         | Tracker Thermal Control Electronics |
| TTCS         | Tracker Thermal Control System |
| TTEC         | Tracker Thermal Electronic Control Board |
| TTEP         | Tracker Thermal Electronic Power Board |
| TTPP         | Tracker Thermal Pump & Pressure sensors Board |
| TVT          | Thermal Vacuum Test |
| USS          | Universal Support Structure |
I-DEAS Visualizer
Display 1
Assembly_Fem3
B.C. 9, NORMAL_MODE 1, DISPLACEMENT_1
I:\TTCS\ZYY_Result_TTCS_Frequency_31.mfl
DISPLACEMENT Magnitude Unaveraged Top shell
Min: 0.00E+00 mm Max: 1.00E+03 mm
B.C. 9, NORMAL_MODE 1, DISPLACEMENT_1
I:\TTCS\ZYY_Result_TTCS_Frequency_31.mfl
DISPLACEMENT XYZ Magnitude
Min: 0.00E+00 mm Max: 1.00E+03 mm
Part Coordinate System
Frequency: 4.00E+02 Hz
Figure(s)
Click here to download high resolution image

DETAIL B
SCALE 2:1

(\text{R1.975})

3.95 \pm 0.05

2 \pm 0.05

2.5
Figure(s)
Click here to download high resolution image
## Table 5 Minimum Margins of Safeties and locations

| Structural MofS | Yield MofS | Ultimate MofS | Location       | Bolt MofS | Location                  |
|-----------------|-----------|---------------|----------------|-----------|---------------------------|
| Normal          | 4.97      | 3.35          | Side-plate     | 0.047     | Cover/Base-plate          |
| Fail-safe       | 5.28      | 6.21          | Side-plate     | 0.22      | Pump Bracket/Start up radiator |
| Nomenclature        | Definition                                                   |
|---------------------|--------------------------------------------------------------|
| AHP                 | Accumulator heat pipe                                       |
| AMS                 | Alpha Magnetic Spectrometer                                 |
| APS                 | Absolute pressure sensor                                    |
| CAN (bus)           | Controller Area Network                                     |
| DoF                 | Degree of Freedom                                           |
| DPS                 | Differential pressure sensor                                |
| EM                  | Engineering Model                                           |
| EMC                 | Electro Magnetic compactibility                             |
| ESTEC               | European Space Technology Centre                            |
| FEM                 | Finite element method                                       |
| FM                  | Flight Model                                                |
| HX                  | heat exchanger                                              |
| ISS                 | International Space Station                                 |
| JMDC                | Mission Computers                                           |
| MofS                | Margin of Safety                                            |
| PDS                 | Power Distribution System                                   |
| PWM                 | Pulse width modulation                                      |
| QM                  | Qualification Model                                         |
| RICH                | Ring-imaging Cherenkov (detector)                           |
| RPM                 | Revolutions Per Minute                                      |
| STS                 | Space Shuttle Mission                                       |
| TC                  | Tele-control                                                |
| TM                  | Tele-monitor                                                |
| TS                  | Thermostat                                                  |
| TTBP                | Tracker Thermal Back Plane                                  |
| Code  | Description                                |
|-------|--------------------------------------------|
| TTCB  | Tracker Thermal Component Box              |
| TTCE  | Tracker Thermal Control Electronics        |
| TTCS  | Tracker Thermal Control System             |
| TTEC  | Tracker Thermal Electronic Control Board   |
| TTEP  | Tracker Thermal Electronic Power Board     |
| TTPP  | Tracker Thermal Pump & Pressure sensors Board |
| TVT   | Thermal Vacuum Test                        |
| USS   | Universal Support Structure                |
Table 1 Functions of the TTCS main components.

