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TRL 5 Tests of a Sub-Scale LH2 Feed Line Evaporation Cooler

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Abstract
Propellant conditioning is a challenge for the development of cryogenic upper stages with re-ignitable main-engines. The VINCI engine needs for its operation propellant under specific conditions w.r.t. pressure and temperature to avoid cavitation inside the propellant pumps. After long ballistic phases the temperature of the propellant can increase to respective saturation temperature of the tank pressure due to radiative solar heating. By means of the proposed feed line evaporation cooler 1stly the usual release of the tank pressure for thermally conditioning the propellant and 2ndly the follow-on re-pressurization of the tank with Helium can be avoided. Furthermore, this feedline evaporation cooler allows cooling only the propellant amount that is actually consumed by the engine. In this paper the design of the EC test unit, the LH_2 test bench and respective results of the tests performed with LH_2 will be presented in order to demonstrate the technology's capability and readiness. Additionally, a possible design and assembly on the A6 upper stage propulsion module is suggested.

1. Introduction

The necessity of propellant conditioning is a new challenge for the development of cryogenic upper stages with re-ignitable main engines. E.g. the VINCI engine of the upper stage of Ariane 6 launcher needs for its operation propellant under specific conditions w.r.t. pressure and temperature to avoid cavitation in the impeller regions of the propellant pumps in order to guarantee the required engine performance. After long ballistic phases, the temperature of the propellant can increase to the respective saturation temperature of the tank pressure due to radiative solar heating. The usually applied propellant cooling strategy is a release of the tank pressure in order to cause boiling of the propellant inside the tank. However, this method requires a consecutive re-pressurization with gaseous Helium including the associated storage keeping within high pressure Helium vessels. By means of the proposed feed line evaporation cooler firstly the pressure release for conditioning the propellant and secondly the re-pressurization with Helium can be avoided. Thirdly, the proposed feedline cooler allows cooling only the amount of actual consumption of the engine. The evaporation heat of the propellant is also used for the cooling inside the evaporation cooler (EC). This can be performed externally of the tank inside a capillary tube bundle heat exchanger which has proven to be the most promising design concept. The cooled primary stream flows axially in the external compartment around the tubes of the bundle configuration while the evaporating secondary stream flows through the tubes at a highly reduced pressure (and thereby also reduced saturation temperature). This heat flux generating stream causes a Hydrogen loss, which flows consequently without any further usage into the vacuum of space. In order to minimize the evaporation mass consumption, an optimization of the tube bundle configuration is necessary. Ideally, this mass flow gets close to the theoretical value derived from the enthalpy balance between the two fluxes. Another criterion is the heat transfer to heat exchanger weight ratio which has to be maximized.

In the framework of the DLR co-funded program PREPARE, a downscaled functional unit (~1:180) of the original evaporation cooler was built to demonstrate in dedicated tests with liquid Hydrogen the general feasibility and confirmation of the expected cooling power under vacuum conditions. The capillary tube diameter, tube length, tube distance and tube arrangement of this functional unit was chosen identically to the projected original. Beside the EC design, the manufacturing process was the 2nd column of the project. The necessary spacer discs have not only an influence on the efficiency of the heat transfer and on the flow pressure loss in the outer compartment but comprise particularly a supporting role for dynamic structural loads. The load capability was verified by a numerical analysis of the functional unit by application of the respective Ariane 5 dynamic load specifications.

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2. LH2-Evaporation Cooler

The scope of the application of the LH2-evaporation cooler is to enable missions with cryogenic upper stages including long ballistic phases where LH2 heats up to the saturation temperature of the corresponding propellant tank pressure in the range between 3 and 4 bar. The VINCI engine needs LH_2 with $T < 23.6$ K ($p_s = 2.41$ bar) at the LH_2 pump inlet. The temperature reduction prior to the line chill-down is performed by evaporation cooling of propellant via de-pressurization inside the tank (e.g. ullage blow-down to 1.6 bar; $T_s = 22$ K) which makes a GHe re-pressurization necessary after T-conditioning to 22 K inside the LH_2 tank (e.g. 90 g/s for ~4 min). The consumption of GHe is >16 kg plus dry mass of He-storage tank of each ~92 kg incl. weight for tubing, fixation struts and brackets.

By means of the LH_2 evaporation cooler, the tank de-pressurization can be avoided and only the amount of LH_2 flowing to the engine has to be cooled down. The advantage is that the evaporation heat is used externally of the tank compartment for LH_2 cooling. The cooled main stream (e.g. 4.64 kg/s for a thrust level of 130 kN) flows externally around the evaporation cooler tubes. The evaporated partial stream (e.g. 0.24 kg/s for a thrust level of 130 kN) flows through the tubes at highly reduced pressure (e.g. for 2 K temperature decrease). The cold producing evaporation stream represents a LH_2 loss.

