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National Aerospace Laboratory NLR

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Two-Phase Developments for the International Space Station ISS:
- AMS-2 TTCS, a Mechanically Pumped Two-Phase CO_2 Cooling Loop for the Alpha Magnetic Spectrometer Tracker Experiment
- CIMEX-3, Versatile Two-Phase Loop for the Fluid Science Laboratory

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NLR's Novel Two-Phase Developments for the International Space Station ISS: - AMS-2 TTCS, a Mechanically Pumped Two-Phase CO_2 Cooling Loop for the Alpha Magnetic Spectrometer Tracker Experiment - CIMEX-3, Versatile Two-Phase Loop for the Fluid Science Laboratory

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Abstract

AMS-2 TTCS and CIMEX-3 are novel ISS-related two-phase heat transport technology developments at NLR. TTCS, the Tracker Thermal Control System, concerns the development of a mechanically pumped two-phase CO_2 cooling loop for the Tracker, the most critical part of the Alpha Magnetic Spectrometer AMS, an ISS attached international payload searching for anti-matter, dark matter and lost matter. AMS-2 is an improved version of AMS-1, the demonstration experiment that has successfully flown on STS91. AMS-2 is manifested on Shuttle flight UF-4 for a mission of over three years on ISS. CIMEX-3, NLR's Versatile Two-Phase Loop, is part of the Convection Interface Mass Exchange experiments CIMEX, to be carried out in the Fluid Science Laboratory on ISS, within the ESA Microgravity Applications Programme. The paper discusses the TTCS objectives and requirements, the trade-off based choice and experimental feasibility demonstration of the mechanically pumped two-phase CO2 cooling loop, the development of test set-ups, including and a full-scale TTCS simulation loop, and the results of experiments. It also discusses the CIMEX-3 objectives, development approach, test set-up and test results.

Key Words: Two-Phase Flow, Heat Transport, Cooling, Spacecraft Thermal Control, Microgravity.

1. AMS-2

1-1. Introduction

The Alpha Magnetic Spectrometer AMS [1] is an international experiment searching for anti-matter, dark matter and lost matter. It is a particle detector for high-energy cosmic rays, consisting of several sub-detectors: The (Silicon) Tracker, the Time of Flight (ToF) system, the Veto Counters, the Transition Radiation Detector (TRD), the Synchrotron Radiation Detector (SRD), the Ring Imaging Cherenkov Counter (RICH), and the Electromagnetic Calorimeter (Fig. 1). AMS-1, the demonstration experiment has successfully flown on STS91. AMS-2 an improved version of AMS-1 having a better resolution, is manifested on Shuttle flight UF-4 for a mission of at least three years as attached payload on ISS.

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

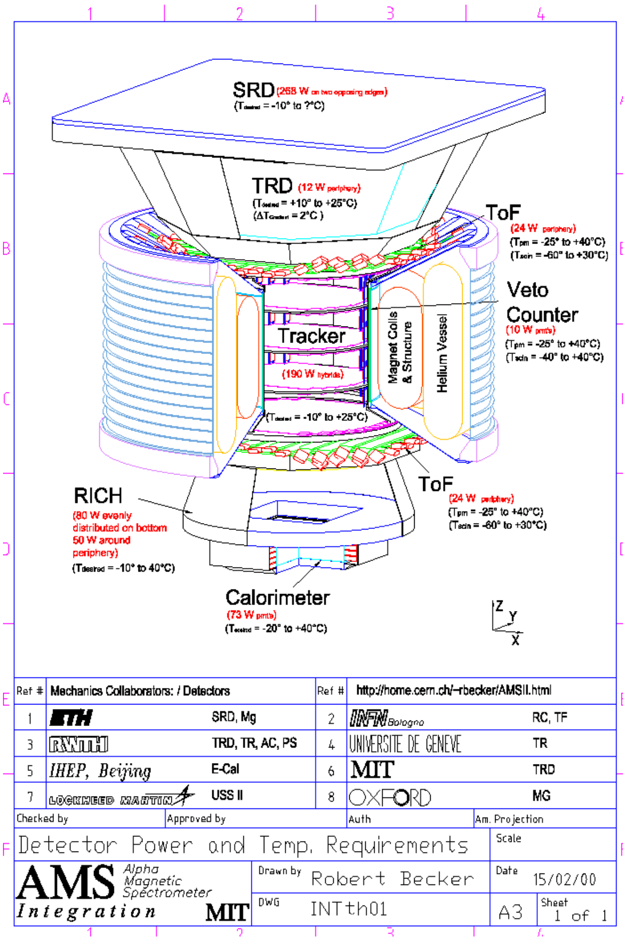


Fig. 1: The Different AMS Experiments.

1.2. Trade-off Yields CO_2 MPL as TTCS Baseline

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

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

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

Keeping the above in mind and following in the next the references 3 and 4, it can be said that:
- The series configuration two-phase Mechanically Pumped Loop (MPL) is compatible with existing Tracker hardware. It is characterised by minimal material inside or near the tracker field of view. It is directly connected to the thermal bars, hence no additional heat collector needed. Multiple source heat input is possible, with minimum T-gradients (< 1 K). It has also the possibility to implement a fully redundant system. Costs and mass are relatively low. The only drawback is the presence of a mechanical pump.
- A Single-Phase (liquid) Mechanically Pumped Loop (SPL) has more or less the same layout as the MPL option, so it is relatively easy to fall back on the SPL solution, in case of unforeseen (serious) problems with the MPL development. It has the possibility of parallel and counter-current flow system set-up. It is a low-risk design, as there is sufficient experience in space with SPL's. Main drawbacks are the far larger temperature gradients (say 10 K), as compared to the nearly isothermal MPL, and larger dimensions.
- Any parallel two-phase system (MPL, LHP or CPL) is not capable to accommodate the existing Tracker hardware (multiple location heat input), by it self in one stage, because of the huge mass and (not available) space needed, especially in case of redundancy. In a two-stage approach, an additional heat collector is needed: A heat pipe or a high conductivity TPG-flange. But this induces significant mass increase and also serious integration problems.

The above makes obvious that by far the best solution is the series two-phase MPL. A parallel or hybrid SPL is a possible back-up solution, but at the cost of more massy and lengthy lines and larger pumps. Parallel concepts are non-recommendable or impossible solutions.

CO_2 has to be the working fluid since:
- It is considered to replace Freon-like refrigerants, as it is environment friendly and non-toxic. It is used for nuclear power plant cooling, as it is inert for radioactive radiation. For AMS-2 this means no ISS safety-related problems.
- It has a very low liquid/vapour density ratio, Order (1-10), being profitable for a series 2-phase system; its alternative, ammonia: Order (10^2-10^3).
- CO_2 experience was gained at NIKHEF, where tests have proven the concept feasibility of CO_2 cooling for the LHCb Vertex detector [5]. For the Tracker this means small tube dimensions (3 mm OD) in case of 2 loops, low temperature drops (< 1 K) and low pumping power (< 10 W).

