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Sensors and components for aerospace thermal control, life sciences and propellant systems

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ABSTRACT
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Abstract

Various aspects of different sensors and components, (being) developed or fine-tuned for aerospace thermal control and propellant systems, are discussed: rotatable radial heat pipe joints, vapour quality sensors, controllable valves, condensers, flow metering assemblies and propellant gauges.

INTRODUCTION

Aerospace heat transport, life sciences and propellant systems incorporate different sensors and components. Some are spatialised versions of existing terrestrial hardware, others are dedicated direct developments for space. Various aspects of different ***sensors*** and components (being) developed or fine-tuned will be discussed in detail: background, applications foreseen, design, and terrestrial and (low-gravity) performance data.

The sensors and components, developed for ESA and the Netherlands Agency for Aerospace Programmes, are:

- Rotatable Thermal Joints, to be used to minimise the temperature drop between e.g. a spacecraft thermal bus and a deployable or steerable heat pipe radiator, the latter resulting in minimum radiator size and mass.
- Vapour Quality Sensors, to measure or control the vapour quality (vapour mass flow ratio) of a flowing vapour/liquid mixture in mechanically/capillary pumped two-phase heat transport and propellant system lines.
- From the Vapour Quality Sensor derived Propellant Gauges to accurately measure the remaining level of fuel (Mono Methyl Hydrazine) or oxidizer (Mixed Oxides of Nitrides) in the tanks of spin-stabilised spacecraft.
- Flow Metering Assemblies, to measure and control the flow rate in aerospace life science systems and single or two-phase thermal control loops and to assess, by integrating the consumption during lifetime, the remaining level of fuel or oxidizer in the propellant tanks of three-axes stabilised spacecraft.
- High Efficiency Low Pressure Drop Condensers for direct or indirect condensation spacecraft radiators.
- Controllable (motorised, three-ways) Valves, to be used in single or two-phase loops to control fluid temperature setpoint, flow rates, pressure drop, vapour quality, etcetera.

ROTATABLE RADIAL HEAT PIPE JOINT

Recalling earlier discussions (Deli1 1987), it is remarked that dedicated heat pipe radiators will be used to reject (spacecraft) waste heat into space. Such a radiator, stowed during launch, will be deployed in orbit. The radiator may even be chosen to be steerable to achieve maximum performance, hence minimum radiator size/mass. In such radiator systems, the coupling to the central (two-phase) loop or heat pipe has to incorporate a rotatable/ flexible thermal joint. Drivers for the design of such joints are low thermal resistance, hence limited temperature drop across the joint, and small deployment/retraction or steering torque. A quantitative discussion on movable joint concepts identified the rotatable radial heat pipe as a promising solution for steerable radiators (Deli1 1987). Figure 1 shows a schematic of a rotatable radial heat pipe. An essential component is the wick to provide the capillary head to return the condensate from condenser to evaporator and to distribute the liquid properly over the evaporator surface. Therefore the fine gauze wick structure should be uniformly fixed to the evaporator surface (inner tube outer surface). In this way bum-out, caused by blockage due to vapour bubbles generated, is prevented. Since the outer tube must be rotatable with respect to the inner tube there must be a clearance between porous structure and tube wall. This clearance is located at the condenser, the less critical side of the heat pipe, where the condensate has to be collected only (relatively easy, especially for a slightly overfilled heat pipe). An accurate design combines proper condensate collection and transport, hence good heat pipe performance, and low rotation torque, hence long lifetime for a steerable radiator. It is obvious that the end caps of a rotatable radial heat pipe must be leak-tight. This problem must be solved using appropriate seals. The thermal performance of a radial heat pipe is hard to predict. A rough estimate follows from flat plate vapour chamber data: heat transfer coefficient $\approx$ 4000 W/m^2. K, for methanol as working fluid, between 250 and 305 K. For a radial joint with an external diameter of 40 mm, this means a conductance of 500 W/K per meter joint length.

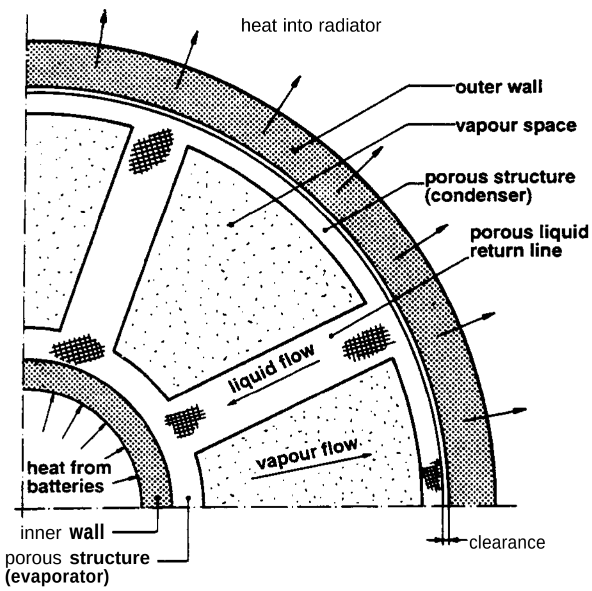

FIGURE 1. Cross-section of a Radial Heat Pipe Joint.