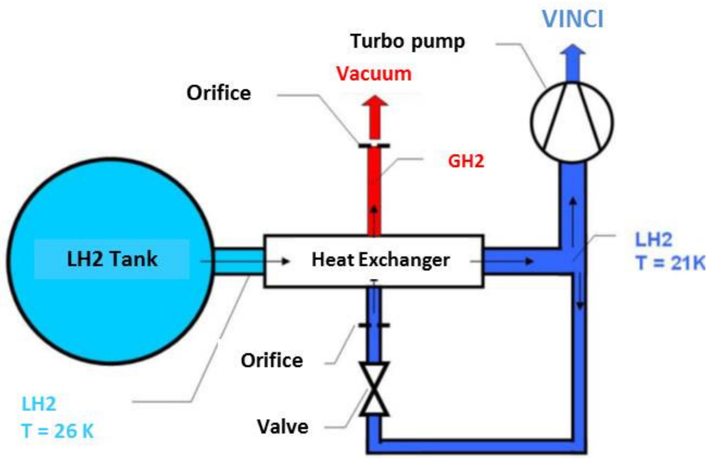

Fig. 2-1: Principal Sketch of the Feed Line Evaporation Cooler

This new technology can be operated repeatedly. It replaces a part of the feed line between the LH_2 tank and the VINCI engine, see Figure 1-1. By means of an automatic valve, the evaporator is switchable to on/off at any time. A kit principle is possible for stage assembly. Every tube has its individual calibrated injection nozzle. The number and length of the evaporation cooler tubes is adjustable: the number mainly scales to the cooling power; the tube length mainly scales to the achievable temperature difference.

The design of the tube bundle configuration has to be optimized to the theoretical value for Hydrogen consumption at lowest possible pressure loss. The evaporator tube diameter, length, distance, arrangement and LH_2-injection design should be identical to a later original 1:1 scale flight model. The optimization of the chosen rod baffle-design w.r.t. machining and assembly offers the supporting role for static and dynamic loads. Therefore, the manufacturing process is the 2nd design objective of the project: the focal point is material choice, assembly, joint and connection technique. The mass estimation of the evaporation cooler is ~30 kg in stainless steel configuration and ~20 kg in Aluminium alloy configuration. Around 10 to 20 kg additional mass has to be taken into account for valve, flanges, connecting pipe segments at in-/outlet and struts & brackets. The utilization of non-usable “thermal” LH_2 residuals inside the tank is also possible.

3. Design and Manufacturing of FM-7R

The Al-alloy AW6060 (AlMgSi0.5) was chosen as the heat exchanger base material, because it has good heat conductivity values at 20 K, can be welded, soldered and precipitation heat treated for increasing material properties after welding and is available in many variants of semi-finished parts due to its wide application range. Capillary

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tubes 4x0.2 mm are available, but rather rare at Al-venders. For the injetion disc with the 7 conical bore holes, stainless steel 1.4571 was chosen due to its better machinability.

After having finalized the thermal design, all relevant dimensions for FM-7R were determined incl. establishing the whole set of manufacturing drawings for the sample SP01 which was used for evaluation of the joint connection by EB-welding parameters for the head plate/capillary tubes as shown in Figure 3-1 and 3-2.

Fig. 3-1: EB welding Sample SP01

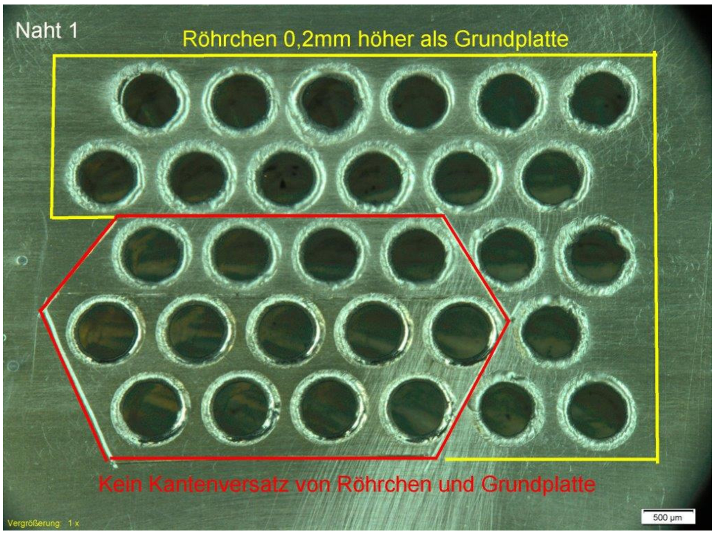

Fig. 3-2: EB Head Plate welding on SP01

Before the welding process, a heat treatment of the outer tube segments was performed to modify the material state from H18 to T4.

After having fixed the welding parameters, the drawings of FM-7R were finalized and all the piece parts were manufactured and EB-welded acc. to the drawing set. A microscopic inspection of the weld confirmed the good welding result. Helium leak tests were performed with 4 bar overpressure in the compartment around the tubes, before and after a 5 min. proof pressure test performed with a water pressure of 30 bar. This was followed by cleaning with water incl. cleanliness level verification and drying with Nitrogen.