In addition it is remarked that [4]:
- The basic difference between mechanically pumped single-phase (caloric heat transport by the liquid) and two-phase systems (transport by latent heat of evaporation/condensation). This implies for dissipating stations in series in a single-phase system a temperature increase in the downstream direction of the loop. For two-phase systems, with evaporators in series, it means an increase of the vapour quality in the downstream direction, accompanied by a (usually small) decrease of the saturation temperature.
- In mechanically pumped two-phase loops, the flow pattern dependent heat transfer coefficient for convective flow boiling is reported to be between say 4 and 5 $kW/m^2 \cdot K$ [6]. This is not true for refrigerants (to be used in the TTCS) at qualities below 0.15 for which the value can increase to say 20 $kW/m^2.K$ at qualities of less than 0.03 [6, 7]. Data from experiments with

CO_2 in small diameter tubes confirm this [8]. The above implies that a mechanically pumped system has to be designed such that any evaporator exit quality is below 0.15 (preferably even much lower) for efficiency reasons.

- In the case of very lengthy mechanically pumped two-phase loop lines the pressure (saturated temperature) gradient has to be kept small to guarantee a small end-to-end pressure (saturated temperature) difference to meet the requested isothermality, and to keep the evaporator exit vapour quality below 0.15, as in flowing refrigerants the vapour quality usually increases with pressure decay [9]. Ethane is an exception: Quality increase below say 0.7, decrease above
- In conclusion: A dedicated hybrid two-phase loop configuration, as it schematically depicted in figure 2, will guarantee both the required isothermality and the preferred quality range.

1.3. TTCS Concept

The proposed TTCS is a closed two-phase system (Figs. 3-5). The heat is absorbed in the evaporators and rejected to space by the radiator panels at the condensers. As the mechanical pump provides the liquid flow rate needed, it has to be located after the condensers, as it needs pure liquid to operate properly. Hence the condensers/radiators need not only to condense all vapour, but also to provide a certain amount of sub-cooling. The blue boxes on top are heat exchangers, thermally connect inlet and outlet of the evaporator together. In this way the absorbed heat can be used to heat the entering sub-cooled liquid from the pump so it gets close to the evaporative temperature needed in the Tracker.
The evaporators consist of two parallel tubes each having an ID of 2.6 mm and a length of 10 metres.

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

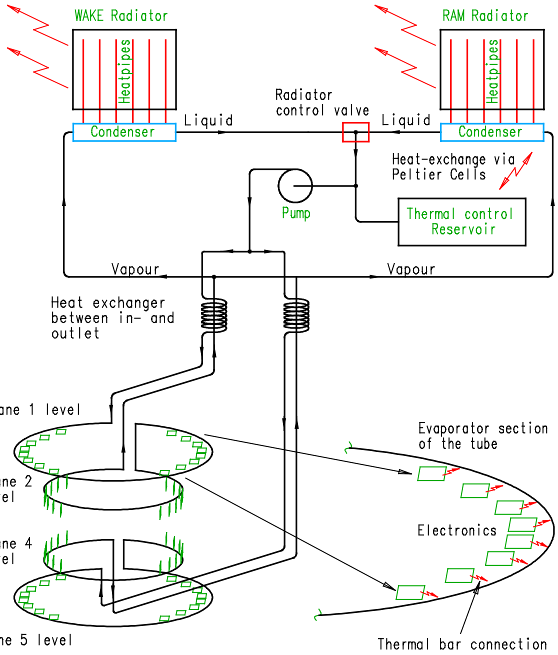


Fig. 2: Hybrid MPL Concept for the TTCS

AMS-2 radiator panels are outside the experiment. They are covered with high emissivity and low solar absorptivity coatings/paints. The two opposite radiator panels are thermally speaking out of phase, meaning that there is always one radiator shaded from the sun, hence able to radiate waste heat to space. The evaporation temperature is adjusted by the system pressure. This pressure is controlled via the accumulator, a small reservoir with a mixture of vapour and liquid. A Peltier element controls the reservoir temperature, hence the system pressure by condenser flooding. The majority of the TTCS hardware is in a box outside on the support structure. The evaporators, heat exchangers and condensers are outside this box.

