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National Aerospace Laboratory NLR

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Research Issues on Two-Phase Loops for Space Applications

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Summary

This publication constitutes a presentation, given during a stay as visiting professor in microgravity fluid physics at the Institute of Space and Astronautical Science (ISAS) in Sagamihara, Japan. The presentation, discussing different research topics on two-phase loops for space applications, was given at ISAS at the Symposium on Space Flight Mechanics, 7-8 December.

The paper gives an overview of heat and mass transfer research issues on the development of spacecraft two-phase thermal control systems, more specifically development of two-phase loop technology. It discusses the justification of two-phase loop research for aerospace applications, distinguishing the different loop options: The Mechanically Pumped Loop (MPL), the Capillary Pumped Loop (CPL) and Loop Heat Pipe (LHP), and the Vapour Pressure Pumped Loop (VPPL).

It describes applications foreseen and results of two in-orbit experiments with NLR involvement, successfully carried out to prove the technology for applications in space. The first one concerns a CPL, ESA's Two-Phase eXperiment TPX I, the second concerns a LHP, the US Loop Heat Pipe Flight eXperiment LHPFX.

It presents also design and development supporting theoretical work: The approach of thermal/gravitational modelling and scaling of two-phase heat transport systems, different aspects of gravity level dependent two-phase flow pattern mapping, and condensation.

It concludes with a brief description of two-phase research issues currently ongoing at NLR, being hardware developments to be flown in the near future on the International Space Station, ISS. One concerns two-phase cooling loops for the thermal control of the 4-years lasting Alpha Magnetic Spectrometer (AMS-2) experiment. The other is NLR's versatile two-phase loop for the Convection Interfacial Mass Exchange Experiment (CIMEX-3), to be executed in the Fluid Science Laboratory, FSL.

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Abstract

The paper gives an overview of heat and mass transfer research issues on the development of spacecraft two-phase thermal control systems, more specifically development of two-phase loop technology. It discusses the justification of two-phase loop research for aerospace applications, distinguishing the different loop options: The Mechanically Pumped Loop (MPL), the Capillary Pumped Loop (CPL) and Loop Heat Pipe (LHP), and the Vapour Pressure Pumped Loop (VPPL). It describes applications foreseen and results of two in-orbit experiments successfully carried out (with NLR involvement) to prove the technology for space: The first being a CPL, ESA's Two-Phase eXperiment TPX I, the other a LHP, the US Loop Heat Pipe Flight eXperiment LHPFX. The paper presents also design and development supporting theoretical work: The approach of thermal/gravitational modelling and scaling of two-phase heat transport systems, different aspects of gravity level dependent two-phase flow pattern mapping, and condensation. It concludes with a description of two-phase research issues currently ongoing at NLR, being hardware developments to be flown in the near future on the International Space Station, ISS. One concerns two-phase cooling loops for the thermal control of the four years long Alpha Magnetic Spectrometer (AMS-2) experiment. The other is NLR's versatile two-phase loop for the Convection Interfacial Mass Exchange Experiment (CIMEX-3), to be executed in the Fluid Science Laboratory, FSL.

ADVANTAGES OF TWO-PHASE LOOPS FOR SPACECRAFT THERMAL CONTROL

Future large spacecraft thermal control systems have to transport large amounts of dissipated power (up to 200 kW) over large distances (up to 100 metres). Though conventional single-phase systems (based on the heat capacity of the working fluid) are simple, well understood, easy to test, relatively inexpensive and low risk, they need to realise proper thermal control with small temperature drops from equipment to radiator (to limit radiator size and mass), thick walled, large diameter, heavy lines and noisy, heavy, high power pumps, and consequently large solar arrays. Therefore the main driver for developing alternatives was to overcome these single-phase heat transport system disadvantages. The most promising alternative is the pumped two-phase system, a mechanically pumped loop (MPL) accepting heat by evaporation of the working fluid at heat dissipating stations (cold plates and heat exchangers) and releasing heat by condensation at heat demanding stations (hot plates and heat exchangers) and at radiators, for the heat rejection to space. Such a system relies on the heat of vaporisation: It operates nearly isothermally and the pumping power is reduced by orders of magnitude, minimising sizes and masses of radiators and solar arrays. Ammonia, carbon dioxide or other refrigerants are most promising candidate working fluids.

The stations can be arranged in a series, a parallel or a hybrid configuration. The series configuration is most simple. It offers the possibility of heat load sharing between the different stations, with some restrictions with respect to their sequence in the loop. But the series configuration has limited growth potential and the higher flow resistance. In the low resistance modular parallel concept the stations operate more ore less independently, therefore offering full growth capability. Figure 1 shows, as an example of a parallel concept, ESA's Two-Phase Heat Transport System TPHTS. But the parallel configuration is the more complicated one, especially when 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, including control logic and actuators to adjust pump speed, fluid reservoir content and throughputs of valves. Sensors needed for control are pressure gauges, flow meters, temperature gauges and vapour quality sensors (VQS), measuring the relative vapour mass content of the flowing mixture. An important VQS application is at the cold plate exits, as a part of a control system, adjusting liquid fed to the cold plate to prevent evaporator dry-out, or maintaining a prescribed quality value at evaporator exits, independent of transient heat sources and heat sink conditions (Delil, 1988, 1995, 1998).

For various applications capillary pumped systems can be very promising alternatives for mechanically pumped loops. In capillary systems the working fluid circulation is by the surface tension driven pumping of capillary evaporators, which transports (like in a heat pipe) the condensate back from condenser to evaporator. Such capillary two-phase systems can be used in spacecraft not allowing vibrations, induced by mechanical pumping. Ammonia is the best candidate working fluid for capillary two-phase thermal control loops. Two different systems (Fig. 2) exist (Cullimore, Nikitkin, 1998): The western-heritage Capillary Pumped Loop CPL (Stenger, 1966; Cullimore, 1993), and the Russian-heritage Loop Heat Pipe, LHP (Bienert, Wolf, 1995; Maidanik et al., 1991, 1995; Kaya, Ku, 1999; Ku, 1999). Active loop set-point temperature control is done by controlling the temperature of the reservoir or compensation chamber thus influencing their liquid contents, hence the amount of liquid in the rest of the loop and consequently the condenser flooding, hence the condenser area available for condensation. In this way the loop set-point can be maintained independent of variations in heat load (transported power) or heat sink (radiator temperature).