Figures 3-3 and 3-4 show the respective piece parts of SP02 EB-welding sample series per CAD drawing where each sample is composed of two 20x1x96 mm tube segments and a simplified version of the rod spacer disc. About 10

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samples have been manufactured. In Figure 3-5, the microsope view of one of SP02 EB-welding samples is shown. This type of sample served as evaluation hardware for an optimization of the EB-welding parameters used for the joint connection of the outer tube/rod disc. The gap visible in Figure 3-5 was decreased by a reduction of the related component part machining tolerances in the vincinity of the weld connection.

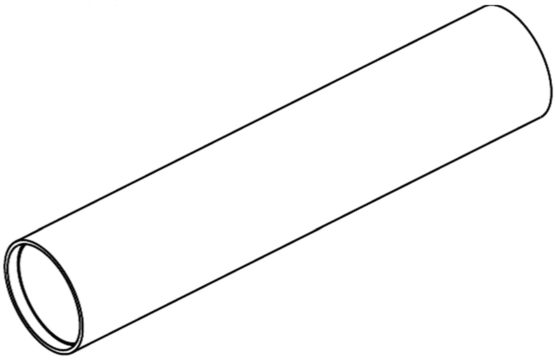

Fig. 3-3: SP02: Pipe 20x1x96 mm in Perspective

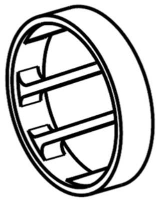

Fig. 3-4: SP02: Rod Spacer Disc in Perspective

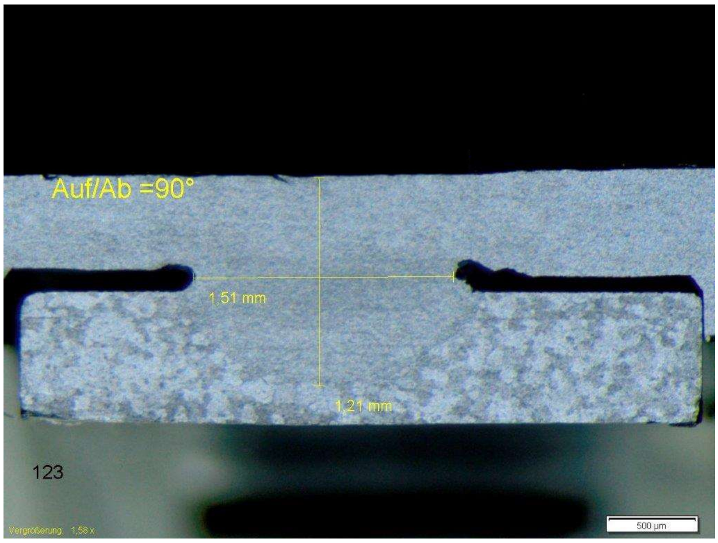

Fig. 3-5: EB Circle Test Welding on a SP02 Type

The functional unit FM-7R is shown in its entirety and its details in Figure 3-6. It has been equipped with 10 resistive temperature sensors type Cernox CX-1070 attached by InSn brazing with equidistant spacing along the external tube for which a special brazing procedure was elaborated.

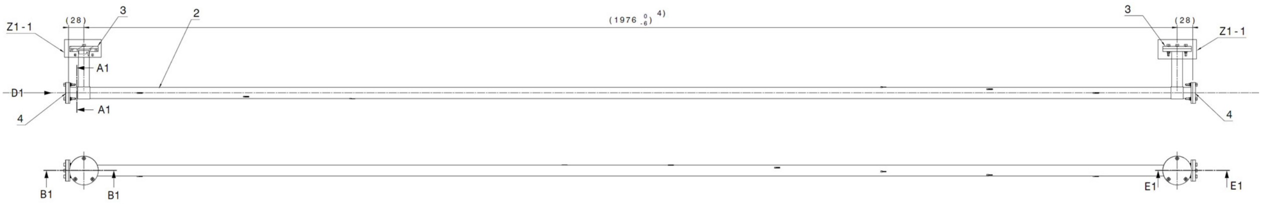

Fig. 3.6: FM-7R Evaporation Cooler

Figure 3-7 shows piece parts of the evaporation cooler which were subjected to a fit-check. They consist of:

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- outer tube with internal evaporator tube bundle and rod spacer discs
- inlet and outlet connection at the top ends of the outer tube
- distribution volume with double-sided connection and interchangeable entry swirl orifice for evaporator tubes
- evaporator tubes inlet and outlet connection

The weld distances are 96 mm between the outer pipe segments with respective internally welded and 120° cyclically twisted rod spacer discs for fixing the tube bundle.

The functional unit FM-7R served for design verification of the hardware and of the predicted cooling power for liquid Hydrogen at saturation state for LH_2 propellant tank pressure level to lower the propellant temperature to an acceptable level for the subsequent main engine. The evaporation cooler has to be compatible under cryogenic conditions and be sufficiently insulated against the terrestrial thermal environments with LH_2/GH_2.