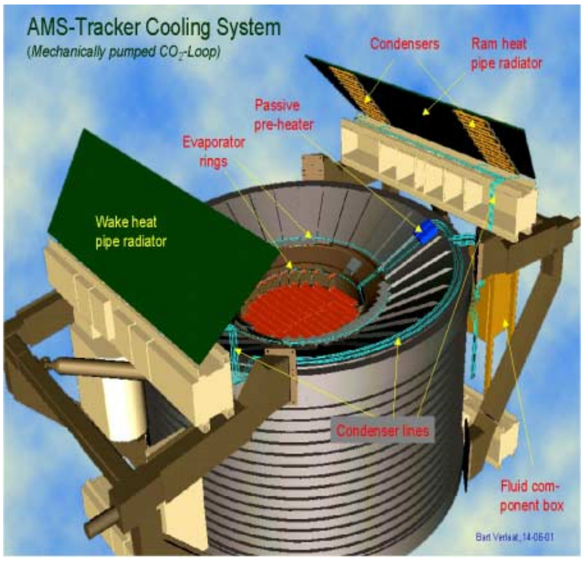


Fig. 3: Artist's Impression of Integrated TTCS

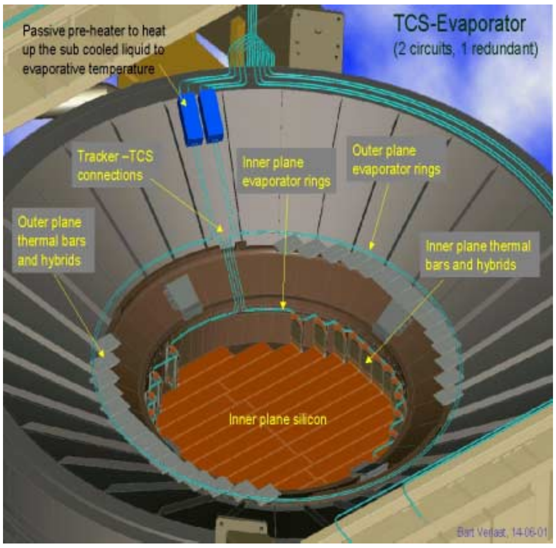


Fig. 4: Details of TTCS Evaporator

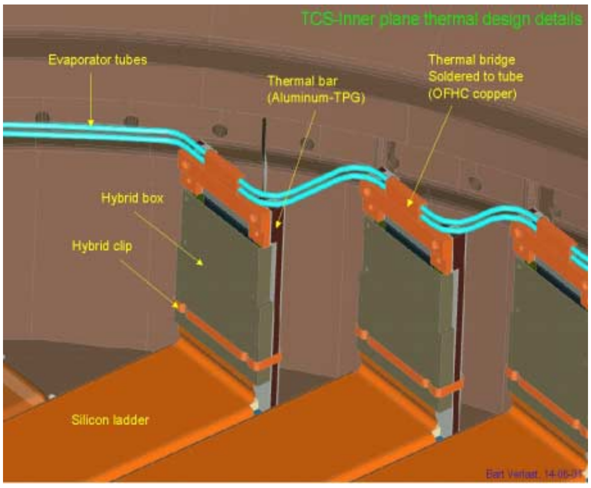


Fig. 5: TTCS Connection to Hybrids

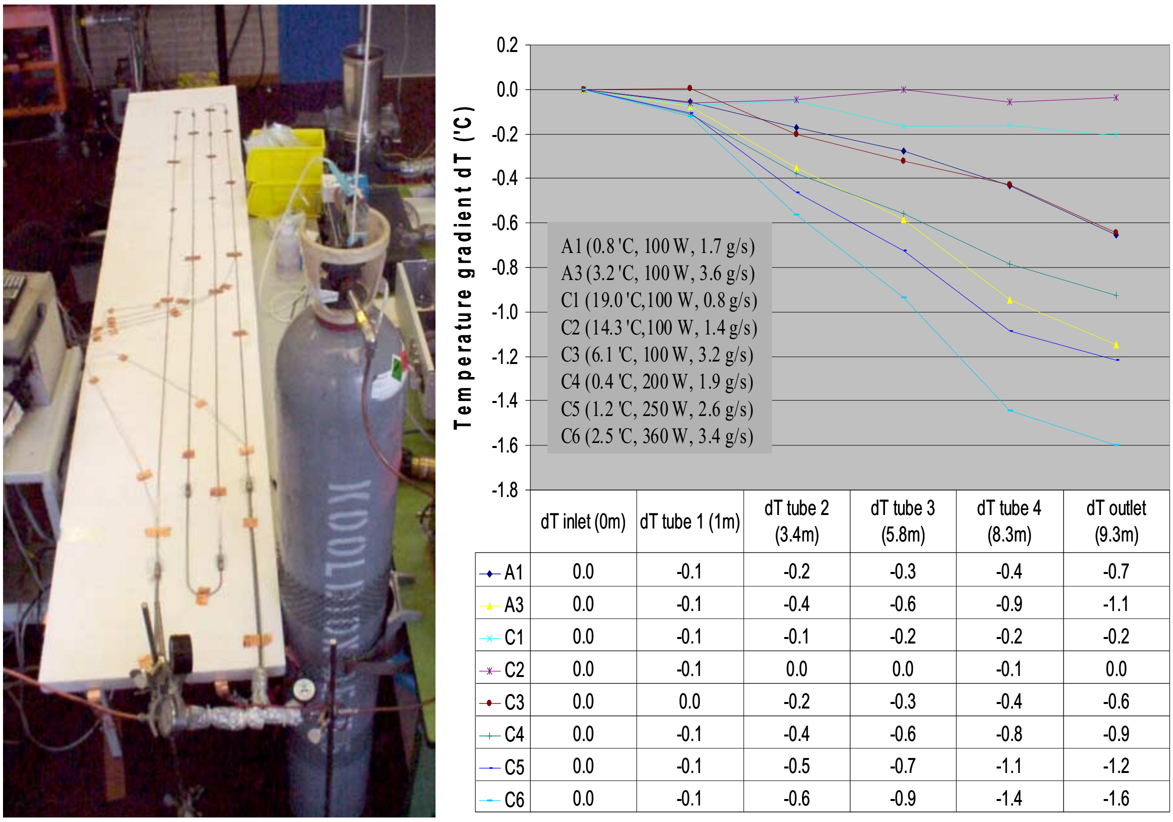
1.4. Test Set-ups and Test Results

An open test set-up [4], built at NIKHEF to prove the feasibility of the TTCS evaporator concept for CO_2, consisted of an evaporator section connected to a liquid CO_2 filled bottle. The CO_2 flow was adjusted by a needle valve, the pressure in the test tube by a spring-relieve valve (at the exit). In the real TTCS all thermal bridges are individually connected to evaporator tubes. In the feasibility test heat is applied over the test section tube wall using the electric resistance of the tube as heater. Flow, pressure drop and temperatures along the tube were measured. Figure 6 shows a picture of this test set-up and some test results, which suggest that CO_2 is an adequate refrigerant for the TTCS.

More experiments were done next, at NIKHEF [4] to confirm this in a closed loop test set-up (Fig. 7), which more realistically simulates the TTCS.

The goals of the experiments were:

- To measure the pressure drop characteristics and heat transfer coefficients at different flow rates,



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

Fig. 6: Feasibility Test Set-up and Test Results

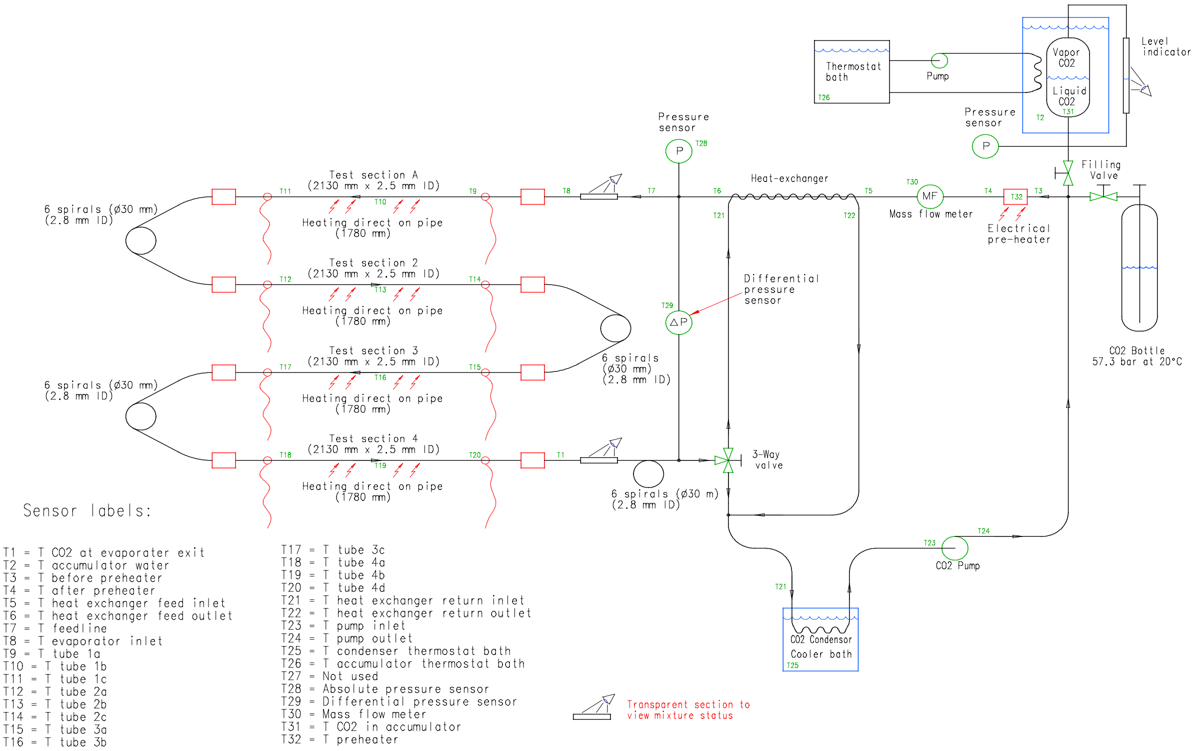


Fig. 7: Schematic of TTCS Test Loop at NIKHEF.