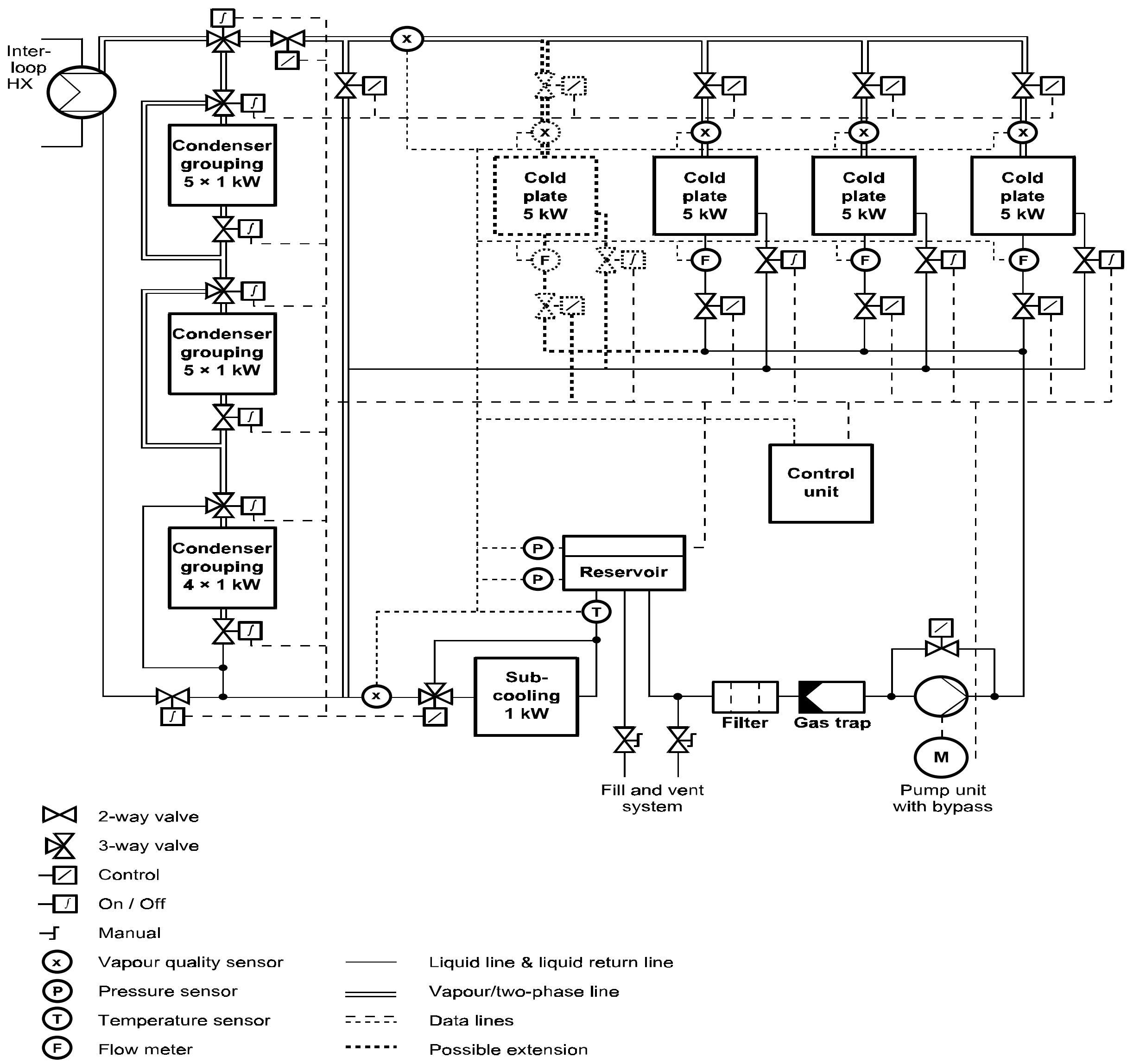

Figure 1. Schematic of ESA's R114 Two-Phase Heat Transport System

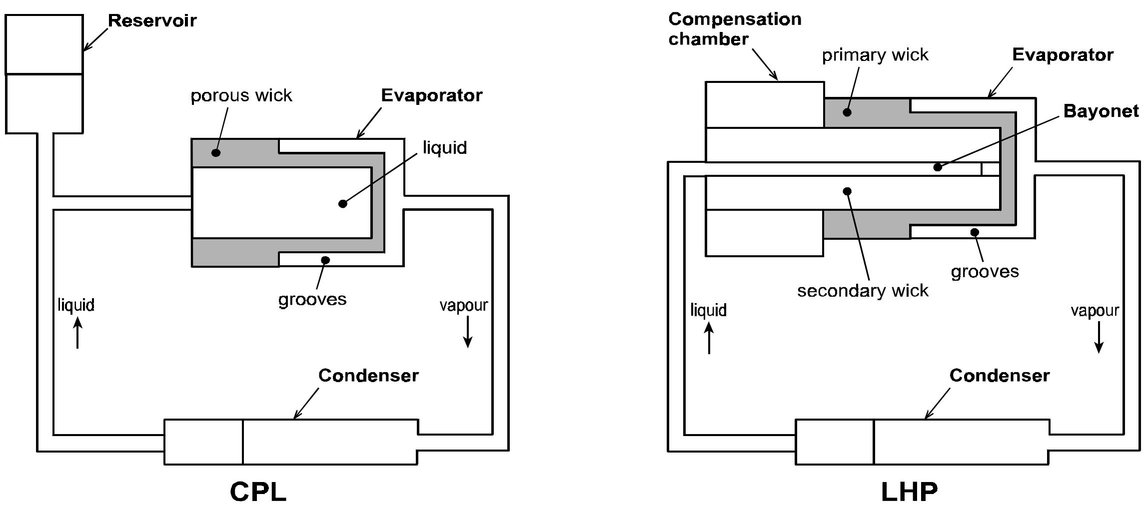

Figure 2. Schematics of Capillary Pumped Loop and Loop Heat Pipe

Though initially perceived by many as alternatives to heat pipes at high transport powers (500 W to 24 kW), in recent years the intrinsic advantages of a small-diameter piping system without distributed wick structures were exploited at low powers (20 to 100 W). Many CPL and LHP advantages are only truly exploited when these devices are considered early in the design, rather than treat them as replacement for existing heat pipe based designs. These advantages are:

- There is no additional energy source required for the pumping action.
- Easy application in fixed conductance or variable conductance mode, fast and strong diode action.
- The tolerance of large adverse tilts (heat source up to 4 m above heat sink, facilitating ground testing and enabling many terrestrial applications) and the possibility of easily accommodating mechanical pumps.
- Apparent tolerance of a LHP for large amounts of non-condensable gases. This means extended lifetime. The tolerance of very complicated layouts and tortuous transport paths, easy accommodation of flexible parts, make/break joints, vibration isolation.
- The separation of heat acquisition and rejection components for independent optimisation of heat transfer footprints and even integral independent bonding of such components in larger structures.

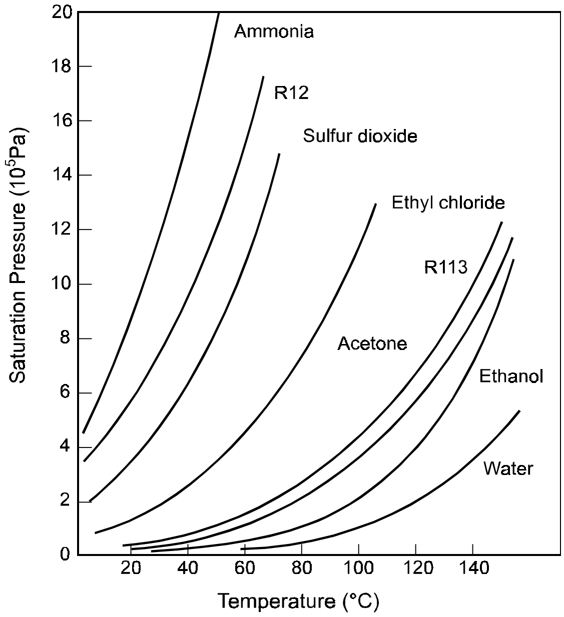

Figure 3. Liquid Vapour Pressure Versus Temperature for Various Working Fluids

Development supporting, scientific experiments were also carried out in the last decade, within research programmes which concentrate on the physics of two-phase flow and heat transfer in micro-g (Leontiev et al., 1997). Several experiments were done in drop towers (e.g. Wőlk et al., 1999), others during Microgravity Science Laboratory missions on the Space Shuttle (e.g. Allen et al., 1999, 1998). Other investigations were executed during low-gravity aircraft flight trajectories (e.g. Lebaigue et al., 1998; Hamme, Best, 1997; Reinarts et al., 1996, 1995; Antar, Collins, 1996; Fore et al., 1996; Jayawardena, 1996; McQuilen,, Neuman, 1996; 1993; Rite, Rezkallah, 1994; Miller et al., 1993; 1997, Zhao, Rezkallah, 1993; Huckerby, Rezkallah, 1992; Crowley, Sam, 1991; Colin et al., 1991; Kawaji et al., 1991). Unfortunately, only the first three of the low-g aircraft experiments were two-phase single-component experiments (working fluid and its vapour), being representative for what is going on in two-phase heat transport loops. The results of the other experiments, mostly two-phase two-component (air and water) experiments, are useful, but less relevant for two-phase heat transport loops.

TWO SUCCESSFUL IN-ORBIT EXPERIMENTS: TPX I & LHPFX

Two successful flight experiments to demonstrate CPL & LHP technology in-orbit, will be described here, using excerpts of the original presentations on ESA’s Two-Phase eXperiment TPX I (Delil, 1995, 1997) executed on the Space Shuttle Discovery during the STS-60 mission in February 1994, and on the Loop Heat Pipe Flight eXperiment LHPFX (Bienert et al., 1998; Delil, 1999) carried out on Space Shuttle Columbia during the STS-87 mission in November 1997.

ESA’s Two-Phase eXperiment TPX I

TPX I (Delil et al., 1995) started in 1990, by prime contractor NLR, SABCA, Bradford Engineering, Stork Products Engineering and Fokker Space. The experiment was a downscaled ammonia capillary pumped loop, containing scaled-down components of mechanically pumped loops: Multi-channel condensers, vapour quality sensors (VQS) and a controllable 3-way valve. TPX has run autonomously in Get Away Special canister G557 on STS-60, with own power supply, data handling and experiment control.