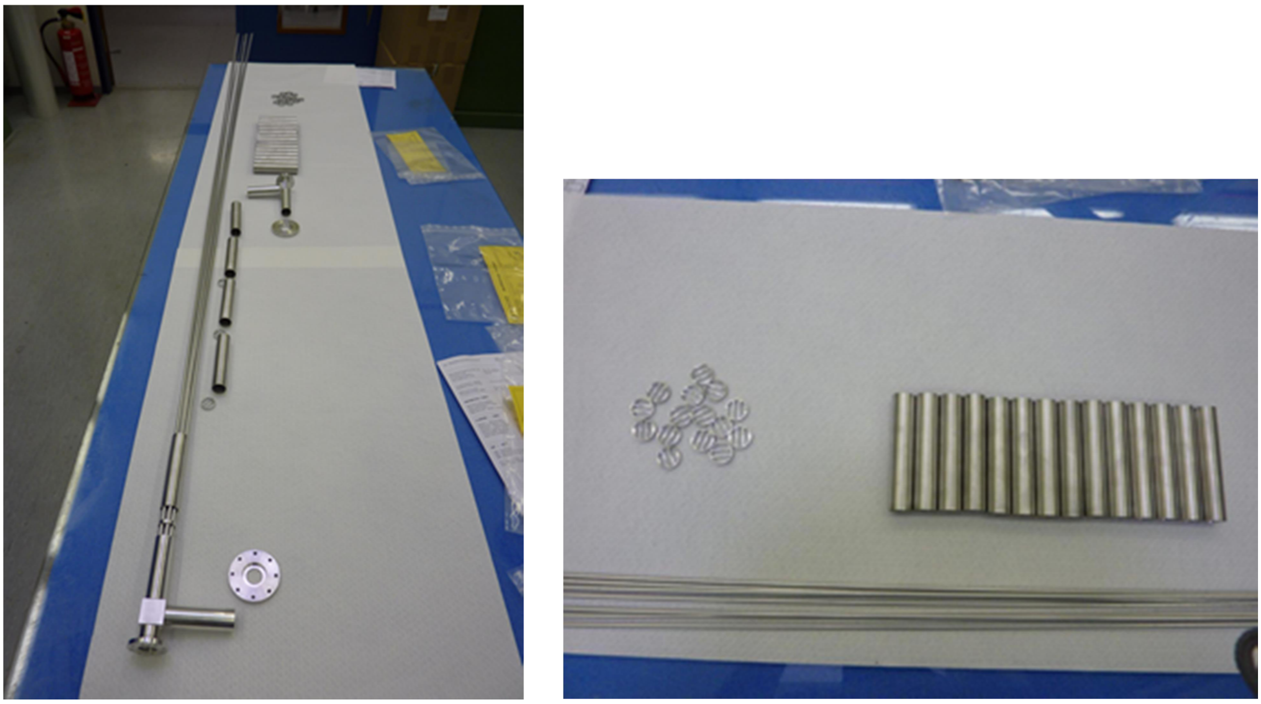

Fig. 3-7: Piece Parts of the Functional Unit FM-7R during Fit-Check

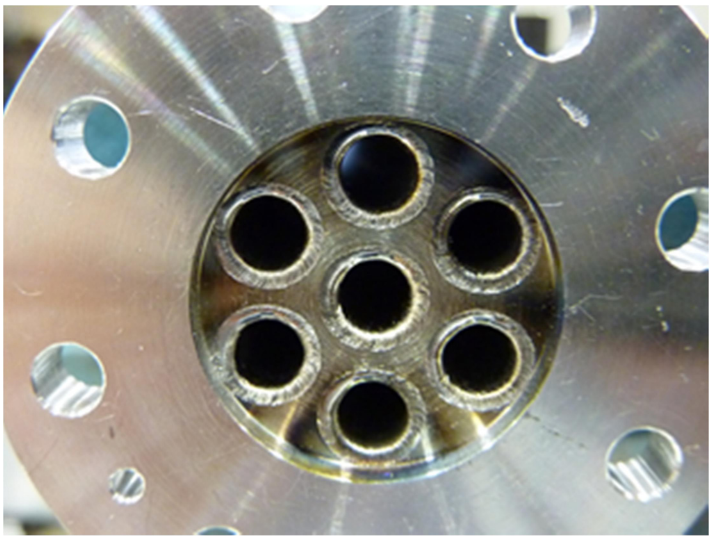

Fig. 3-8: Welded Head Plate of the Functional Unit FM-7R

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In order to evaluate the head plate EB-welding as shown in Figure 3-8, 10 tensile test samples were manufactured. The results with precipitation heat treatment of 160°C/18h showed an averaged tensile strength value of 205 N/mm[2], i.e., an increase of strength of ~90% w.r.t. material state T0 obtained after welding in the heat impacted zone.