heat input and evaporation temperatures, using a 10 m long, 2.5 mm ID test evaporator, with helical sections between the long sections to simulate the multiple bends in the real Tracker.

- To compare the test outcomes to theoretical predictions and experimental data produced in a NIKHEF/SINTEF CO_2 test set-up.
- To prove the merits inserting a heat exchanger (as pre-heater) between evaporator in- and outlet.
- To yield recommendations for further TTCS development, on pumping rates and evaporators.

Though many experiments were executed [10], the results given here pertain only to the 10 m long, 2.5 mm ID evaporator performance, i.e.:

- Figure 8 showing the pressure and temperature drops, as a function of the mass flow, at 273 K.
- Figure 9 showing the heat transfer coefficients and observed flow patterns versus vapour quality

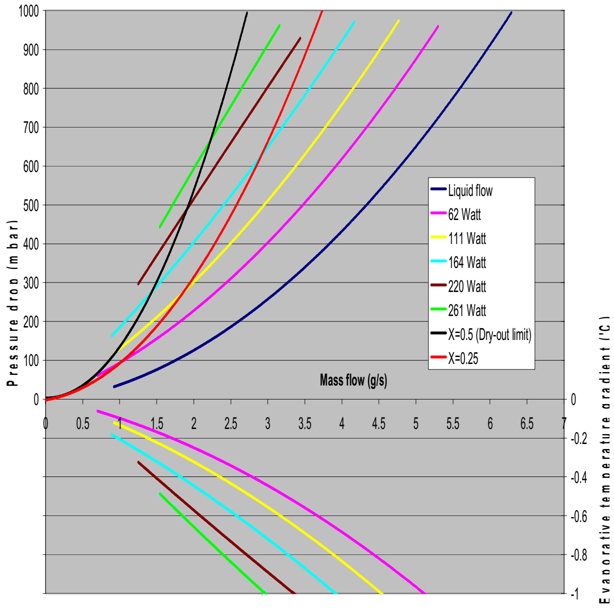


Fig. 8: Power Dependence of Pressure & Temperature Drops at 273 K

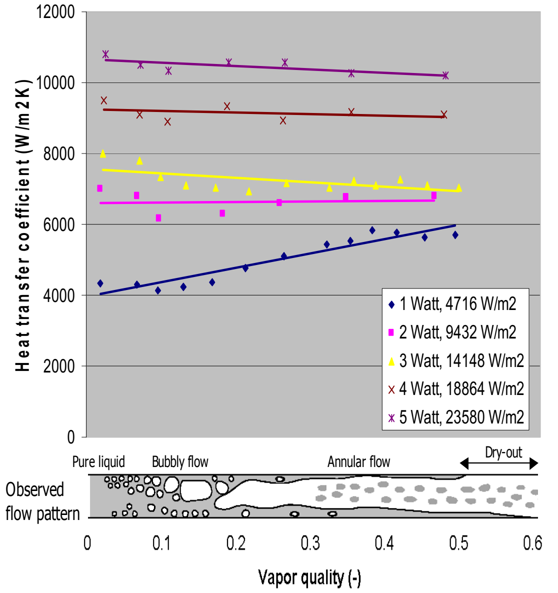


Fig. 9: HTC and Power (Density) Versus Observed Flow Patterns & Vapour Quality, at 2.7 g/s & 278 K

and heat flux, at 278 K and nominal flow 2.7 g/s.
Finally it is remarked that preliminary test results confirm the usefulness of the presence of a heat exchanger as pre-heater between the in- and outlet of the evaporator. It was observed that up to say 90% of the heat collected in the evaporator could be reused for pre-heating the sub-cooled liquid coming from cold radiators. This amount of heat replaces part of the power to be added to the electric pre-heater that has to condition the liquid such that the fluid entering the evaporator is a pure liquid, close to saturation temperature as desired. It is obvious that the above yields a substantial power saving. Apart from this power saving impact, it can be said that the presence of the heat exchanger has also a stabilising effect on the temperature excursions of the evaporator during orbital radiator temperature variations.

1.5 Full Scale Test Rig

Next step in the development was the creation of a full-scale test set-up at NLR to more realistically simulate the TTCS. A preliminary rig was designed and built. Based on experimental results obtained with this rig, the full-scale test set-up was designed and manufactured. Figure 10 shows the schematic, and a photograph of the current set-up in the NLR climate chamber. Details are shown in figure 11, evaporators, and 12, a specimen and element of the baseline TTCS condensers, which will interface the Ram & Wake heat pipe radiators (Fig. 3).

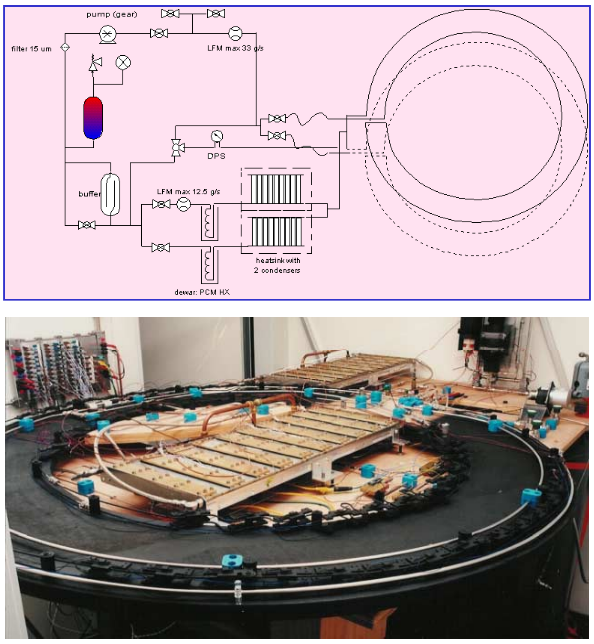


Fig.10: Schematic/Photograph of Test Rig at NLR

The first experiments with this full-size test set-up yielded very encouraging results: The pressure drops across the system turned out to be even smaller than predicted. Consequently a very good isothermality is envisaged.