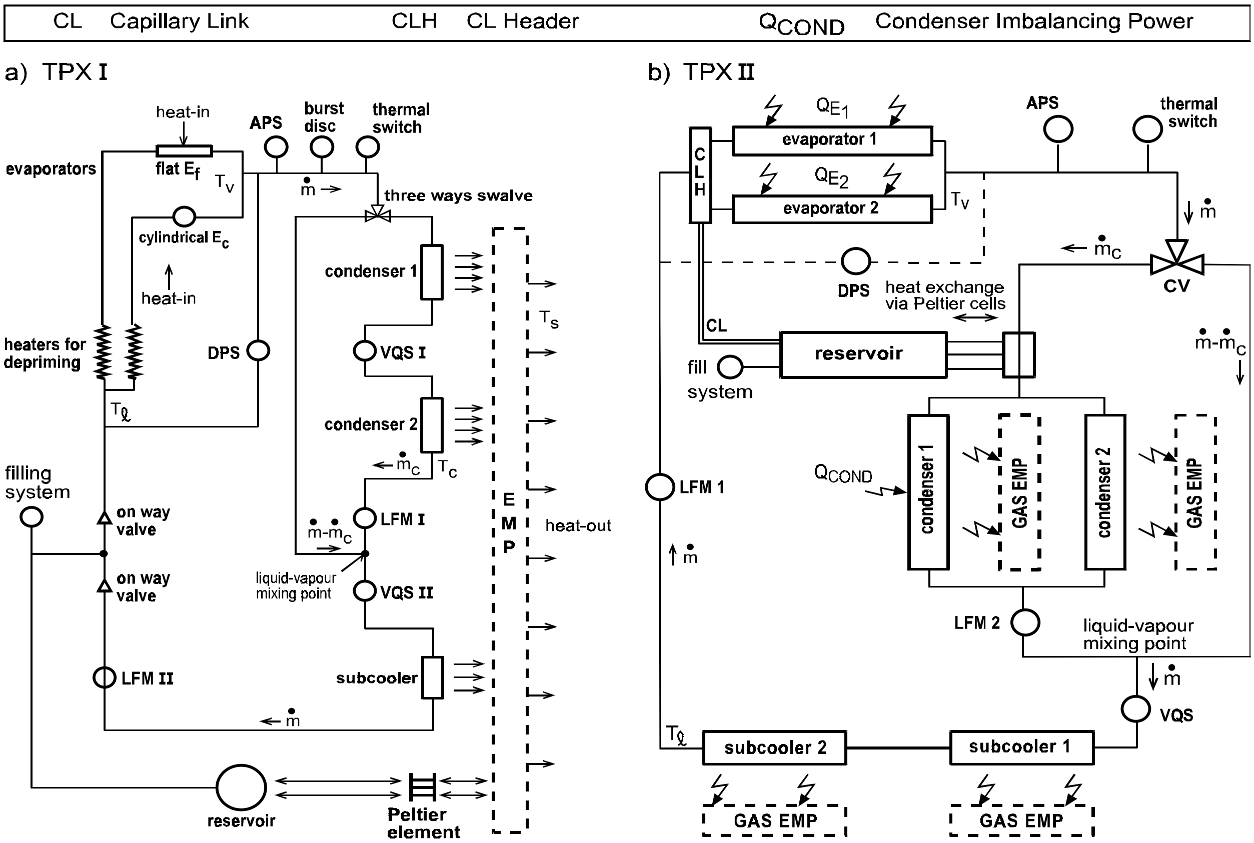

Figure 4. Schematics of TPX I and its follow-up TPX II

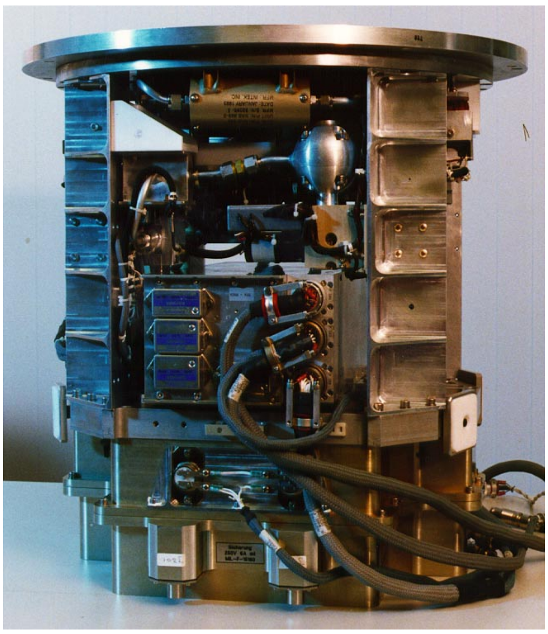

Figure 5. TPX I Hardware

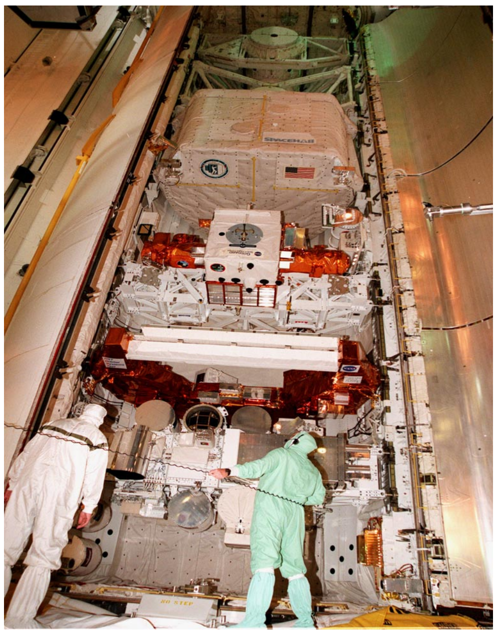

Figure 6. GAS Canister in Shuttle Bay

The experiment schematic is shown in figure 4. Heat, supplied to two parallel capillary pumped evaporators (a flat and a cylindrical one), causes evaporation of the working fluid, sets the mass flow rate and generates the pumping pressure to maintain the working fluid circulation in the system. The heat, extracted from the fluid in the condenser sections and sub-cooler, is dumped to space via the GAS canister lid. The control of the loop temperature setting is by a Peltier element controlling an accumulator (reservoir), which contains liquid and vapour in equilibrium. In addition, the loop contains two vapour quality sensors, a controllable three-way valve with a vapour bypass line, and de-priming heaters for the two evaporators. The complete experiment had to fulfil the GAS requirements and restrictions: allowable volume (135 litres) and mass (90 kg maximum), no power and data communication connections to STS (hence limited battery energy and internal data storage), Shuttle attitude dependent thermal sink conditions and limited crew action (only on/off). Figure 5 shows a photograph of the hardware. Figure 6 depicts the Get Away Special canisters in the cargo bay of the Space Shuttle.

The TPX I baseline had to meet the many objectives for the different experiment constituents: Capillary pumped loop (CPL), vapour quality sensors (VQS) and multi-channel condensers, each of them being a scaled-down version of a concept developed for power systems up to 10 kW. The downscaling was intended not to affect the goals of the in-orbit demonstration of these concepts.

To fulfil the objectives of the CPL and of the different components an extended experimental programme was carried out, until battery exhaust. These objectives can be summarised by:
- The capability to smoothly/continuously transport heat and to start-up from low temperatures.
- Proper operation for different heat loads applied to two evaporators in parallel.
- The capability to share heat load between the evaporators, to maintain a constant and homogeneous temperature.
- The capability to prime an evaporator by a controlled management of the reservoir fluid content.
- The capability to control a set-point temperature (while operating under different, varying heat load and sink conditions) by proper reservoir fluid content control.
- Determination of transport limits, maximum pumping pressures, and evaporator heat transfer coefficients.
- De-priming and re-priming by controlled reservoir actions.
- The interaction of evaporators in parallel, also with respect to heat load sharing.
- To assess and compare the (limits of the) CPL heat transport capability under low gravity and terrestrial conditions and to compare these with predictions resulting from modelling with thermal analyser program ESATAN.
- To prove the feasibility of the VQS concept in space, and to demonstrate proper VQS performance for ammonia, the most promising working fluid for space systems.
- To carry out vapour quality control exercises to prove the usefulness of VQS for system control and to demonstrate the proper performance of the controllable three-way valve.
- To compare the performance of the two sensors in order to assess the influence of the location within the loop and of small construction differences, to perform calibrations, and to assess differences in low-g and terrestrial sensor performances (important for the design of future space-oriented vapour quality sensors).
- The use of low-g and one-g TPX I test data and outcomes of testing in terrestrial two-phase test loops, to verify the NLR approach for thermal-gravitational scaling two-phase flow and heat transfer (Delil, 1991, 1992, 1998, 2000).

The results of the flight data, all together 2 megabytes gathered during 43 hours experimenting, can be summarised by:
- The CPL start-up was properly realised at all power levels.
- The CPL was capable to transport heat smoothly/continuously, with two evaporators in parallel up to 2 x 95 W.
- There was proper evaporator heat load sharing with the ability of the loop to maintain a smooth operation.
- The adjusting/maintaining set point temperature has accuracy better than 0.3 K for all heat loads/sink conditions.
- The CPL properly primed using the reservoir contents control.
- The heat transfer coefficient values are constant, but 2000 W/Km^2 higher than the predictions assuming annular flow along the condenser, while in reality part of the condensation path is slug flow with the better heat transfer.
- There is a significant difference between 1-g and low-g VQS responses. Terrestrial annular vertical down-flow does not represent accurately actual 0-g annular flow. This is due to the draining if the liquid layer by gravity.

In summary it is remarked that TPX I was successful, many objectives have been met. The design has clearly shown to be a good balance between the consequences of very limited flight opportunities and two conflicting requirements. The viability of 0-g two-phase technology has been proven. But more in-orbit investigations are to be carried out.