4. Liquid Hydrogen Test Bench

The development and assembly of the LH_2 test bench, Figures 4-1 to 4-4, as well as respective LH_2 tests were performed in the framework of a subcontract at DLR Lampoldshausen, a large scale rocket motor test facility situated in the south of Germany. The user installation was set-up in P8 test cell TC2, see Figure 4-1. In Figure 4-2, the heat exchanger test bench as a schematic with its principal piece parts is shown.

Fig. 4-1: View of LH_2 User Installation inside P8 TC2

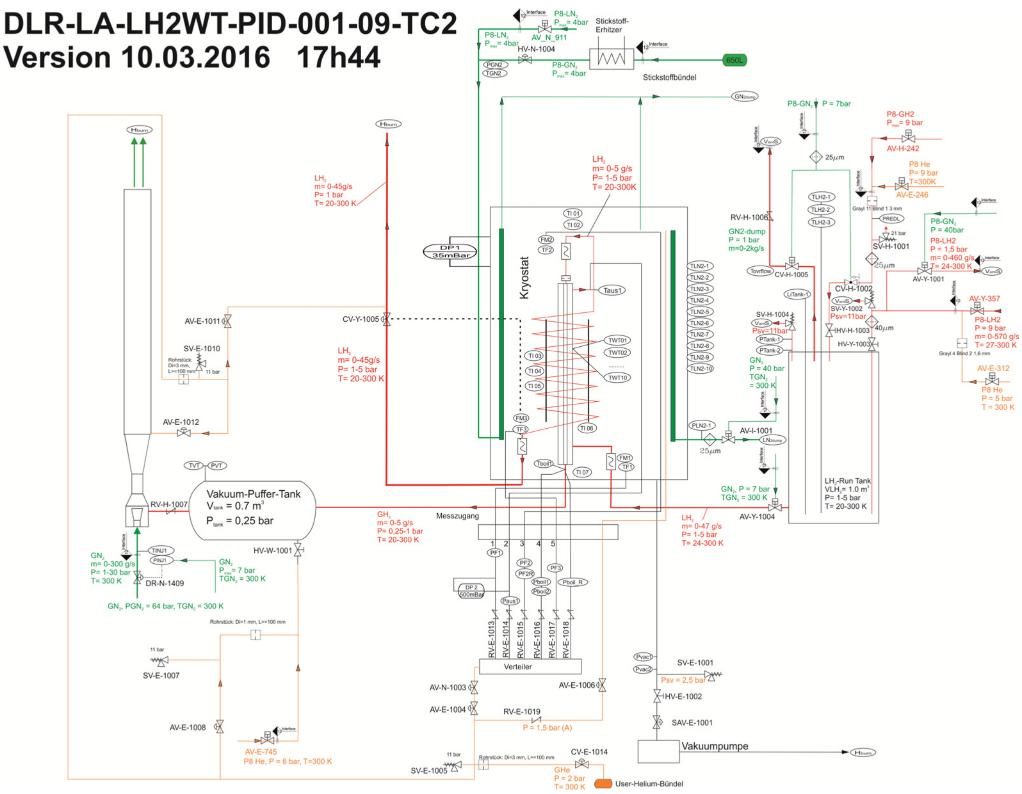

Fig. 4-2: LH_2 Evaporation Cooler User Installation Schematic

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The LH_2 user installation consists of a 1 m^3 LH_2 run tank, a cryostat for the evaporation cooler and a flow control valve at its outlet. The evaporation cooler is mounted inside the cryostat which consists of several layers: external foam insulation, followed by a liquid Nitrogen annular gap boiling pool, a vacuum volume in which a copper shell surrounded by a copper spiral are assembled, see Figures 4-2, 4-3 and 4-4. The evaporation cooler is placed inside the LH_2 cooled shell to highly reduce environmental heat loads. The inlet temperature is given by the condition inside the LH_2 feed tank. It can additionally be altered by the chosen loading pressure of the run tank, in which the liquid at loading is present in boiling state. It should be noted that during a test, vertical temperature stratification results inside the LH_2 run tank. The cooler mass flows are controlled with the downstream control valve CY-Y-1005 in conjunction with the LH_2 tank pressure. The evaporator mass flows are controlled by a set of swappable injection nozzles and by the associated boiling state of the monitored evaporator inlet conditions.

The tank and therefore the system pressure in the liquid part can be influenced by the pressure regulator at the 1 m^3 run tank to avoid boiling up to the exit control valve CY-Y-1005 and up to the injection holes in the evaporator part of the evaporation cooler. The run tank is used during the active phase for the supply of liquid Hydrogen. The exchange of injection nozzles at the evaporator head of the heat exchanger is the only option for adjusting the evaporation mass flow rate. The injection nozzle disc cannot be exchanged during test day.

The evaporated Hydrogen flows into a 0.7 m^3 vessel kept at ~0.1 bar via a Nitrogen driven jet pump. The 1 m^3 Hydrogen tank is pressurized to 5 bar during test operation. The measurement equipment includes basically 3 turbine flow meters, 24 resistive temperature sensors, 10 thermocouples and 10 pressure sensors.