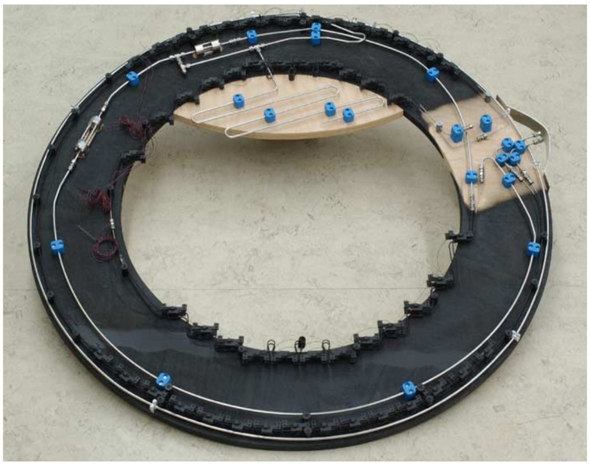


Fig. 11: TTCS Evaporators

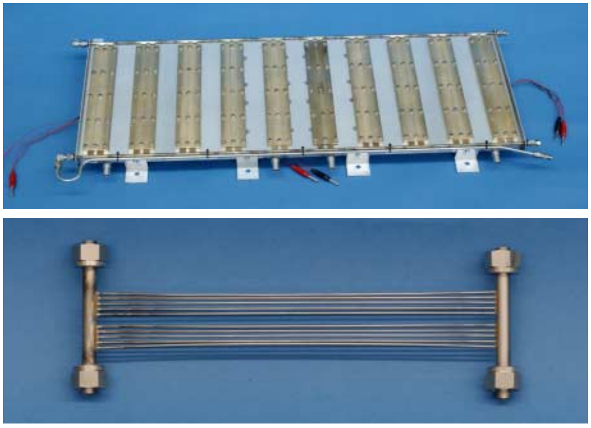


Fig. 12: TTCS Condenser & Condenser Element

1.6. Thermal Modelling

Calculations with a very detailed transient TTCS model have been done for eight possible orbital (environmental loading) cases. The outcomes indicate that:

- The TTCS will operate without problems at the nominal loop set-point temperature 273 K, for the nominal case and most other thermal loading cases.
- The set-point temperature of the loop has to be increased by up to say 10 K in some hot orbital cases.
- The incorporation of the heat exchanger between evaporator in- and outlet considerably reduces the pre-heater power needed.

Currently the model is being refined and more accurate environmental loading conditions are expected to be provided by the "AMS Overall Thermal" main contractor. Using these new boundary conditions, new calculation runs will be carried out, but only after integrating useful data obtained from the full-size test rig experiments.

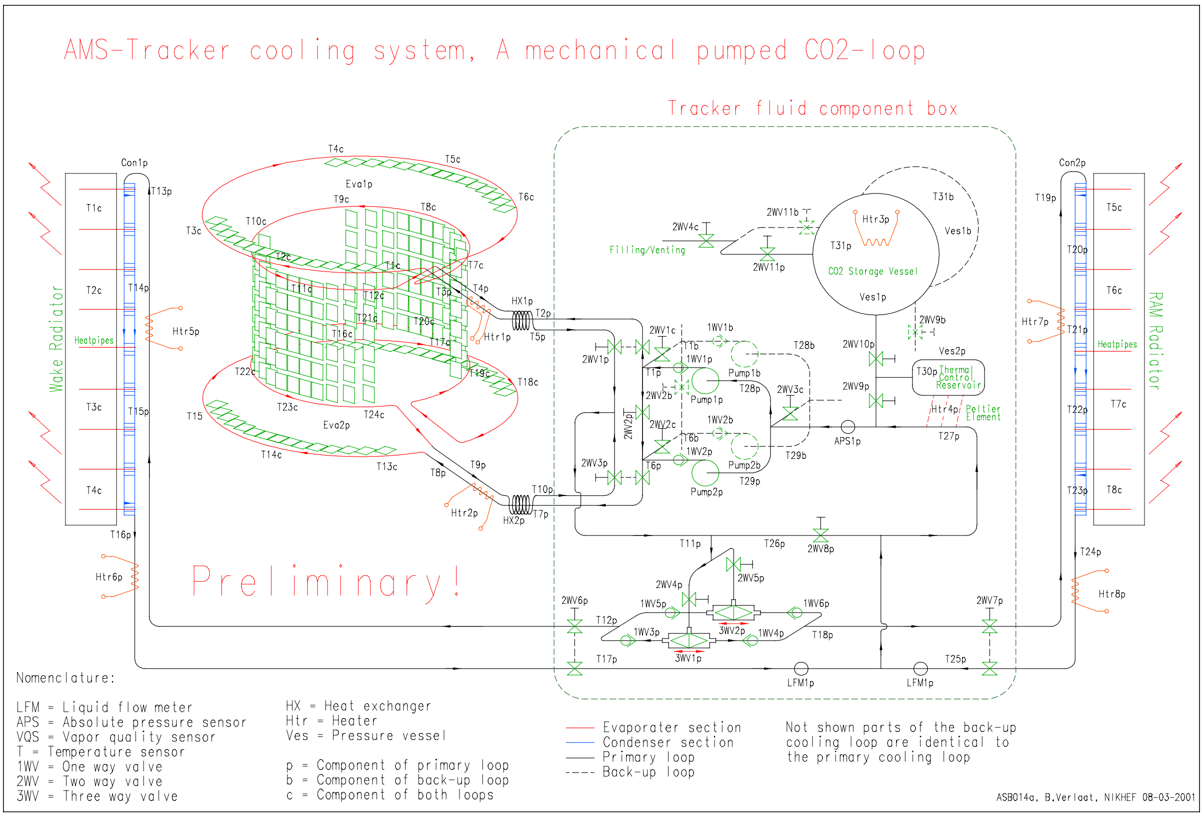


Fig. 13: Preliminary Fully Redundant TTCS, Equipped with Extra Experiment Components

1.7. In-orbit Experiments & Concluding Remarks

Apart from the challenge to develop a novel two-phase thermal control system for such an advanced experiment as AMS-2, NLR interest also pertains to the acquiring of in-orbit experience with real two-phase thermal control systems. NLR joined the AMS Collaboration, as it was guaranteed that the AMS-2 dormant (non-operation) periods could be used by NLR to execute dedicated experiments to study in-orbit two-phase heat transport system technology issues. Therefore the TTCS will be equipped with some extra heaters, sensors, and meters. The baseline philosophy will be that:

- There is minimum risk for Tracker and AMS-2.
- Any period AMS is not active can be used for thermal experiments
- There is at least one week of thermal experiments during the first six months
- Minimum power and mass will be added.
- The TTCS loop will, in principle, not be intruded.