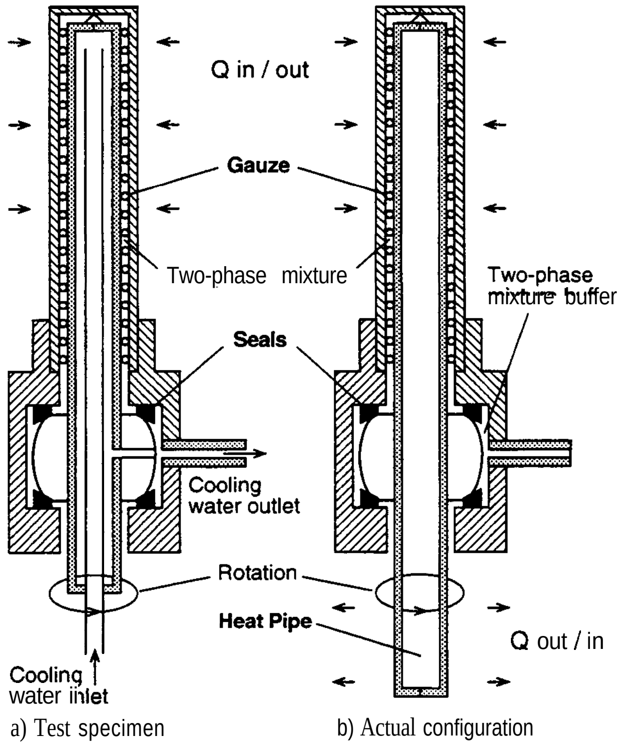

FIGURE 2. Rotatable Radial Heat Pipe Joint.

To prove the feasibility of the concept, a simple 10 cm long test specimen (Figure 2a) has been manufactured. It simulates the realistic configuration shown in figure 2b, and consists of: A 10/12 mm inner tube, cooled by liquid flow, simulating the heat pipe. A 13/15 mm outer tube, heated by a heater (simulating the heat source: a condensing two-phase mixture). A rotatable section (ball valve) allowing the outer and inner tube to rotate with respect to each other. The 0.5 mm clearance between the tubes contains a wick simulating metal gauze and working fluid R114.

Figure 3 shows the results of a test to determine the optimum working fluid content. Starting with pure liquid, the temperature drop across the joint is ≈ 13 K. By stepwise blow-off R114, this temperature drop is reduced to 7 K at the optimum mixture quality. Continuing blow-off causes increase of the temperature drop up to 26 K (pure vapour conduction/solid conduction of the gauze). The optimum joint conductance is 3 W/K for this 0.1 m long, 13 mm OD R114 joint, or 600 W/K for the mentioned 4 cm diameter, 1 m long methanol filled joint. This is ≈ 1500 W/K if ammonia is the working fluid. Figure 4 presents the (optimally filled) joint performance during rotation (at 17

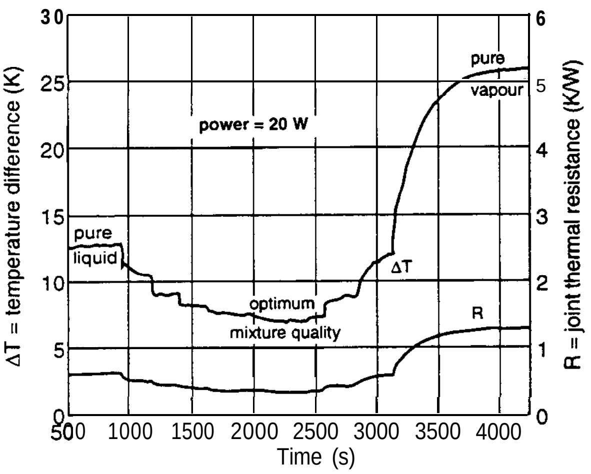

FIGURE 3. Determination of Optimum Filling.