The tests have been performed for 3 different inlet temperatures for the cooler: 24/25/26 K. The LH_2 run tank is filled with LH_2 at corresponding saturated pressure conditions, i.e. 2.6/3.3/4 bar. The operational test pressure was between 4 and 5 bar and all tests were performed manually from the control room of P8.

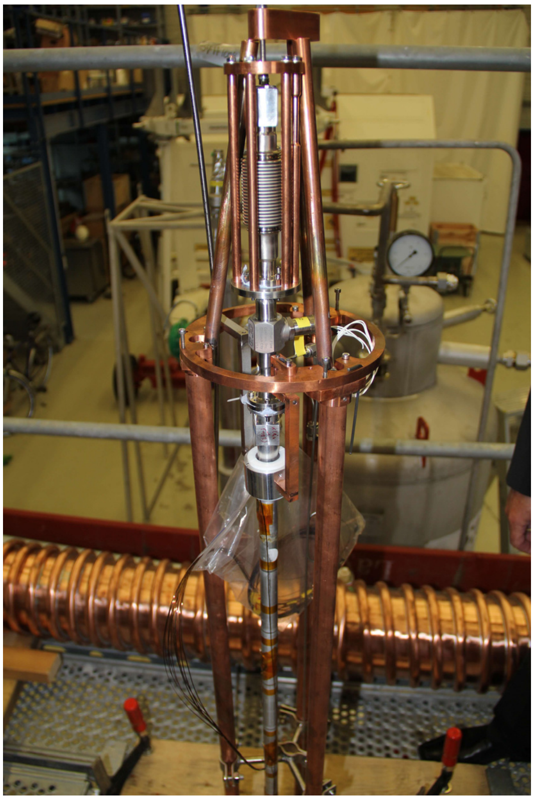

Fig. 4-3: Top View inside Cryostat

Fig. 4-4: Bottom View inside Cryostat

The flow rate through the evaporation cooler was controlled by the control valve at the cryostat outlet while the flow rate through the evaporator tubes can be slightly controlled via the operational pressure and modified by nozzle disc exchange in between test days. Four injection nozzle discs have been tested in sequence to obtain a wider operational range for the cooler characterization with respective flow rates being in the order of 2/3/4/5 l/min. Total flow rates have been varied between 15 and 56 l/min by adjusting the control valve. Exhaust Hydrogen from the cooler was

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burned while chill down Hydrogen from the run tank and respective interconnection line between the 11 m^3 storage tank of P8 and the1 m^3 run tank in TC2 of P8 was vented-off unburned via the P8 chimney.

5. Liquid Hydrogen Tests

The data record during the development tests ensure that the heat exchanger provides the required cooling capabiliy for the specified mass flow rates and temperatures for liquid Hydrogen.

The following measurements were recorded:

- pressure differences across the tube bundle interior and evaporator tubes
- inlet and outlet temperature and in the external tube compartment
- inlet temperature and pressure of evaporator tubes at the injector head
- outlet temperature and pressure of evaporator tubes
- mass/volume flow through the tube bundle outer compartment and evaporator tubes
- temperature at LH_2 Cu-radiation shield
- temperature at selected points of the inner Cu-supporting structure
- temperature and pressure in the LN_2 radiation shield / boiling volume
- temperatures along the heat exchanger casing tube

The LH_2-tests were performed in accordance with the steps listed below:

- mechanical pump based vacuum suction inside the vacuum volume of the cryostat
- filling of the cryostat annular jacket space with LN_2
- set into operation the remote controll of P8 and LH_2 user installation
- GHe purge of all Hydrogen segments of the fluid system
- set into operation of the GN_2 jet pump
- filling of the LH_2 run tank with liquid Hydrogen at 4 bar including a parallel chill-down of all LH_2 parts of the heat exchanger and the cryostat to LH_2 conditions by opening the tank outlet valve AV-Y-1004
- pressurizing the LH_2 run tank up to test pressure
- LH_2 flow through the heat exchanger and cryostat with controlled test mass flow rates via CV-Y-1005
- interrupting the liquid hydrogen flow into the heat exchanger by closing the valve AV-Y-1004
- decrease of the pressure to the boiling pressure of the next test temperature, in order to chill down the Hydrogen inside the LH_2 run tank
- pressurizing the LH_2 run tank to test pressure
- measurement phase while "draining" of LH_2 run tank
- pressure relief and GHe flushing of the cryostat
- draining of the LN_2 jacket of the cryostat by expedited boiling of LN_2 in the cryostat
- switching off the P8 and user installation systems

Before conducting the LH_2 tests as defined for the test matrix, appropriate preliminary LN_2 tests have been carried out jointly by ASL Bremen and DLR Lampoldshausen.

The results of these pre-tests were used for the definition of the test sequence and parameters (e.g. need of nozzle disc exchange, pressure variation, etc.). After having performed the preliminary tests, the final sequence of the test matrix was defined.