| Components           | Functions                                                                 |
|---------------------|---------------------------------------------------------------------------|
| Evaporator          | To collect and transport the heat from the Tracker to the CO$_2$ loop    |
| Condenser           | To conduct the heat from the loop to the radiators that dissipate the heat to the space |
| Accumulator         | To compensate the mass of CO$_2$ in the loop and to control the operation temperature of the system |
| Pump                | To provide driving power for the loop                                     |
| Heat-exchanger      | To exchange heat between the saturated CO$_2$ and the sub-cooled liquid CO$_2$ |
| Pre-heater          | To heat the sub-cooled liquid CO$_2$ into saturated state before flowing into the evaporator |
| Start-up heater     | To avoid sub-cooled liquid CO$_2$ flow into the Tracker to damage the electronics at extremely cold environmental condition |
| Cold orbit heater   | To prevent the CO$_2$ from being cooled to the freezing point by effectively heating the fluid |
| De-freezing heater  | To defreeze the solid CO$_2$ inside the tubes from the manifolds to the condensers |
| Radiator heaters    | To defreeze the solid CO$_2$ inside the condensers mounted on the radiators |
| Component box       | To assemble the components except for the evaporators and the condensers |
Table 2 The Beta and Euler angles range of the ISS.

| Angle                | Variation Range                  |
|----------------------|----------------------------------|
| Beta angle           | $-75^\circ$ to $+75^\circ$       |
| Yaw (Z) attitude angle | $-15^\circ$ to $+15^\circ$     |
| Roll (X) attitude angle | $-15^\circ$ to $+15^\circ$     |
| Pitch(Y) attitude angle | $0^\circ$ to $+25^\circ$ with docked STS |
|                      | $-20^\circ$ to $+15^\circ$ with undocked STS |
Table 3  Summary of the minimum MofS for all the load cases.

| Components                                      | Static:MofS | Thermal:MofSs |
|-------------------------------------------------|-------------|---------------|
|                                                 | Yield       | Ultimate      |
| Accumulator                                     | 0.03        | 0.11          |
|                                                 | 0.02        | 0.02          |
| Fixed Bracket & Clamp Collar&Wedge              | 1.10        | 2.11          |
|                                                 | 1.00        | 1.82          |
| Sliding Bracket                                 | 4.01        | 3.56          |
|                                                 | 2.76        | 2.95          |
| Heat Pipe                                       | 1.05        | 2.46          |
|                                                 | 0.92        | 1.14          |
| Peltier Fixed                                   | 2.07        | 2.26          |
|                                                 | 0.51        | 1.20          |
| TS & Peltier Heat Exchanger & Peltier heat      | 0.61        | 1.13          |
| exchanger press &Spring Support                 |             | 0.68          |
|                                                 |             | 1.22          |
| Joints                                          | Static: bolt MofS | Thermal: bolt MofS |
| AccuBracket Clamp&Collar Bolt                   | 0.12        | 0.09          |
| PipeFix&Clamp Bolt                              | 0.123       | 0.122         |
| Press&Saddle Bolt                               | 0.107       | 0.106         |
Table 4 Summary of the minimum MofS for all load cases (Fail-safe)

| Component Name                                      | Static: MofS | Thermal: MofS |
|-----------------------------------------------------|--------------|---------------|
|                                                     | Yield        | Ultimate      | Yield        | Ultimate      |
| Accumulator                                         | 0.54         | 1.80          | 0.53         | 1.55          |
| Fixed Bracket & Clamp Collar & Wedge                | 1.61         | 5.17          | 1.49         | 4.66          |
| Sliding Bracket                                     | 6.91         | 8.85          | 3.68         | 6.92          |
| Heat Pipe                                           | 1.07         | 9.19          | 1.87         | 7.31          |
| Peltier Fixed                                       | 4.94         | 16.41         | 0.76         | 3.17          |
| **TS & Peltier Heat Exchanger & Peltier heat**      | **0.98**     | **3.20**      | **0.24**     | **2.64**      |
| **Joints**                                          | **Static: bolt MofS** | **Thermal: bolt MofS** |
| Accumulator.Bracket Clamp & Collar Bolt             | 0.34         |                | 0.30         |                |
| PipeFix & Clamp Bolt                                | 0.50         |                | 0.49         |                |
| Press & Saddle Bolt                                 | 0.19         |                | 0.20         |                |