Figure 13 depicts how such a fully redundant, for extra NLR experimenting equipped, TTCS can look like. However, it can already be said now that AMS-2 overall mass reduction certainly will lead to a less complicated system by partly reducing the redundancy level required and by the deleting of some components.

As said before the mechanical pumps are critical issues in the TTCS, because of:

- The almost complete lack of in-orbit experience with mechanical pumps, certainly not for long duration missions as the AMS-2 mission.
- The working fluid CO_2, which has to operate at set-point temperatures, which can be relatively close to critical point.

As a consequence of the above, the baseline TTCS philosophy is to include two or even three pumps per loop. These currently developed pumps are upgraded versions of the Mars Rover pump, being adapted for CO_2-operation.

In conclusion it can be said that, though there is much work to be done, the Tracker Thermal Control System is on the proper track.

2. CIMEX-3

2.1. Introduction

Convective Interfacial Mass Exchange Experiment CIMEX (Fig. 14) is a project in ESA's Microgravity Application Promotion programme, consisting four different experiments to be carried out in the Fluid Science Laboratory (FSL), aboard the ISS. One experiment is CIMEX-3, NLR's Versatile Two-Phase Loop Experiment: A multi-

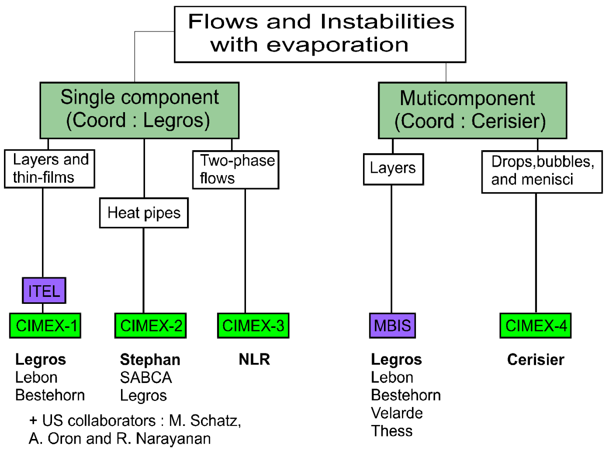


Fig. 14: CIMEX 1 to 4 Experiments for the FSL

purpose loop with a mechanically and a capillary pumped option, different types of evaporators (capillary and swirl), and the possibility to operate using different working fluids. The complete rationale behind CIMEX-3 (Ref. 12) will be summarised next.

Primary objectives of the CIMEX-3 experiment (Fig. 15) are to study micro-g two-phase flow and heat transfer issues, by developing transparent (swirl) evaporators and high efficiency low pressure drop condensers, by measuring void/mass fraction in the adiabatic line for the Vapour Quality Sensor (VQS) calibration, by flow pattern characterisation and creation of flow pattern maps, and by the viability demonstration of Mechanically and Capillary Pumped two-phase Loops (MPL & CPL). Different working fluids or mixtures will be used. The justification for studying the different topics will be elucidated.

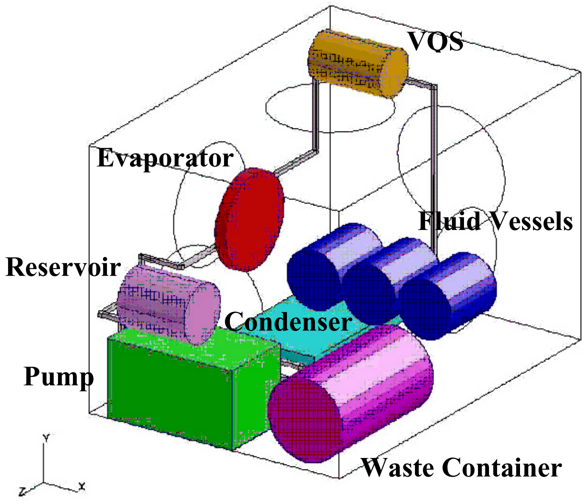


Fig. 15: NLR's Versatile Two-Phase Loop CIMEX-3

In addition, the CIMEX-3 loop may accommodate some other CIMEX experiments, for instance to study the impact of Marangoni-convection on heat transfer and evaporation, to study micro-scale heat and mass transfer in single-groove structures, in new heat pipe capillary structures and in new capillary evaporators, and to study instabilities near drops and bubbles.

2.2. Development Activities

The first step in the development of a versatile two-phase loop for CIMEX-3 was the design and manufacture of a two-phase test rig in order to develop and study the functioning of candidate components for the CIMEX loop. This test loop (Fig. 16) consists of a pump, liquid flow meter (LFM), swirl evaporator, reservoir (accumulator), condenser and transparent sections. The black dots are thermocouples. Only 5 thermocouples are drawn on the evaporator, though 15 are present. The loop can be operated with different working fluids, different evaporators and condensers. As first iteration towards a transparent swirl evaporator, a swirl evaporator of copper piping soldered on a copper plate was built. After some improvements of the instrumentation and the data-acquisition, a first series of measurements with this copper evaporator was carried out in the ethanol filled test loop.

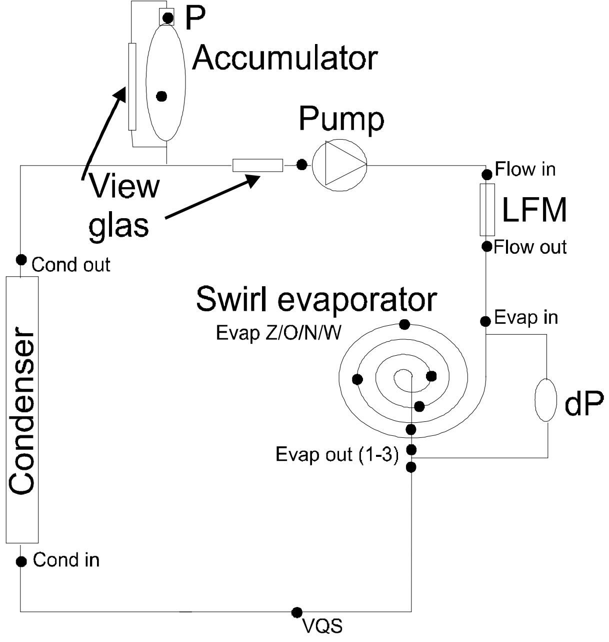


Fig 16: Test Loop Schematic.

The preliminary results were encouraging although not conclusive. Figure 17 depicts, as example, the temperature histories during power steps from 0 to 90 W, for some reservoir temperature set-points. Figure 18 presents a photograph of the copper evaporator and an infrared picture of this swirl evaporator during test.