During the preliminary tests, the following points were determined and tested:

- The achievable mass flow rates depending on the pressure difference across one of the 4 injector plates were determined - as a kind of calibration - to assign the remaining injector discs to the evaporator mass flow rates foreseen for the follow-on LH_2 tests. In order to avoid boiling, it was decided to make sure that upstream the injector disc a sufficient overpressure above the saturation point will be obtained.
- Appropriate inlet temperatures, associated evaporator mass flow rates and system pressures were chosen for theselected nozzledisc in order to ensure test relevance.
- It was checked, whether stationary conditions can be achieved in the heat exchanger and how much time is needed to achieve those conditions.
- The consistency between simulation and measurement results was checked – especially, whether there are unexpected deviations between the predicted and measured outlet temperature and corresponding amount of vapor at the evaporator outlet.

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- The pre-tests were used to determine the final order of the tests with the associated nozzle discs and system pressure as well as the best point in time for disc exchange.

As foreseen since the planning phase of the project, four injection discs with the nozzle diameter were used: 0.25 / 0.30 / 0.35 / 0.40 mm.

The mass flow rates measured during the tests were slightly lower than the numerically predicted mass flow rates, which can be explained by both, a 25% higher friction loss coefficient (in comparison to the predicted loss coefficient) at the outlet of these conical nozzle and by a critical pressure ratio at the evaporation tubes' outlet. The most relevant evaporator mass flow rate is 3.85 g/s, as this is the reference mass flow rate, the heat exchanger was designed for.

As an example for a representative LH_2 test result, a test sequence for the 0.35 mm nozzle disc with an adjusted volumetric flow rate of ~27 l/min at 26 K / 4.6 bar cooler inlet conditions is chosen and shown in the subsequent Table 5-1 and Figure 5-1.

In Figure 5-1, the temperatures across the evaporation cooler are shown. The measured values are plotted as dotted lines while the simulated values are plotted as straight lines. The inlet temperature is colored black, the outlet temperature is colored red and the evaporator inlet temperature is colored green. The green line is about 0.5 K above the cooler outlet temperature due to non-perfect insulation in the copper head of the inner shell of the cryostat which is conductively cooled only, whereas the cylindrical part of the inner shell of the cryostat is cooled by a coiled LH_2 tube. The achieved temperature decrease along the cooler is 5 K for this test case.

	Test	ESPSS Simulation
P_{cool} (W)	1698	1846
P_{loss} (W)	226	225
x	0.956	1,0
P_v (W)	1786	1775
Vu (ml/s)	445.9	447.3
Vv (ml/s)	63.7	63.3
T_{out} (K)	21.1	20.7
T_{boil} (K)	17.0	16.8

Tab. 5-1: Steady State Comparison: Test/Simulation

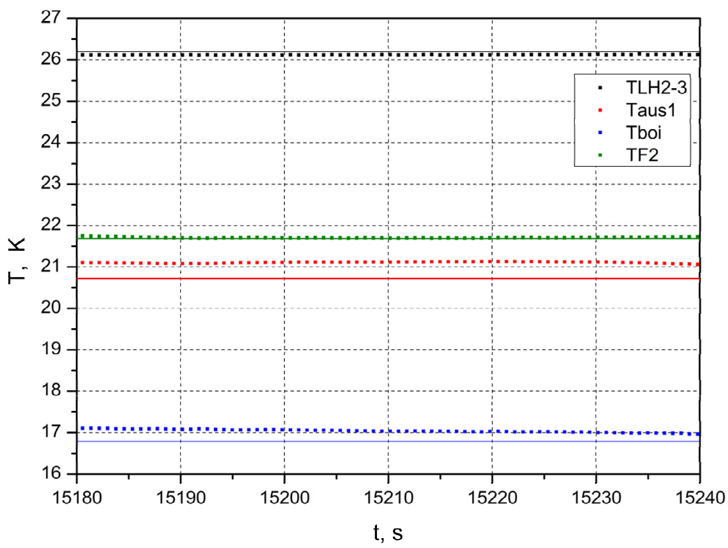

Fig. 5-1: Temperatures across Cooler vs Test Time

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The baseline for the evaporation cooler design layout is 3.9 g/s for the evaporator and 28.4 g/s for the cooler mass flow rate at 26 K inlet temperature and 5 K temperature decrease for the LH_2 cooling (coming originally from an early A5ME/VINCI requirement) which corresponds to an efficiency of 86.3%. For this exemplary case the efficiency for test/simulation is 84.3% for a temperature difference equal to 5/5.5 K, see Table 5-1 (grey blue).

6. Possible ARIANE 6 Design of the Evaporation Cooler

Figure 6-1 shows a CAD drawing of the best fitted position of the LH_2 evaporation cooler on an A6 upper stage. The evaporation cooler can replace a section of the feed line between the tank and the stage main engine. The cooler weight estimation is about 20 kg in case it is made from an Aluminum alloy.