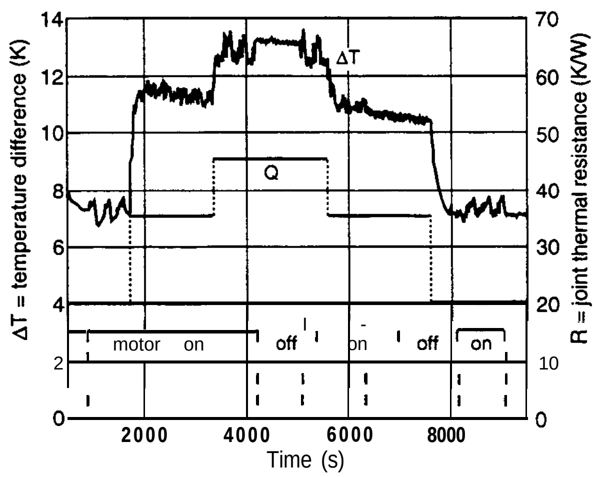

FIGURE 4. Power Dependence of Joint Resistance (non-rotating and rotating at 17.5 rpm).

revolutions per hour) and in non- rotating periods, for different power values (45, 35 and 20 W). The figure clearly confirms the aforementioned joint conductance value both for the rotating and non-rotating case. This conductance, showing the more stable values in the non-rotating case, increases slightly with power (temperature) level.

Summarizing, the concept is feasible as the joint did not leak and the performance figures are promising. Seal improvements and the use of a buffer volume (also filled with the working fluid at approximately the same, heat pipe, temperature) are expected to lead to the realisation of a mature long lifetime rotatable radial heat pipe joint.

VAPOUR OUALITY SENSOR AND CONTROLLABLE VALVE

Thermal management systems for future large spacecraft have to transport large amounts dissipated power over large distances. Conventional single-phase systems (based on the heat capacity of the working fluid) are simple, well understood, easy to test, inexpensive and low risk. But for a proper thermal control task with small temperature drops from equipment to radiator (to limit radiator size/mass), they require noisy, heavy, high power pumps and large solar arrays. As an alternative for single-phase systems one considers mechanically pumped two-phase systems: pumped loops, accepting heat by working fluid evaporation at heat dissipating stations (cold plates and heat exchangers) and releasing heat by condensation at heat demanding stations (hot plates, heat exchangers) and at radiators, for rejection to space. Such a system relies on heat of vaporisation: it operates nearly isothermally and the pumping power is reduced by orders of magnitude, thus minimising the sizes of radiators and solar arrays. The stations can be arranged in a pure series, a pure parallel or a hybrid configuration. The series configuration is the simplest, it offers the possibility of heat load sharing between different stations, with some restrictions with respect to their sequence in the loop. But it has limited growth potential and the higher flow resistance. In the low resistance modular parallel concept, the stations operate relatively independently, thus offering full growth capability. However, the parallel configuration is more complicated, especially if redundancy and heat load sharing (some cold plates operating in reverse mode) is foreseen. In addition, a parallel configuration requires a control system consisting of various sensors, monitoring the loop performance at different locations, control logic and actuators to adjust pump speed, fluid reservoir content and throughput-s of valves. Sensors necessary for control are pressure gauges, flowmeters, temperature gauges and vapour quality sensors, measuring the relative vapour mass content of the flowing mixture (Deli1 1988). An important application for Vapour Quality Sensors (VQS) is at cold plate exits, as a part of a control system adjusting the liquid fed into a cold plate to prevent evaporator dry-out or to maintain a prescribed quality value at evaporator exits, independent from transient heat sources and sink conditions.

As two-phase flow and heat transfer characteristics are different in l-g and low-g, the technology of two-phase heat-transport systems and their components was to be demonstrated in orbit. Therefore, a Two-Phase experiment (TPX) has been developed within the ESA In-orbit Technology Demonstration Programme, by NLR (prime), Fokker Space, SABCA, Bradford and SPE. TPX is a scaled-down capillary pumped two-phase ammonia system together with scaled-down components of a mechanically pumped loop: multichannel condensers, vapour quality sensors and a controllable three-way valve. TPX has successfully flown in the Get Away Special G5.57 canister (5 ft^3, Nitrogen gas filled), aboard Space Shuttle STS-60, February 1994 (Deli1 et al. 1995). The experiment has run autonomously, using own power supply, data handling and experiment control after a switch-on command from the Shuttle crew.

One TPX objective was the in orbit calibration of the VQS, by setting the VQS vapour quality by adjusting the 3-ways Controllable Valve (CV), mixing the by-passed vapour and liquid leaving the condenser. In-orbit test data and terrestrial calibration curves differed considerably (Figure 5). This VQS (Figure 5), with updated electronics, will refly in TPX II (TPX follow-up) as G467 aboard STS-90, April 1998. Figure 6 shows the TPX II schematic.