Loop Heat Pipe Flight eXperiment LHPFX

LHPFX was developed and (flight) tested by a team, led by Dynatherm Corporation. The team consisted further of members from industry (Hughes), the US government (the NASA Center for Space Power and NASA Goddard Spaceflight Center, the US Air Force Phillips Laboratory, US Air Force Wright Laboratory/BMDO, Naval Research Laboratory and the Aerospace Corporation) and NLR, the National Aerospace Laboratory of the Netherlands.

It is recalled that LHP's, being currently base-lined as integral thermal control components for the next generation of large communication satellites, constitute an enabling technology for deployable thermal radiators. Their capability to function in almost any orientation facilitates ground testing. The small diameter transport lines permit easy routing around equipment within the spacecraft. At least one major US spacecraft manufacturer is committed to LHP's for the next series of satellites; most manufacturers are actively evaluating the technology. Applications for LHP's in aircraft are also under development. The high capillary pumping capability of a LHP permits operation under high accelerations in aircraft. Applications being developed include de-icing of control surfaces using waste engine heat, and cooling of actuators. LHP's are also being considered for roof top solar installations because of their ability to transport heat against gravity. Other interesting applications are the thermal control of Moon/Mars bases and cooling of remote communication sheds in hot desert environments by transporting the heat into the ground.

LHP's were originally developed in the former Soviet Union. The Russians have incorporated the LHP in several of their satellites and have demonstrated their reliable, long-term operation in micro-gravity. But unfortunately only very limited test data are available in the open literature. Dynatherm, through its parent organisation DTX, transferred the Russian technology to the US through a co-operative agreement with TAIS, a Russian firm in Moscow. To qualify the LHP for use in the US, the ability to duplicate the Russian technology needed to be demonstrated and a US made device flight-tested on a US spacecraft. This was main objective of the LHPFX. A second objective was to provide a database for the correlation and the verification of the analytical models developed. Figure 7 shows the LHPFX layout.

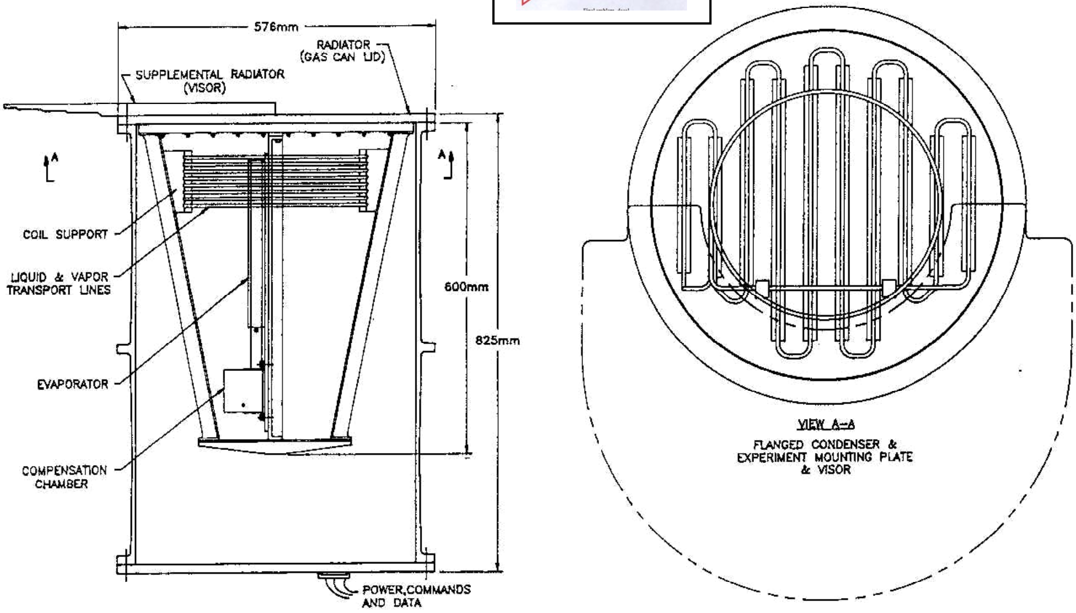

Figure 7. LHPFX Layout

LHPFX was designed to transport more than 800 W over the temperature range from -40 to +65 ˚C. But the available experiment power limited operation in space to 400 W. The overall conductance was estimated to be approximately 50 W/˚C, for a fully active condenser. The experiment was in a standard, 5 ft^3 NASA Hitchhiker canister. In order to package the device inside the compact canister, the 4.5 m long vapour and liquid transport lines were coiled. The flanged condenser was bonded to the canister upper lid, serving as the basic thermal radiator, whose area was enlarged by a visor. Radiator and visor were silver-teflon covered. All other external surfaces were insulated. The canister was mounted at the starboard sidewall in the Shuttle cargo bay.

The experiment was instrumented with 36 temperature sensors, kapton tape heaters on the evaporator allowed the input power to be varied in steps of 12.5 W from zero to 388 W. A small auxiliary heater and a thermostat were fixed on the compensation chamber. Their purpose was to evaluate the temperature control capability of the LHP at a fixed set point. Another auxiliary heater was fixed to the radiator plate. Its purpose was to adjust the initial temperature of the radiator prior to starting the LHP. Standard Hitchhiker services for power, data and command of the experiment were used. The command and telemetry interface between experiment and Hitchhiker electronics was via a Data Acquisition & Control

Unit. Real time monitoring/command of the experiment was accomplished through ground support equipment from the Hitchhiker Control Center at NASA Goddard.

The original test plan called for approximately 60 hours of experiment operation. It consisted of: Start-up and power changes at low (-50 to -40 °C), medium (-15 to 0 °C) and high temperatures (20 to 35 °C), and of quasi-steady state runs with constant high power (200 W) and with constant low power (25 W).

Temperature set-point control with varying input power and sink conditions: The objectives of the original test plan were met with one exception: the desired low start temperature of -50 to -40 °C was not reached with the available attitudes of the Space Shuttle. The minimum radiator temperature was only -20 °C during the first cold test. The cold start-up test was repeated toward the end of the mission with a more favourable Shuttle attitude, which resulted in a minimum radiator temperature of -34 °C. In addition to the planned tests, a large number of auxiliary tests were conducted. As a result, the LHP accumulated in total 213 hours of operating time in micro-gravity. In summary: LHPFX was very successful.

DESIGN SUPPORTING THEORETICAL WORK

Design supporting theoretical work consists of the thermal-gravitational modelling and scaling of two-phase loops (based on dimension analysis and similarity considerations), the assessment of the constitutive equations for two-phase flow and heat transfer and studying the issues of two-phase flow patterns.

Background of Thermal-Gravitational Modelling and Scaling

Summarizing earlier discussions (Delil, 1989, 1991, 2000), it is repeated that there are many examples of scaling of two-phase flow and heat transfer in the power and the process industries. Scaling physical dimensions is the principal interest in the process industry: Large-scale industrial systems are studied by reduced-scale laboratory model systems. Scaling the working fluid is of principal interest in the power industry: Large-scale industrial systems (high heat fluxes, temperatures, and pressures) are translated in full size systems, operating at lower temperature, heat flux and pressures (e.g. high pressure water-steam systems scaled by low pressure refrigerant systems of identical sizes). Thermal-gravitational modelling and scaling of two-phase heat transport systems was done at NLR to get a better understanding of two-phase flow and heat transfer phenomena, to provide means for data comparison and generalisation, to develop a useful tool to design two-phase systems, and to reduce costs.

Main goal of scaling space-oriented two-phase heat transport systems is developing reliable spacecraft systems, whose reduced-g performance can be correctly predicted by results of terrestrial experiments with scale models. Scaling of spacecraft systems can be useful also for in-orbit technology demonstration (as the performance of spacecraft heat transport systems prototypes can be predicted using the outcomes of in-orbit experiments on models with reduced geometry or a different working fluid) and for defining in-orbit experiments to isolate a particular phenomenon to be looked at (e.g. excluding gravity-induced disturbing buoyancy effects on alloy melting, diffusion and crystal growth) for a better understanding of the physics. The magnitude of the gravitational scaling varies with the objectives: From 1 g to 10^{-6} g for terrestrial scaling of orbiting spacecraft, from 1 g to 0.16 g for Moon base and 0.4 g for Mars base systems, from 10^{-2} g or 10^{-6} g to 1 g for isolating gravity-induced disturbances on physical phenomena investigated, from a low-g level to another or the same low-g level in low-g aircraft or sounding rockets. NLR developments originally pertained to the scaling of mechanically and capillary pumped two-phase loops for use in micro-gravity. The activities were based on dimension analytical similarity considerations. They were extended later to applications for Moon and Mars bases (Delil, 1998, 1999, 2000), and in the last few years to planetary super-gravity and super-g accelerations in spinning satellites and military combat aircraft.

Dimension Analysis & Similarity Considerations

Similarity considerations (for details see the aforementioned references) led to the identification of 18 dimensionless groups (so-called π-numbers), considered crucial for the thermal-gravitational scaling of two-phase loops. This set of 18 π-numbers, called "the most complete list of dimensionless numbers for two-phase flow and heat transfer" (Issacci, 1995), is shown in the first column of Table 1. It is marked by • in the columns whether a typical π-number is relevant in a particular section of a two-phase loop: Liquid lines (with or without heat exchange), capillary or swirl evaporators, vapour or two-phase lines, and condensers.