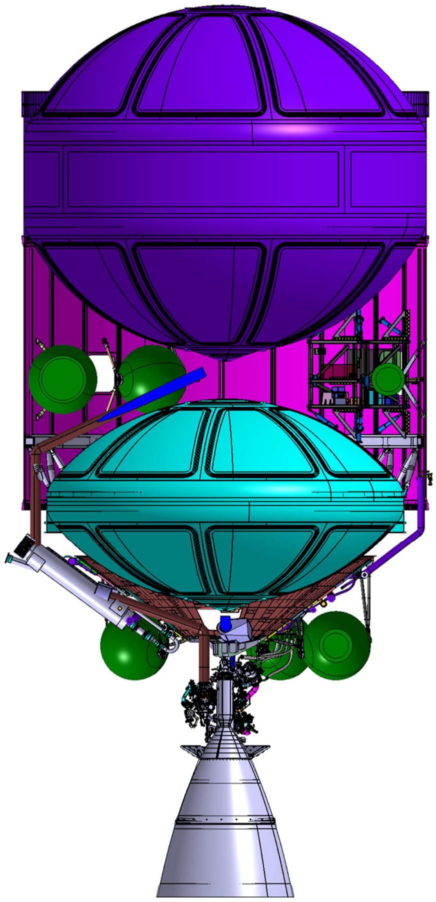

Fig. 6-1: Possible Position for the EC on Ariane 6 U/S

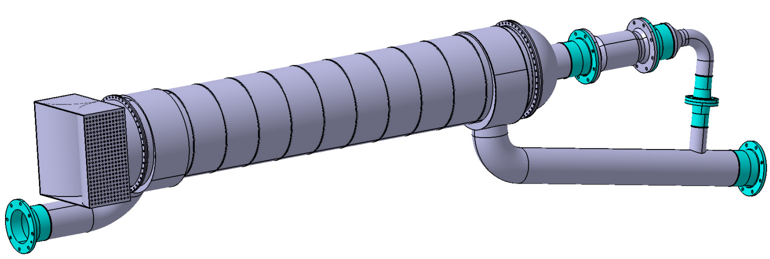

Fig. 6-2: Evaporation Cooler (CAD) for Ariane 6 U/S

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Figure 6-2 shows a design proposal for the Ariane 6 upper stage. It is designed for 2.5 K temperature decrease which means that the active cooling length can be reduced accordingly. The number of tubes would be in the order of 1300. The GH_2 vapor flow of the cooler is divided into two opposite jet streams for momentum free exhaust. A valve at the inlet of the evaporator allows on/off switching of the evaporation compartment of the evaporation cooler on demand.

7. Conclusion

The presented new concept "LH_2 feed line evaporation cooler" provides the opportunity to cool down propellant directly during tank draining and main engine operation. The core elements - nozzles and capillary tubes - and related dimensions inside the FM-7R sub-scale cooler are already real scale and therefore directly applicable to a full scale evaporation cooler assembly. Only the number and the length of the tubes need to be adapted to the real case flow rates and cooling power requirements.

The LH_2 test campaign has demonstrated that the chosen design of the evaporation cooler fulfills the original 5 K cool down requirement with good alignment to the estimated efficiency elaborated during the design phase of the evaporation cooler. The thermal and hydraulic design was mainly determined by a transient 2-phase flow tool. The chosen Al-alloy AW6060 is widely available in all kinds of semi-finished parts. It has good heat conductivity at cryogenic temperature and is easy to weld. A further advantage is the precipitation heat treatment which allows to re-strength the material properties in the weld seams.

Generally, the FM-7R has been manufactured for important domains according to Ariane 5/6 manufacturing rules. The manufacturing was accompanied by detailed macroscopic and microscopic examinations of performed EB-welds and investigation of critical aspects e.g. achievable cleanliness level, leak tightness.

"Cooling on demand" by such kind of evaporation cooler in the LH_2 feed line can save mass compared to classical conditioning methods performed at the end of ballistic flight phases for cryogenic upper stages, i.e. cooling by ullage gas depressurization.

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Nomenclature

Latin letters

A	integral value of	
C	integration constant	
D	delta	
L	length	m
T	absolute temperature	K

Greek letters

α	thermal expansion coefficient	1/K
ε	thermal strain	

Indices

o	initial

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Definitions, Acronyms, Abbreviations

A6	**A**riane **6** Launcher
BMWi	**B**undes**m**inistierium für **Wi**rtschaft und Energie
CAD	**C**omputer **A**ided **D**esign
DLR	**D**eutsches Zentrum für **L**uft- und **R**aumfahrt
EB	**e**lectron **b**eam
EC	**e**vaporation **c**ooler
ESPSS	**E**uropean **S**pace **P**ropulsion **S**ystem **S**imulation
FEM	**f**inite **e**lement **m**ethod
FM-7R	**F**unktions**m**uster **7** **R**ohre
PREPARE	**Pr**ogram to **E**nhance Upper Stage **P**erform**a**nce and **Re**liability
QSL	**q**uasi **s**tatic **l**oad
SP	**S**chweiß**p**robe
U/S	**U**pper **S**tage
vs	versus