Control exercises with VQS and CV could not be carried out in TPX, because the vapour quality control setpoint chosen turned out to be in the unstable chum flow pattern regime (Figure 5). The control excercises will be redone in TPX II (with the TPX II CV depicted in figure 7). Control will be done around two quality setpoints, one in the slug flow regime, the other in the annular flow regime. The NLR ammonia test rig, used to calibrate the VQS, will be used to assess the CV characteristics to control both vapour quality and pressure drop across a flow resistance.

CONDENSERS

High Efficiency Low Pressure Drop condensers/radiators are crucial for two-phase systems. Two radiator solutions can be distinguished: A direct condensing radiator: condenser attached to the radiator, radiating condensation heat to space, and a hybrid condenser radiator, where the condenser is not an integrated radiator part (condensation heat is transported from condenser via central heat pipe to heat pipes distributing the heat over the radiator).

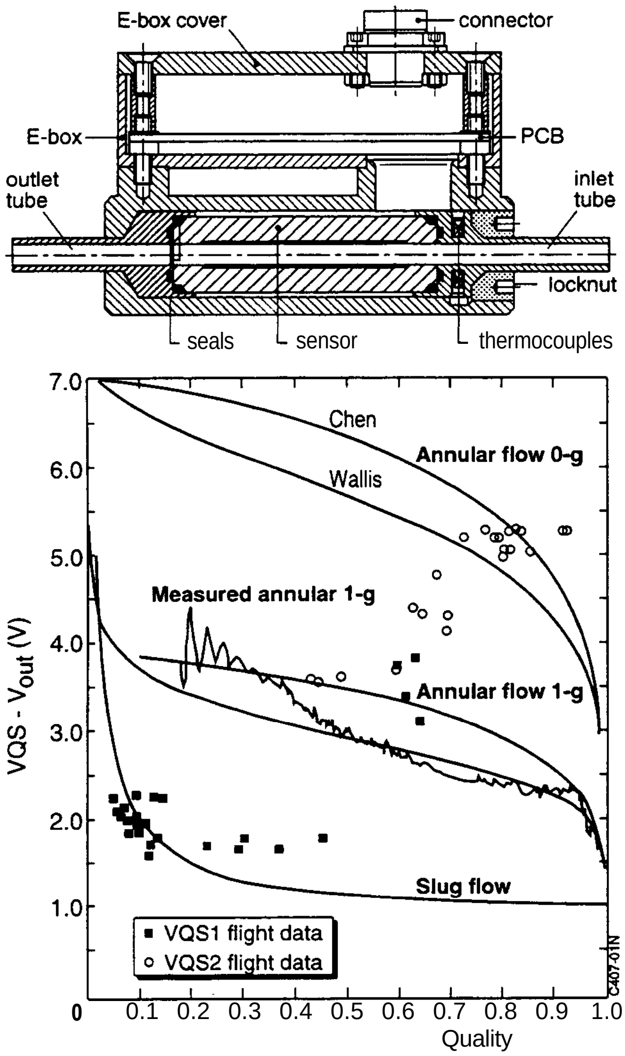

FIGURE 5. VQS, plus Theoretical Response and Test Data.

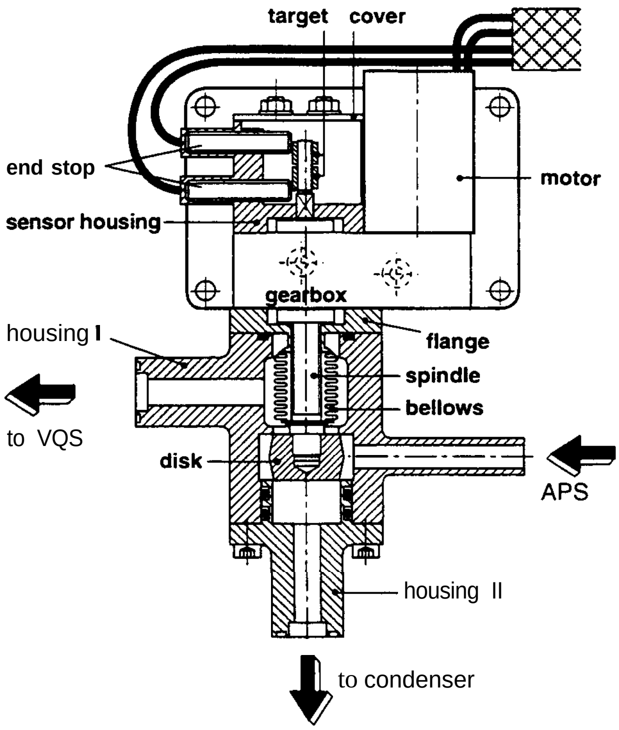

FIGURE 7. TPX II Controllable Valve.