There is perfect similitude between model and prototype if all dimensionless numbers are identical in prototype and model. Only then scaling is perfect. It is evident that this is not possible for two-phase flow and heat transfer, as the phenomena are too complex, the number of important parameters or π-numbers is too large. Fortunately also imperfect (distorted) scaling can give useful results (Murphy, 1950). But, therefore a careful estimation of the relative magnitudes of the effects is required. Unimportant effects make the identity requirement for some π-numbers superfluous for the problem considered. The set of 18 π-numbers is rather arbitrarily chosen: Several numbers contain only liquid properties. They can be transferred into vapour properties containing numbers, using π_6 to π_8. π_1 can be used to interchange a characteristic length (duct length, bend radius) and some characteristic diameter (duct diameter, hydraulic diameter, surface roughness, bubble size). The best scaling approach is to choose π-number combinations suiting the problem under investigation. An extensive discussion on the various critical issues and limitations of the approach, on examples of choices of combinations for different cases, and on details of equations for some important π-numbers is given in the publications mentioned (Delil, 1989, 1991, 2000).

Relevance of π-numbers for thermal Gravitational scaling of two-phase loops	Liquid Parts		Evaporators Swirl & Capillary	Non-liquid Lines Vapour/2-Phase	Condensers
	Adiabatic	Heating/Cooling			
π_1 = D/L = geometry	•	•	•	•	•
$\pi_2 = Re_l = (\rho v D/\mu)_l$ = inertia/viscous	•	•	•	•	•
$\pi_3 = Fr_l = (v^2/gD)_l$ = inertia/gravity	•	•	•	/•	•
$\pi_4 = Eu_l = (\Delta p/\rho v^2)_l$ = pressure head/inertia	•	•	•	•	•
$\pi_5 = \cos \nu$ = orientation with respect to g	•	•	•	/•	•
π_6 = S = slipfactor = v_v/v_l			•	•	•
π_7 = density ratio = ρ_v/ρ_l			•	•	•
π_8 = viscosity ratio = μ_v/μ_l			•	•	•
$\pi_9 = We_l = (\rho v^2 D/\sigma)_l$ = inertia/surface tension			•	/•	•
$\pi_{10} = Pr_l = (\mu Cp/\lambda)_l$		•	•		•
$\pi_{11} = Nu_l = (hD/\lambda)_l$ = convective/conductive		•	•		•
$\pi_{12} = \lambda_v/\lambda_l$ = thermal conductivity ratio			•		•
$\pi_{13} = Cp_v/Cp_l$ = specific heat ratio			•		•
$\pi_{14} = \Delta H/h_{lv}$ = Bo =enthalpy nr. = X = quality		•	•	•	•
$\pi_{15} = Mo_l = (\rho_l \sigma^3/\mu_l^4\, g)$ = capillarity/buoyancy			•	/•	•
$\pi_{16} = Ma = v/(\partial p/\partial \rho)^{1/2}{}_s$			•	•	•
$\pi_{17} = (h/\lambda_l)(\mu_l^2 g)^{1/3}$			•		•
$\pi_{18} = L^3 \rho_l^2\, g\, h_{lv}/\lambda_l \mu_l (T-T_o)$			•		•

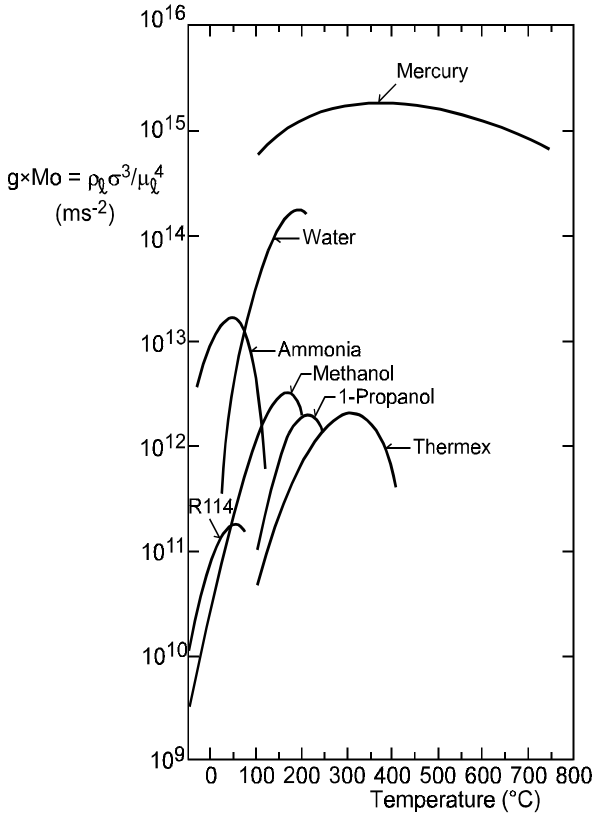

Figure 8. $\rho_l.\sigma^3/\mu_l^4$ Versus Temperature for 7 Fluids

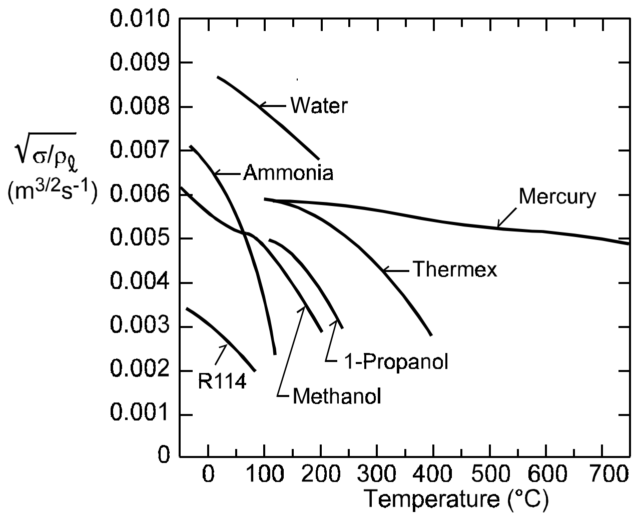

Figure 9. $(\sigma/\rho_l)^{½} = D.g^{½}.(We/Fr)^{-½}$ Versus Temperature

Here the discussion is restricted to the Morton number Mo_l (important for scaling two-phase flow with respect to gravity, as it contains only liquid properties, surface tension and gravity), and We/Fr (equal to Eö = 4 Bo), defined by:

$$Mo_l = Re_l^4 Fr_l / We^3 = \rho_l \sigma^3 / \mu_l^4 g \, , \tag{1}$$

$$We/Fr = Eö = 4\, Bo = g\, D^2\, (\rho_l - \rho_v)/\sigma \approx g\, D^2/(\sigma/\rho_l) \tag{2}$$

Scaling consequences are derived from figures 8 and 9, showing the temperature dependence of $g.Mo_l = \rho_l.\sigma^3/\mu_l^4$ and $(\sigma/\rho_l)^{½} = D.g^{½}/(We/Fr)^{½} = D.g^{½}/(Eö)^{½} = D.g^{½}/2(Bo)^{½}$. Figure 8 yields the gravity levels related issues: Fluids, gravity levels and temperatures corresponding to of the identity of Morton number of prototype and scale model. Once knowing these, figure 9 will yield the corresponding length scaling between prototype and scale model. Some examples are given next as illustrations.

Scaling at the same gravity level means a fixed $g.Mo = \rho_l.\sigma^3/\mu_l^4$-value for prototype and model. Figure 8 shows that the value $\rho_l\, \sigma^3/\mu_l^4 = 2*10^{12}$ m/s^2 can be realised by 115°C ammonia, 115°C methanol, 35°C water, 180°C propanol, 235°C propanol, 250°C thermex and 350°C thermex. The length scales follow from reading the with these temperatures corresponding (σ/ρ_l)-values in figure 9, and inserting identity in $g/(We/Fr)^{½}$, the geometric ratios 2.5 : 4.5 : 8.4 : 4.2 : 3.0 : 5.0 : 3.6. Figure 8 also shows that scaling a high-pressure (say 110 °C) ammonia system can be done by a low-pressure (say –50 °C) ammonia system, which might be attractive for safety reasons or will to reduce the impact of earth gravity in vertical two-phase sections. It follows from figure 9 that the geometric scaling ratio between high-pressure prototype and low-pressure model (both characterised by $\rho_l\, \sigma^3/\mu_l^4 = 2.10^{12}$ m/s^2) is about 0.4. Figure 8 shows also that scaling with respect to gravity is restricted to maximal two decades, if the fluid in prototype and model is the same (water or methanol). The figures 8 and 9 illustrate also that “fluid to fluid”-scaling offers many possibilities, hence is far more interesting. A very attractive scaling possibility is the scaling of a two-phase prototype for a Mars or a Moon base, by a terrestrial model with the same or a scaled working fluid. As the ratio of gravity levels between prototype and model is not far from 1 (Mars 0.4, Moon 0.16), the sizes of the model have to be only slightly larger than the geometric sizes of the prototype. Adjustment of the inclinations (cos υ) of non-horizontal lines in the terrestrial model may lead to almost perfect scaling. For further details it is referred to earlier publications (Delil, 1989; 1991, 1998, 1999, 2000).