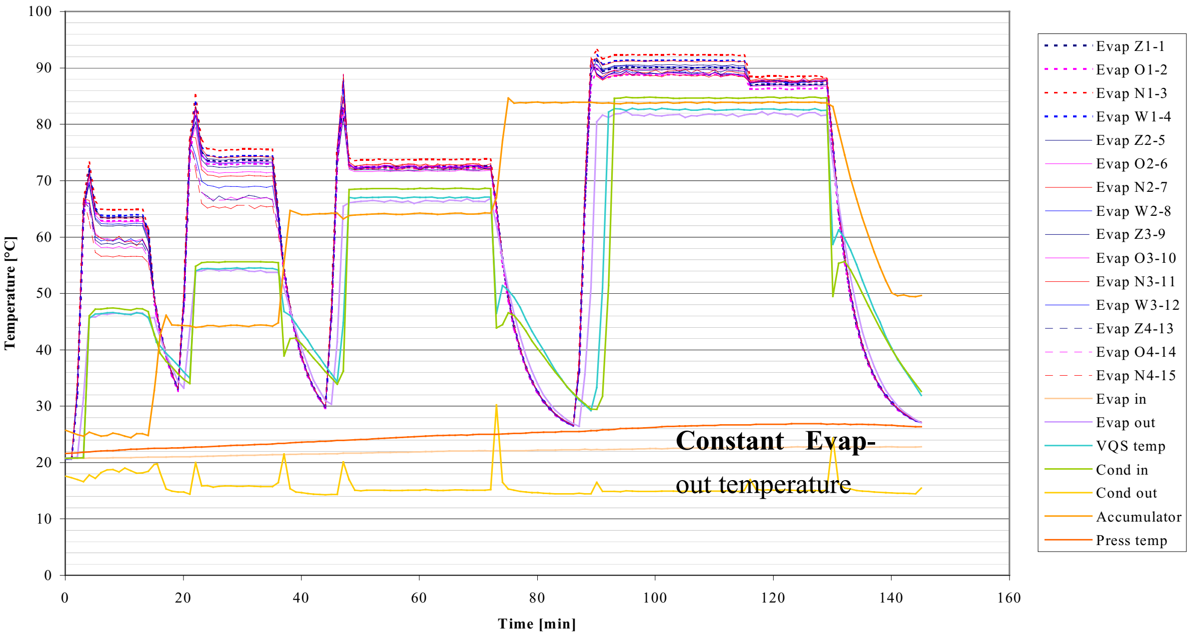


Fig. 17: First Experimental Results Obtained in the Ethanol-Filled Test Loop

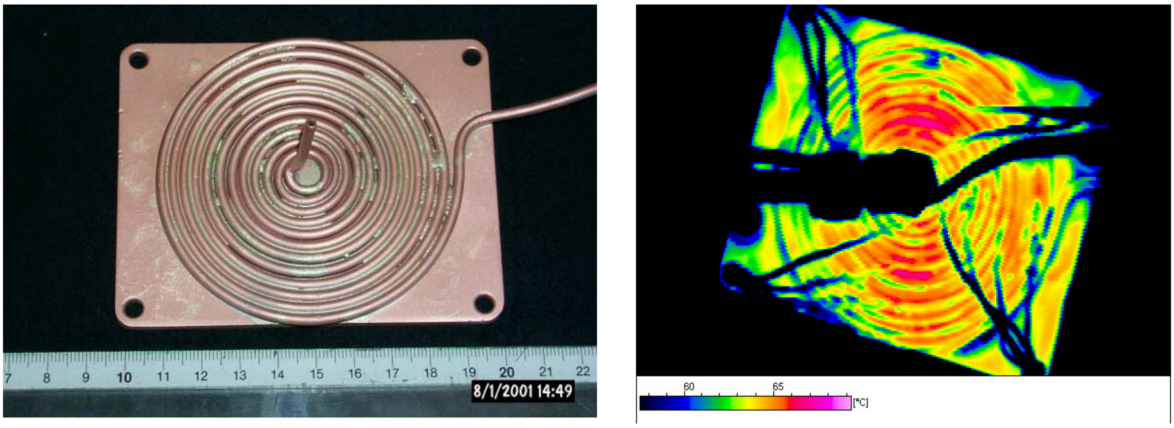


Fig. 18: Picture and Infrared Image of Copper Tubing Swirl Evaporator

Many experiments have been carried out to measure the dynamic behaviour of the two-phase system. Especially the behaviour at the inception of evaporative cooling and during flow pattern changes was and is being studied. In parallel a transparent swirl evaporator has been manufactured (Fig. 19).

Fig. 19: Picture of the Glass Swirl Evaporator

An illustrative experimental result was obtained for a mass flow of 0.2 g/s, by stepwise changing the applied power input by 45 W every 75 minutes, starting at zero W, going up to 90 W, and going back to zero.. The resulting temperature histories are presented in figure 20. Clearly visible is the phenomenon of superheating after the first time the power of 45 W has been applied. After evaporation has started, the temperatures on the evaporator decrease, and the pressure drop increases because of the created vapour. In addition it can be noted that the temperature of the liquid/vapour mixture after the evaporator is hardly changing. Only the vapour quality changes.

The experiments with a continuous increase of the heat input, followed by a continuous decrease show similar results (Fig. 21). However, the superheating is more pronounced in this case.