APS	Absolute Pressure Sensor
DPS	Differential Pressure Sensor
C V	Controllable 3-way Valve
TV	Vapour Temperature
T_l	Liquid Temperature
EMP	Experiment Mounting Plate (GAS canister lid)
GAS	Get Away Special
LFM	Liquid Flow Meter
$\dot{m}$	Mass flow
$\dot{m}_C$	Flow Rate in Condenser Branch
Q_{EF}	Fiat Evaporator Heater Power
Q_{EC}	Cylindrical Evaporator Heater Power
Q_{COND}	Condenser Imbalancing Power
VQS	Vapour Quality Sensor

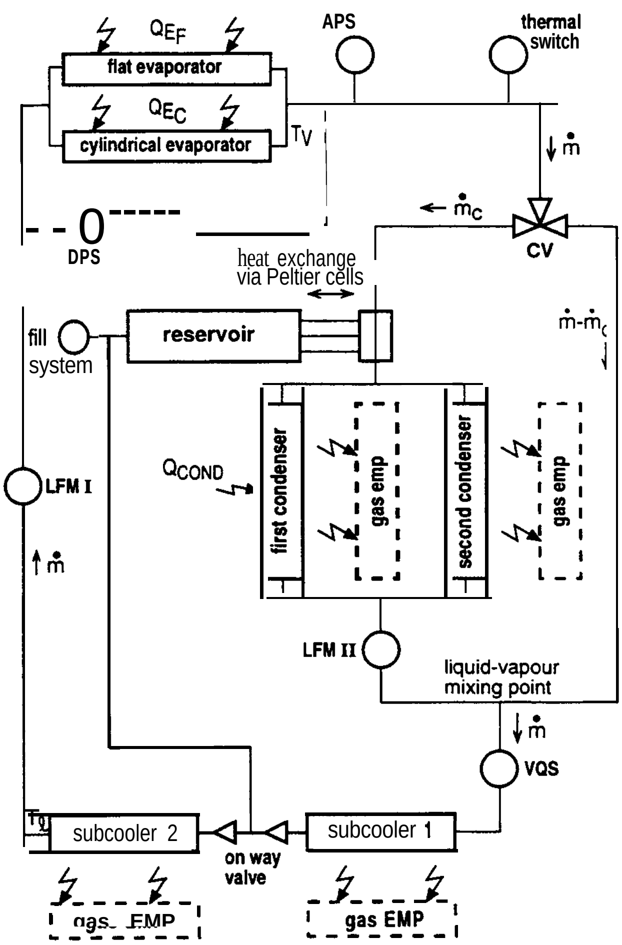

FIGURE 6. TPX II Schematic.

Direct condensing radiator:

Two direct condensing radiators have been designed and manufactured for the ATLID Laser Head Thermal Control Breadboard (Figure 8), developed for ESA by MSS-UK (prime), NLR and Bradford (Dunbar 1996). They are configured to represent the allowable areas for the ATLID instrument on the Polar Platform. One radiator, 1.05 m high by 1.0 m wide (radiator A), is fixed to the instrument baseplate and supported by struts. The other radiator (B), 0.8 m high and 1.45 m wide, is deployable and fixed only along its edge by cantilever support beams. The

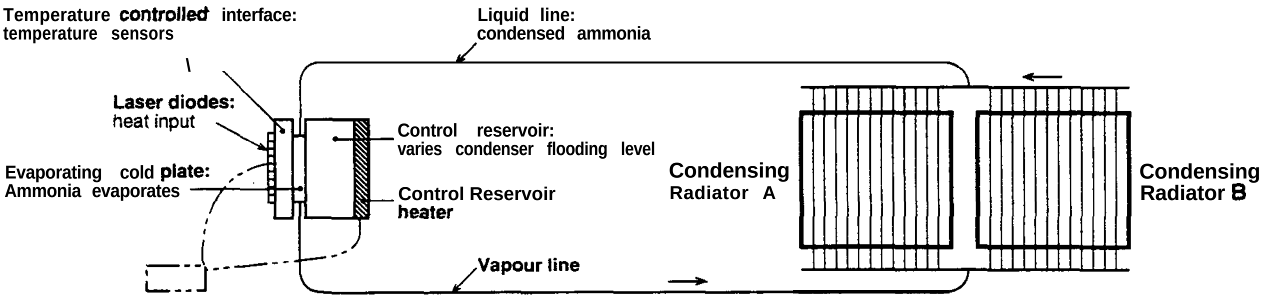

FIGURE 8. ATLID Laser Head Thermal Control Schematic.