The majority of the remarks on two-phase thermal-gravitational modelling and scaling made above are directly applicable for pulsating two-phase loops. The only new issue to be accounted for is the proper design of the desired driving pressure, which is directly coupled to the corresponding difference of the saturation temperatures in evaporator and condenser. It is obvious that for substantial temperature differences a constant fluid property approach will not be maintainable. This considerably complicates, not only the equations and their solution, but also the various scaling issues.

Pressure Drop & Heat Transfer Equations for Annular Flow

The pressure drop, in the different two-phase sections, is considered crucial for two-phase loop modelling and scaling. The next considerations therefore will concentrate on pressure drops in condensing and adiabatic flow and will restrict the discussion to annular flow in straight tubes with circular cross-sections. The total local pressure gradient $(dp(z)/dz)_t$ is the sum of three constituents: friction, momentum and gravity. The equations for these constituents are given below (deleting the z-dependence to shorten the notation). Fluid properties are assumed independent of z, since they depend only on the mixture temperature, which usually is almost constant in adiabatic and condensing sections. The complete set of flow and heat transfer equations is given below. Details on the derivation and assumptions are discussed in elaborate articles on the subject (Soliman, 1968; Delil, 1991).

$$(dp/dz)t = (dp/dz)_f + (dp/dz)_m + (dp/dz)_g : \tag{3}$$

$$(dp/dz)_f = -(32m^2/\pi^2\rho_v D^5)(0.045/Re_v^{0.2})[X^{1.8} + 5.7(\mu_l/\mu_v)^{0.0523}(1-X)^{0.47}X^{1.33}(\rho_v/\rho_l)^{0.261} + 8.1(\mu_l/\mu_v)^{0.105}(1-X)^{0.94}X^{0.86}(\rho_v/\rho_l)^{0.52}] \tag{3a}$$

(X is local quality X(z), Reynolds number $Re_v = 4\dot{m}/\pi D\mu_v$, β=2 (laminar), 1.25 (turbulent liquid flow).

$$(dp/dz)_m = -(32\dot{m}^2/\pi^2\rho_v D^5)(D/2).(dX/dz)\,[2(1-X)(\rho_v/\rho_l)^{2/3} + 2(2X-3+1/X)(\rho_v/\rho_l)^{4/3} + (2X-1-\beta X)(\rho_v/\rho_l)^{1/3} + (2\beta - \beta X - \beta/X)(\rho_v/\rho_l)^{5/3} + 2(1-X-\beta+\beta X)(\rho_v/\rho_l)]. \tag{3b}$$

$$(dp/dz)_g = (32\dot{m}^2/\pi^2\rho_v D^5)\{1-[1+(\rho_v/\rho_l)^{2/3}(1-X)/X]^{-1}\}[\pi^2 D^5 g \cos\nu(\rho_l-\rho_v)\rho_v/32\dot{m}^2]. \tag{3c}$$

$$(1-\alpha)/\alpha = S\,(\rho_v/\rho_l)\,X/(1-X)\,, \tag{4}$$

$$S = (\rho_l/\rho_v)^{1/3}\,, \tag{5}$$

relates quality X and volumetric vapour void fraction α, with a slip factor S, that (for simplicity reasons and for comparison with results of calculations found in literature) is chosen to be a simplified version of the slip factor for minimum entropy generation in annular flow (Zivi, 1964). Another relation is needed defining the z-dependence of X. The missing equation is

$$\dot{m}\, h_{lv}(dX/dz) = -\,h\pi D[T(z)-T_s]\,, \tag{6}$$

relating local vapour quality and heat transfer. h is the local heat transfer coefficient h(z), which equals, assuming that the major thermal resistance is the laminar sub-layer of the turbulent condensate film, plus a liquid layer conduction term (Soliman, 1968):

$$h = 0.018(\lambda_l \rho_l^{1/2}/\mu_l)\, Pr_l^{0.65}\, |-(dp/dz)_t|^{1/2}\, D^{1/2} + R\,(4\lambda_l/D)\,\ln\,[1 + (\rho_v/\rho_l)^{2/3}\,(1-X)/X] \quad 0 < R < 1. \qquad (7)$$

The two-phase flow path is almost isothermal, implying constant temperature drop $T(z) - T_s$ (for a constant sink temperature T_s), constant fluid properties and constant Prandtl number, defined in Table 1. The total condensation pressure drop is:

$$\Delta p_t = \int_0^{L_c} (dp/dz)_t . dz\ . \qquad (8)$$

The above equations can be combined, yielding an implicit non-linear differential equation in variable X(z), which can be rewritten into a solvable standard form for differential/algebraic equations (Dam, 1992)

$$F\ (dX/dz,\ X) = 0\ . \qquad (9)$$

Figure 10 yields the calculated pressure gradient constituents for ammonia at two temperatures (–25 °C & +25 °C). The curves prove that at low temperature the gravity constituent is overruled by the other contributions, confirming that low-g behaviour can be investigated by terrestrial tests at low temperature. The calculated curves (Delil, 1991) for low-g aircraft experiments with an adiabatic R114 loop (Chen, 1991), lying within the uncertainties of the measured data, clearly support the model developed for annular flow.

Calculations were extended to condensing flow in a straight duct (Delil, 1992) to investigate the impact of g-level on the duct length needed for complete condensation (g-levels considered are zero g, Earth gravity 9.8 m/s^2, Mars gravity 3.74 m/s^2, Moon gravity 1.62 m/s^2, and super-g 19.6 m/s^2). This impact, reported to lead to duct lengths being more than one order of magnitude larger for zero gravity as compared to horizontal orientation in earth gravity (Da Riva & Sanz, 1991), was assessed for various mass flow rates, duct diameters and thermal (loading) conditions, for ammonia and R114. A summary of results of calculations for ammonia is presented next. To compare the results of calculations with data from literature, the condenser defined by Da Riva the baseline. Main characteristics are power 1 kW, line diameter 16.1 mm, temperature 300 K and temperature drop to sink 10 K. Figure 11 shows the vapour quality X along the condensation path (as a function of non-dimensional length z/D) for all g-levels mentioned, including the curves for 0-g and horizontal condensation on earth of Da Riva. From this it can be concluded that: the length required for full condensation strongly increases with decreasing gravity. Zero-g condensation length is roughly 10 times the terrestrial condensation length. Da Riva's data clearly are extremes. To assess impact of saturation temperature, curves were calculated for other temperatures and the parameter values given (Delil, 1992). Calculations show that full condensation length increases with temperature in 0-g, decreases for other g-levels: Differences between 1-g and 0-g decrease with decreasing temperature, confirming that gravity impact is reduced