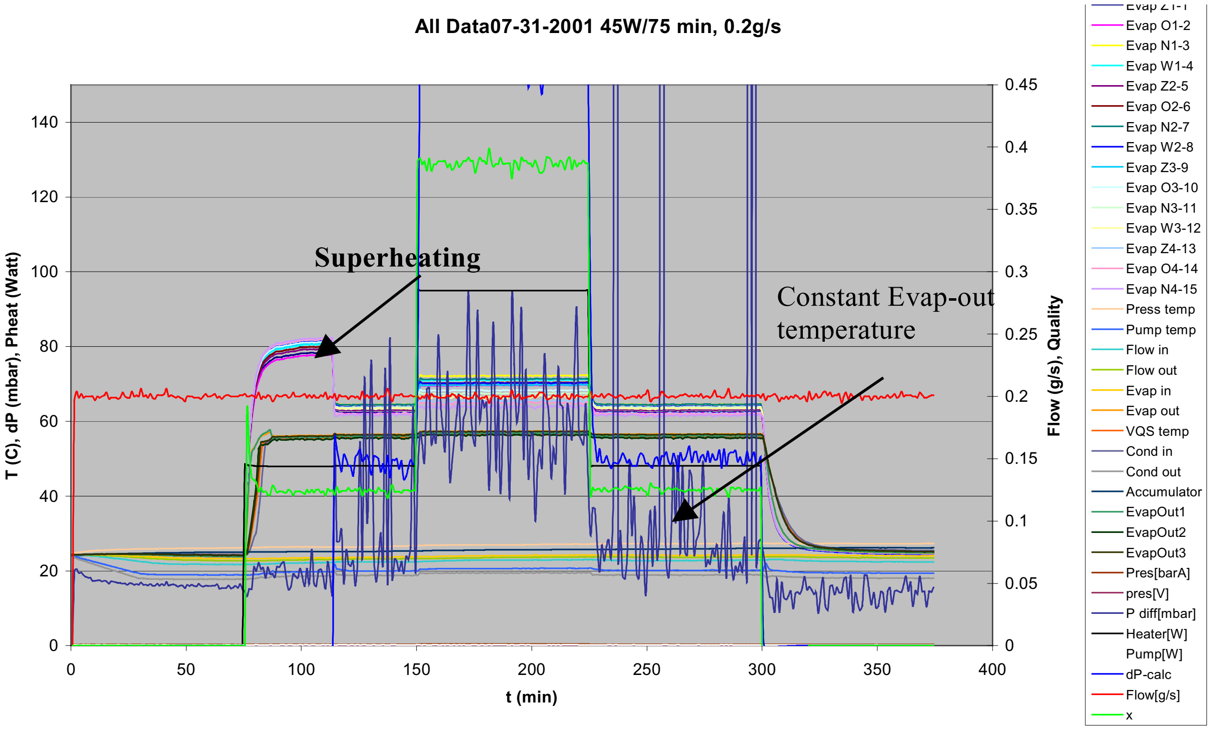


Fig. 20: Loop Temperatures Responses for a Stepwise Increase and Successive Decrease of Heat Input

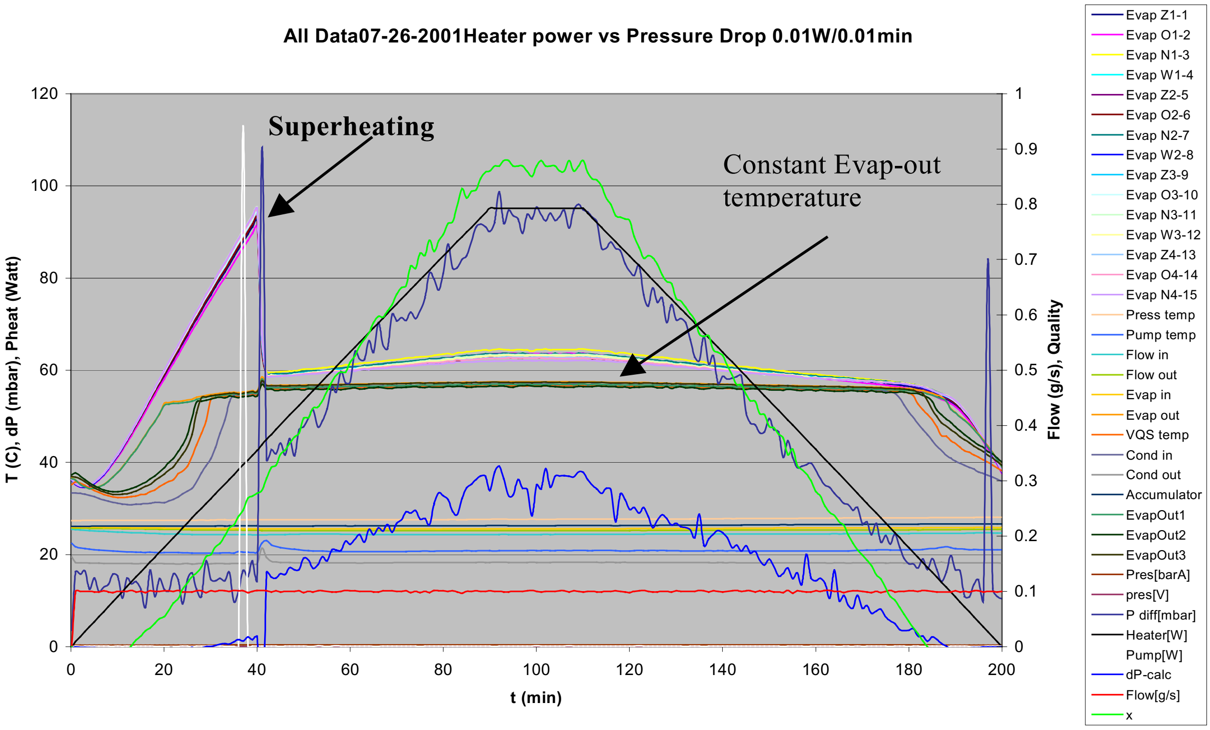


Fig. 21: Loop Temperatures Responses for Continuous Increase and Successive Decrease of Heat Input

2.3. Concluding Remarks

As a result of all experiments done the following issues were proposed and are currently carried out:

- The differential pressure sensor (DPS) will be re-located such that it is in the same horizontal plane as the evaporator. This is done to increase the stability, hence the accuracy of the pressure drop measurements.
- An extra evaporator is added in front of the swirl evaporator: Powering this additional heater, while zero power is fed to the swirl evaporator, will yield basic information on the pressure drop across the swirl evaporator as a function of the mass flow rate, and of the entering vapour quality and observed flow pattern. It may also give fundamental information on the flashing phenomenon: Change of the vapour quality and

flow pattern, not by heat addition or withdrawal, but because of pressure decay. Transparent sections will be added in the loop for flow pattern observation (e.g. with video equipment).

- The manufacturing of some swirl evaporators with larger internal tube diameters.
- The incorporation of the NLR developed turbidity sensor as vapour quality sensor.
- FC-87 will replace ethanol as working fluid.

3. NOMENCLATURE

AIP	American Institute of Physics
AMS	Alpha Magnetic Spectrometer
APS	Absolute Pressure Sensor
CIMEX	Convective Interfacial Mass Exchange
CPL	Capillary Pumped Loop
DAC	Data Acquisition System
DPS	Differential Pressure Sensor
DP	Pressure Difference (Pa or mBar)
FSL	Fluid Science Laboratory
HTC	Heat Transfer Coefficient (W/m^2.K)
INFN	Italian Institute for Nuclear Physics
ISAS	Inst. of Space & Astronautical Science
ISS	International Space Station
LFM	Liquid Flow Meter
LHP	Loop Heat Pipe
MPL	Mechanically Pumped Loop
NIKHEF	Dutch Inst. for Nuclear & Particle Physics
NLR	Dutch National Aerospace Laboratory
RICH	Ring Imaging Cherenkov Counter
SPL	Single-Phase Loop
SINTEF	Norwegian Foundation for Scientific and Industrial Research
SRD	Synchrotron Radiation Detector
STS	Space Transportation System (Shuttle)
TC	Thermal control
TM	Thermal Model(ling)
ToF	the Time of Flight
TPG	Thermal Pyrolytic Graphite
TPHTS	Two-Phase Heat Transport System
TRD	Transition radiation Detector
TTCS	Tracker Thermal Control System
VQS	Vapour Quality (Mass Fraction) Sensor

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