struts for radiator A are constructed from filament wound carbon fibre tubes with aluminium end fittings. The cantilever beams of radiator B are 100 mm deep to provide adequate stiffness. The radiators are too small to reject the heat load in steady state conditions. They are only just capable of meeting the heat rejection requirements when a full orbital cycle is considered. The radiator B deployable design incorporates a unique torsion/helical bending configuration to minimise pipe strain and allow multiple repetition of the deployment. Although the instrument requires deployment only for ground access, the design is equally suitable for flight deployment. The radiator surfaces would for flight be covered with advanced glass OSR's to give low beginning and end of life solar absorptivities. For the breadboard tests sunlight has been simulated by altering heat sink temperatures, and the radiators are simply black painted. The radiators are constructed from extruded aluminium profiles rivetted together to form a continuous surface. Each profile section contains one 2 mm internal diameter condensing pipe, clamped into good thermal contact with a channel in the extrusion. Isolators in each liquid line and one at the liquid header outlet ensure even vapour distribution and prevent differential dryout. The rivetted construction provides stiffness in two axes, and the remaining axis is stiffened by the addition of a beam crossing all the profiles. The ATLID test programme conclusions (Dunbar 1996) report the following achievements:

- The two-phase system is treated as just another thermal tool able conform to installation, accommodation and structural requirements imposed by the overall instrument.
- The system has successfully completed severe sine and random vibration tests to qualification levels.
- The deployable radiator concept has been demonstrated.
- The tests demonstrated that the ATLID breadboard meets or exceeds nearly all performance requirements. In particular the principal requirement to maintain the laserdiode interface to within I °C of nominal temperature during simulated low earth orbits was met with a significant margin. Due to restrictions on radiator area the end of life heat rejection performance only just meets the requirements. Some extra margin is recommended.
- Some modifications will be necessary if the 125 Hz first radiator frequency is to be met for the actual flight units, but these have been identified and are not considered critical.

Detailed information can be found in the aforementioned reference.

Hybrid condenser:

For ESA, a high efficiency low pressure drop condenser (Figure 9) for a hybrid (heat pipe) radiator has been successfully developed and brought up to pre-qualification level, by NLR (prime), Bradford and DASA RI (Deli1 et al. 1996). This condenser has been subjected to tests in the test rig under conditions reflecting realistic in-orbit conditions: vapour temperature between 263 and 313 K, for a condensed power up to 300 W. The tested hybrid condenser design (Figure 9) consists of a concentric tube around a liquid cooled inner tube, simulating the heat pipe. Vapour entering the condenser is uniformly distributed by a cone. The condensing part is an annulus with ID 25 mm and OD 28 mm, hence a gap width 1.5 mm. Six wires with a diameter of 1.5 mm subdivide the annulus

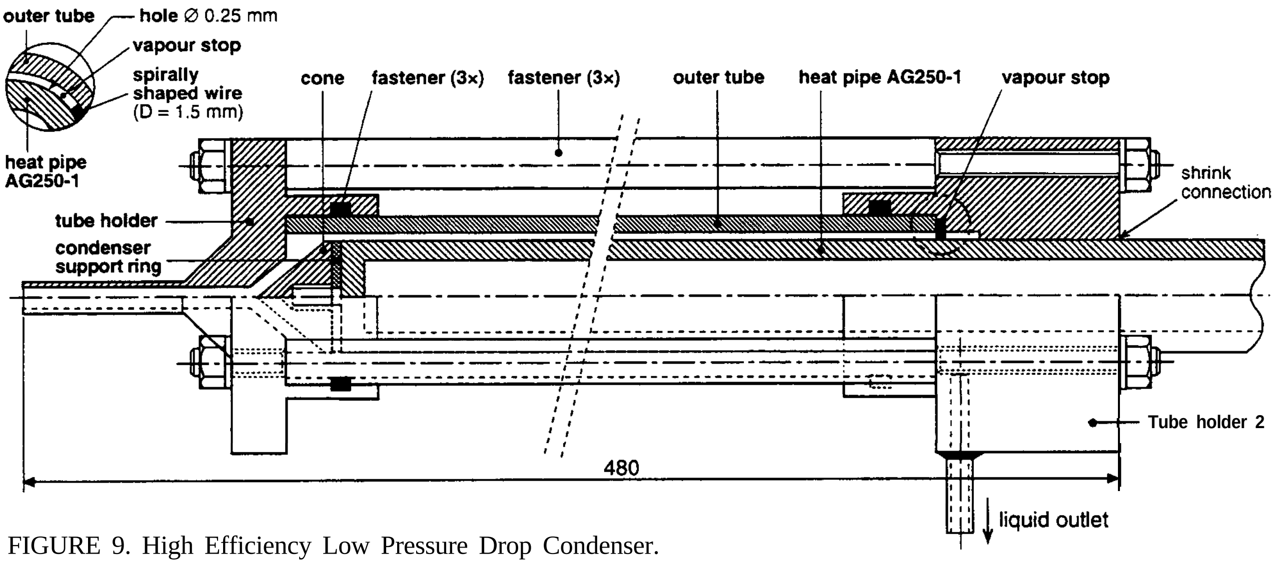

FIGURE 9. High Efficiency Low Pressure Drop Condenser.