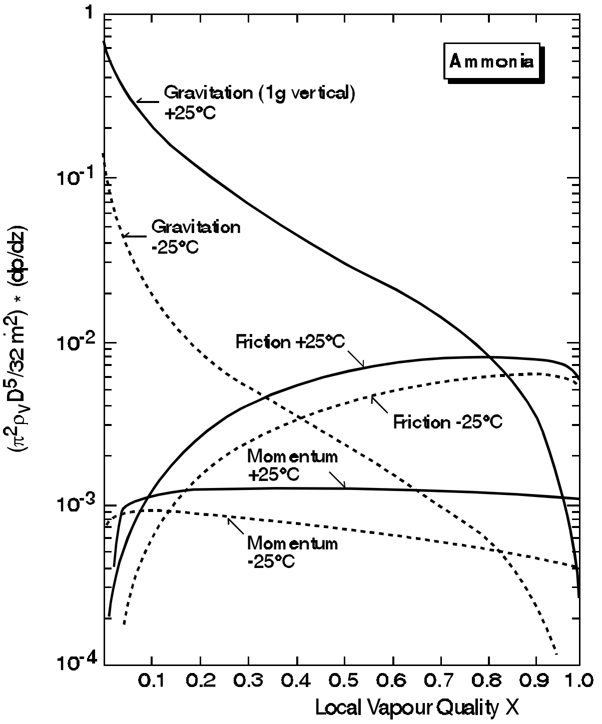

Figure 10. Pressure Drop Constituents at –25 and +25 °C

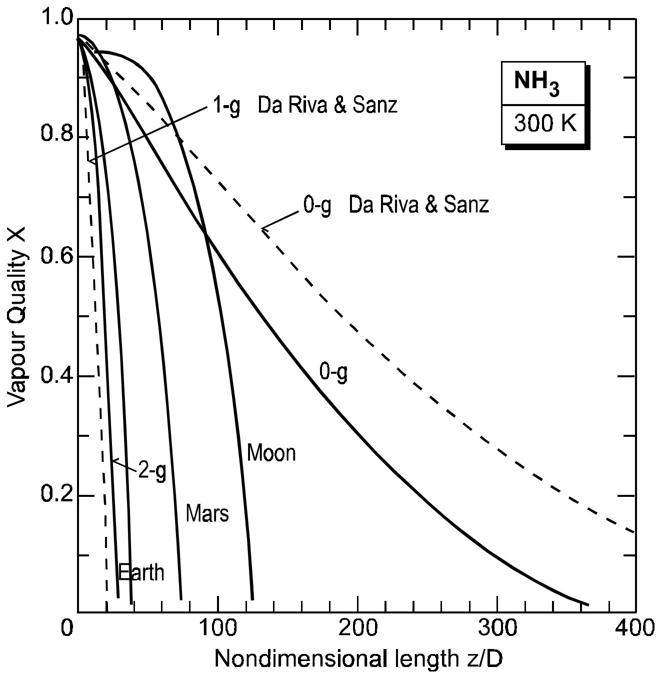

Figure 11. Vapour Quality along Reference Duct

Calculations of the vapour quality distribution along the 16.1 mm reference duct for condensing ammonia (at 300 K) under Earth gravity and 0-g conditions, for power levels ranging from 0.5 kW up to 25 kW, yielded (Delil, 1992) that a factor 50 in power, 25 kW down to 500 W, corresponds in a zero gravity environment to a relatively minor reduction in full condensation length, i.e. from 600 D to 400 D (9.5 to 6.5 m). Also are, under earth gravity conditions, power and full condensation length strongly interrelated: from L_c = 554 D at 25 kW to only 19 D at 500 W. The gravity dependence of the full condensation length decreases with increasing power, until the differences vanish at roughly 1 MW condenser choking conditions.

Calculation of the vapour quality along the duct for three gravity levels (0, Earth and 2-g) and three duct diameters (8.05, 16.1 and 24.15 mm) at 300 K, yielded the ratio of absolute duct lengths L_c needed for full condensation under zero-g and one-g respectively (Delil, 1992). It is concluded that the ratio of full condensation lengths in zero-g and on Earth ranges from roughly 1.5 for the 8.05 mm duct, via 11 for the 16.1 mm duct, up to more than 30 for the 24.15 mm duct: Small line diameter systems are less sensitive to gravity level differences than larger diameter systems. This is confirmed by TPX I flight data (Delil, 1995).

FLOW PATTERN ISSUES

As the developed model is for annular flow, it is worthwhile to investigate the impact of other flow patterns in the condenser duct (mist flow at high quality, slug and bubbly flow at low quality and wavy-annular-mist in between). Therefore one has to investigate whether the pure annular flow assumption, leads towards slightly or substantially overestimated full condensation lengths. In addition, flow pattern transitions occur at quality values, which strongly depend on temperature and line diameter. Knowledge of the gravity level dependent two-phase flow regimes is crucial for modelling/designing two-phase heat transport systems for space, as flow patterns (or regimes) determine thermal hydraulic characteristics of two-phase flow & heat transfer.

Flow Pattern or Flow Regime Mapping

It is obvious that flow pattern (regime) maps are to be created, preferably in a non-dimensional format show in figure 12 (Oshinowo, Charles, 1974). Figure 13 (Wallis, 1969) qualitatively illustrates the flow pattern dependence of the apparent friction factor or normalised pressure drop. The 3-D flow pattern maps, shown in the figures 14 and 15, were created by using many K135 aircraft flight data obtained with a R12, 10.5 mm line diameter experiment (Hamme, Best, 1997). The data were obtained at various g-levels, realised during numerous flights ($j_v = v_v.A_v/A$; $j_l = v_l.A_l/A$). The figures clearly show the gravity level dependency of the shifts in transitions from annular flow to slug flow or to stratified flow, and from slug/plug flow to annular flow and stratified flow.

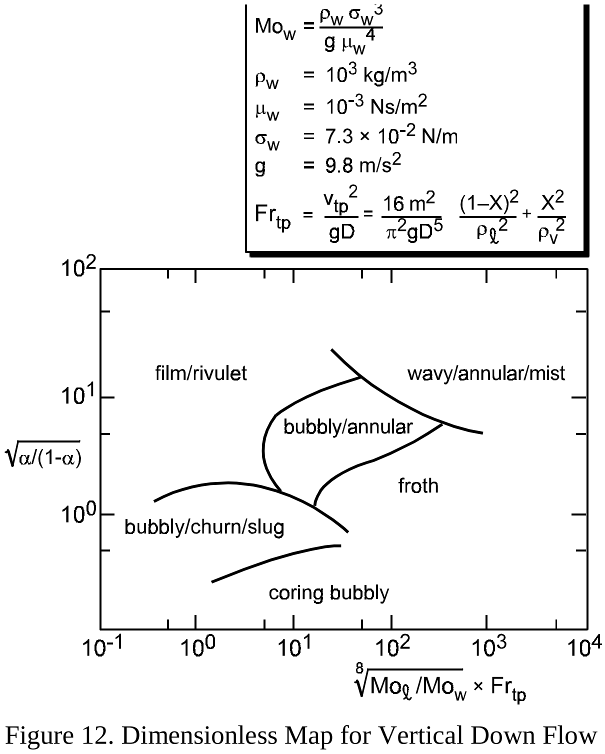

Figure 12. Dimensionless Map for Vertical Down Flow

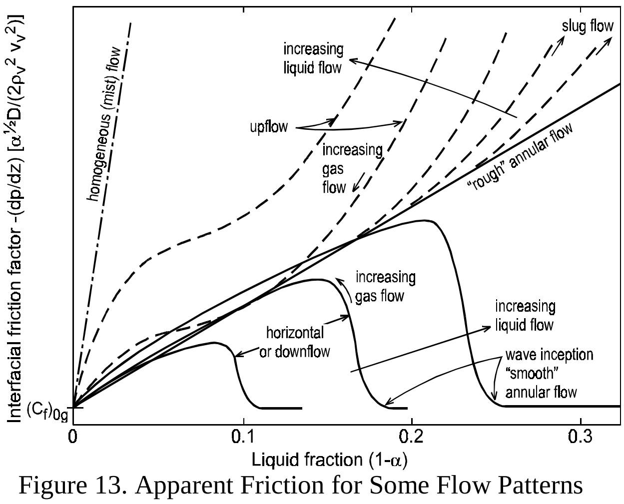

Figure 13. Apparent Friction for Some Flow Patterns

Figure 16 summarises the 0-g data. It is a cross-section at 10^{-2}-g of the figures 14 and 15. Figure 17 depicts data of recent low-g aircraft experiments with Cyrène, an ammonia system with a 4.7 mm line diameter (Lebaigue et al., 1998). Figure 18 depicts a 0-g map derived from TPX I (ammonia, 4.9 mm line) VQS flight data (Delil, 1995).