into six parts. The wires are coiled around the central tube, leading to helical condensation channels, providing a swirling to improve performance. The tests proved me quality of the design, being a good compromise between high-efficient thermal performance and low pressure drop (Figure 10): for 300 W a temperature drop below 7.5 K at a pressure drop below 400 Pa (the latter can be considerably reduced by increasing the number of condenser outlet vapour stops). The tests proved that there is no significant difference in performance for vertical and horizontal orientation. Furthermore the condenser design satisfied all other requirements. Three of these condensers in series, equipped with 25 mm OD central heat pipes, are part of the ESA Capillary-pumped Loop Engineering Model CLEM currently developed by MMS-UK (prime), MMS-F, Bradford and NLR.

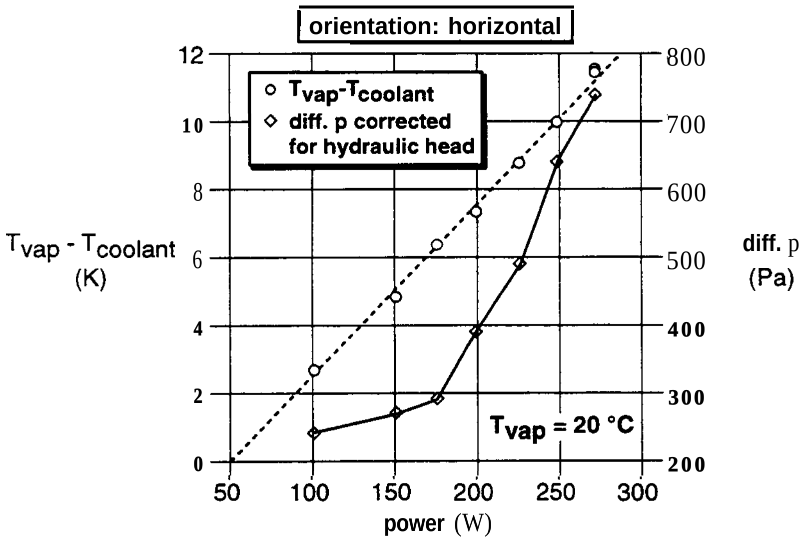

FIGURE 10. Temperature and Pressure Drops as a Function of Power for the Horizontal Condenser.

FLOW METER ASSEMBLIES

Activities to spatialise commercial Flow Metering Assemblies (MA) for ESA (by NLR, prime, SPPS/Bradford and SABCA), started with selecting and screening more than 80 commercial meters. Trade-offs identified possible candidates for applications in spacecraft thermal, life sciences and propellant systems. The most promising ones were subjected to a test programme that included qualification level functional performance/environmental tests. A dedicated test facility has been developed for performance testing and calibration. The test rig accomodates all type of working fluids: thermal (ammonia, freons), life science (water) and propellants (MMH, MON). Tests can be executed between 233 and 358 K, for flows up to 3 g/s for ammonia, to 200 g/s for water and propellants. Test bench accuracy: 0.025 % Full Scale, flow meter accuracy 0.1 % Full Scale. The system can be pressurised up to 2.5 Mpa. Results of extensive testing led to the choice of two meters to be spatialised: ITT Barton 7182 turbine meter for water, ITT Barton 7506 pelton wheel meter for ammonia. The activities will be concluded December 1997.

Other flow meter activities of Bradford/SPPS (prime), NLR and Panametrics focus on the development of a non-intrusive ultrasonic meter for applications in propellant systems of three-axes stabilised spacecraft. The accuracy has to be better than 0.1 % Full Scale (design goal 0.05 % FS) as the meters are to be used to assess remaining propellant mass by totalising the propellant consumption.

PROPELLANT GAUGES

Since the introduction of the de-orbit requirement for geostationary spacecraft, increased attention has been paid to accurate and reliable on-board gauging of propellants. Various gauging systems have been developed and are in use with a wide spreading of accuracy and complexity (Hufenbach et al. 1997). A from the VQS derived capacitive gauge is currently being developed to very accurately determine the remaining fuel (MMH) and oxidiser (MON) in propellant tanks of spin-stabilised spacecraft. The gauges will be integrated parts of the tanks of the Meteosat Second Generation Unified Propulsion System (Hufenbach et al. 1997). This Gauging Sensor Unit (GSU), depicted in figure 11, consists of a measuring unit and electronics. The measurement principle is schematically shown in figure 12. The platinum covered central glass rod is the inner electrode of the GSU, the titanium holder is the outer one. The combination of a segmented inner electrode, intelligent electronics and a dedicated ground handling protocol, yields level accuracies ranging from 0.015 mm for chemically stable liquids (Freons) to 0.3 mm for less stable liquids (MON). The GSU breadboard model has been subjected to extensive testing. Figure 13 shows the

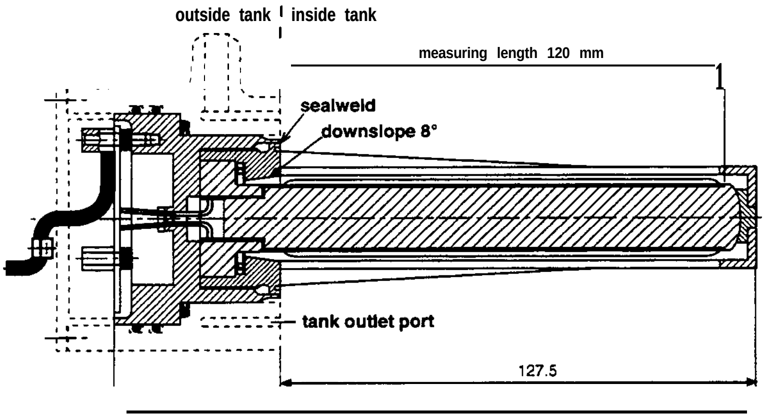

FIGURE 11. Propellant Gauging Sensor Unit.

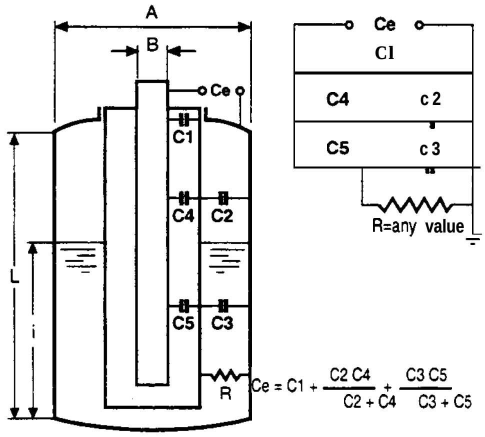

FIGURE 12. Coated Capacitance Probe (Schematic).

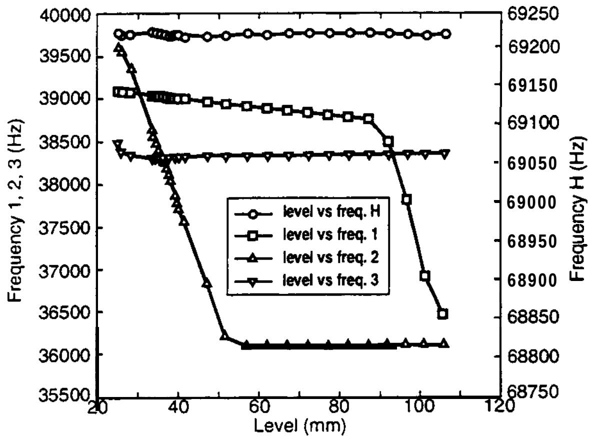

FIGURE 13. GSU Levels versus Frequency Test Data (MON-1).

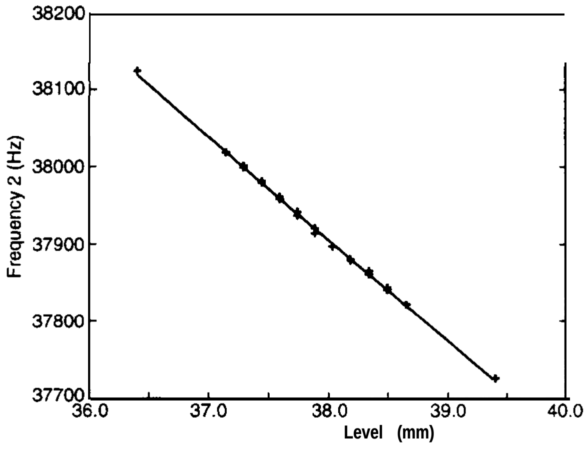

FIGURE 14. GSU Resolution Test Data (MON-I).

measured MON level curves for the different segments. Figure 14 presents the results of the resolution/accuracy verification tests with MON. To correctly interpret the resolution/accuracy data, the liquid properties (dielectric permittivity and electric conductivity) must be known. As this knowledge could not be found in literature, a test rig has been built to characterise dielectric properties of propellants. Successful testing has been recently carried out on MMH and MON (Deli1 et al. 1997).

Acknowledgement

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