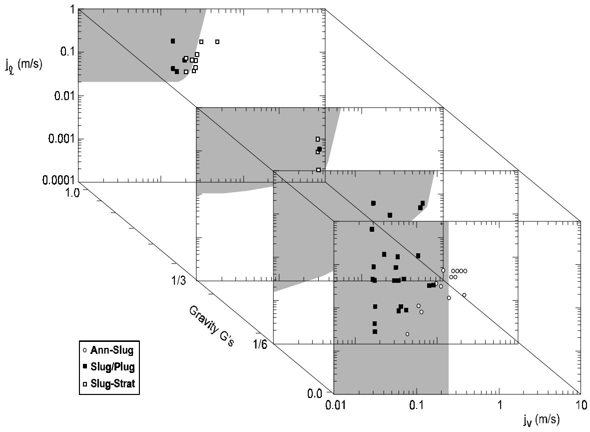

Figure 14. G-Dependent 3-D Slug-Plug Flow Pattern Map

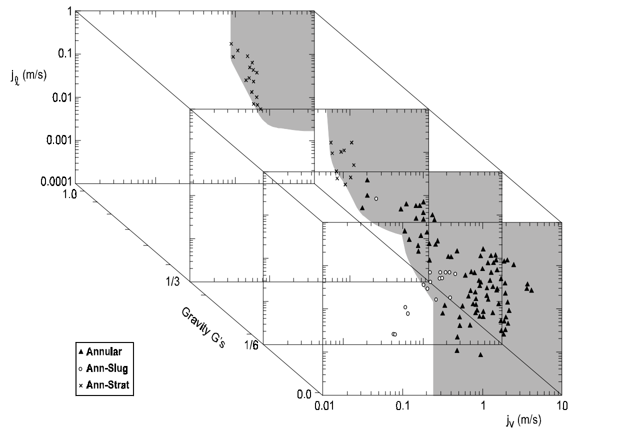

Figure 15. G-Dependent 3-D Annular Flow Pattern Map

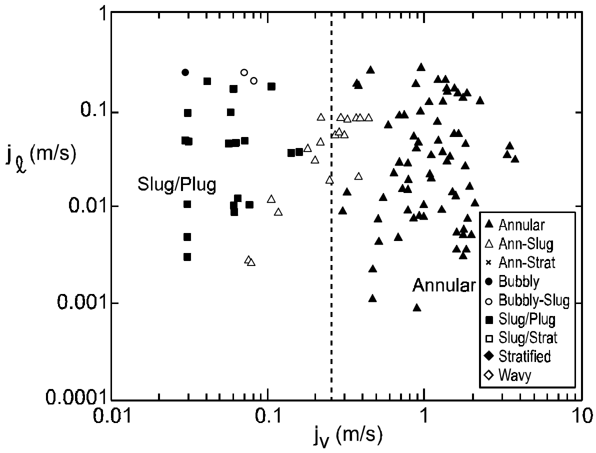

Figure 16. 0-G Cross-Section of 3-D Flow Pattern Maps

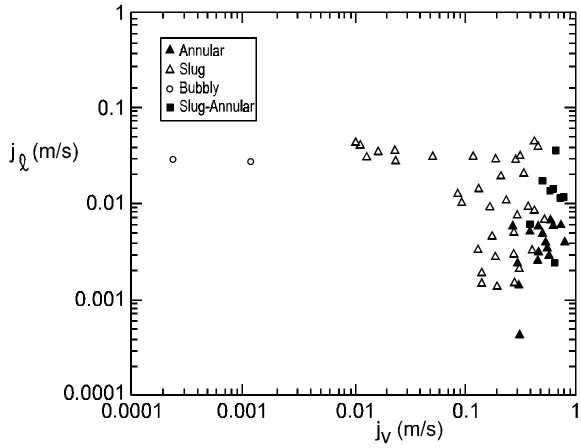

Figure 17. Cyrène Flow Pattern Map Data

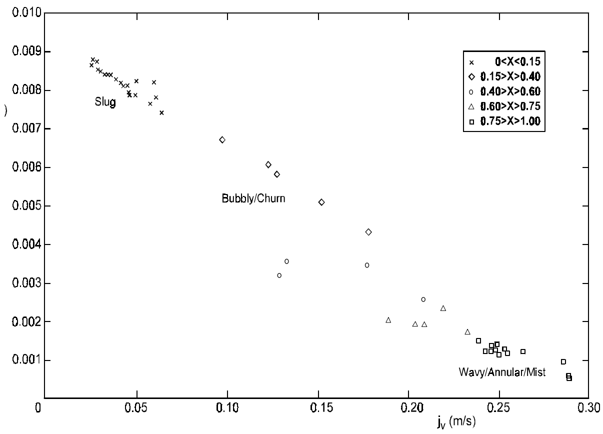

Figure 18: Flow Patterns According TPX I VQS Data

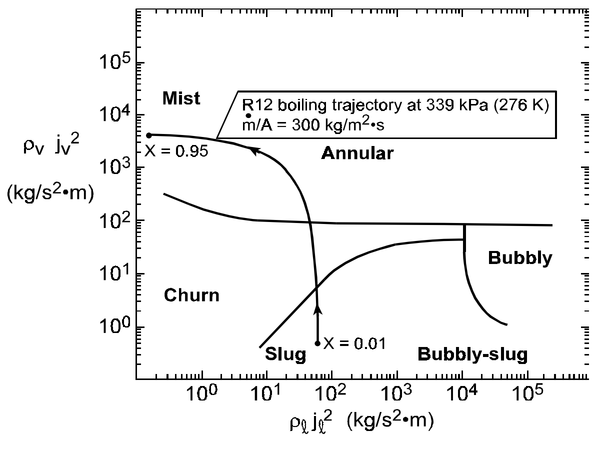

Figure 19. Flow Pattern Map for Vertical Down Flow

Flow Pattern Mapping for Anti-Super-Gravity

The impact of anti-g (against gravity or super-gravity) can be illustrated by recalling figure 10, showing the absolute values of the three pressure drop constituents. The results of pressure drop calculations, presented in the preceding sections, pertained to gravity-assist condensation This implies that the calculations were done for cosν = +1, meaning (as it is gravity-assist) that the contribution of gravity had the opposite sign of the constituents of friction and momentum. But when considering anti-super-g modes (hence cosν = –1), some important issues are to be noted:

- First, any pump has to deliver a pumping pressure that is at least the sum of all pressure losses in the system. In an anti-10g mode, this is mainly the gravitational pressure drop. Figure 10 illustrates that the contributions of friction and momentum are negligible, as compared to the 10-g contribution (which can by obtained by simply shifting the 1-g curve one decade upwards). The 10-g curve clearly overwhelms the curves of the other constituents, for almost all vapour qualities except for qualities over say 0.9, where the flow pattern probably will be homogeneous, instead annular. In case of a mechanical pump, the huge (super-gravity) pressure losses can be overcome by the use of a correctly designed displacement pump. Existing capillary pumped systems, however, will fail completely, since existing capillary structures can operate a two-phase loop against gravity, only if the maximum pumping height to be delivered is less than say 6 metres. The 6 m gravitational pressure drop is at least a factor 20 smaller than the 10-g super-gravity pressure drops. Current high-performance capillary pumps use well permeable wicks with a pore size of 0.5 µm to realise the 6 m pumping height. For a 20 times larger pumping height, the pore size shall be about 25 nm. But a wick with such pores will not have enough permeability for a capable capillary pump.

- Second, pressure and temperature drops are only minor in the gravity-assist condensation curves presented. It means that the condensation is almost isothermal, hence fluid properties can be assumed constant. This is the case for anti-super-gravity conditions, meaning that for such conditions calculations will become very complicated. As said, gravity influences pressure drop and the corresponding temperature drop across the heat transport system. This is confirmed by experimental data (Kiseev, 1999): Compared to 0-g pressure and temperature drops, the drops decrease with increasing gravity-assist, and strongly increase with increasing anti-gravity. Hence it is clear that for pulsating loops working fluids with a large dp/dT in the operating range are to be used, as the pressure drop is the system driver, as in detail discussed by Delil (2000; 2001).
- Third, not only for Moon or Mars anti-g, but also for super-g (assist or anti gravity) conditions no information exists on flow pattern maps and boundaries between different flow regimes. As the various items are expected to differ substantially from existing 1-g ones, the creation of flow pattern maps for super-g environment was started at NLR.

CURRENT LOOP-RELATED R&D ACTIVITIES AT NLR

In addition to the continuation of the activities described, NLR is also focusing on two-phase heat transport systems which are planned for near-term use on the International Space Station, ISS: The Alpha Magnetic Spectrometer experiment AMS-2 and CIMEX-3, NLR's versatile two-phase loop experiment, to be carried out in the Fluid Science Laboratory as a part of the ESA experiment programme on Convection Interfacial Mass Exchange investigations.

AMS-2 Thermal Control

AMS (Viertel, Capell, 1998), an international experiment on ISS, is a particle detector for high-energy cosmic rays, consisting of several sub-detectors: (Silicon) Tracker, Time of Flight System, Veto Counters, Transition Radiation Detector, Synchrotron Radiation Detector, Ring Imaging Cherenkov Counter, and an Electromagnetic Calorimeter.

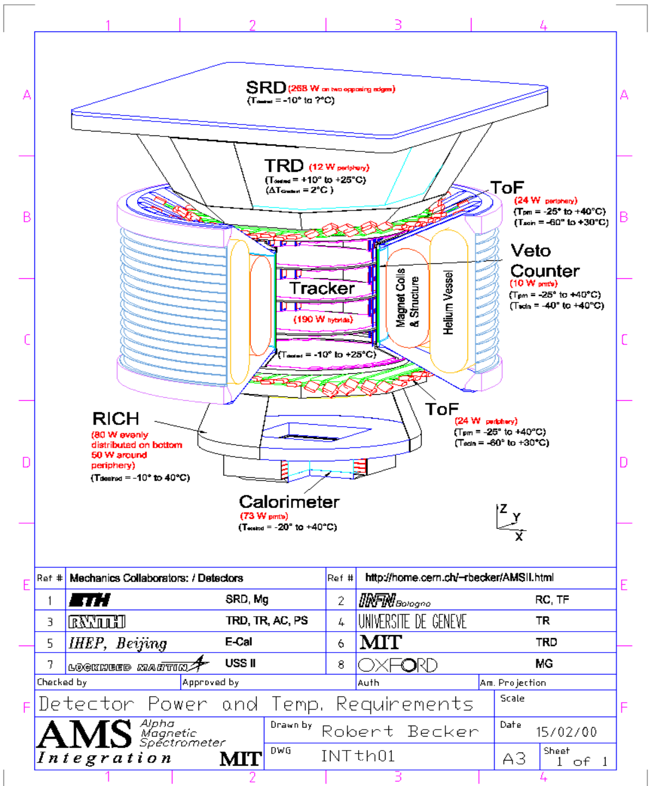

Figure 21. The Different Experiments of AMS

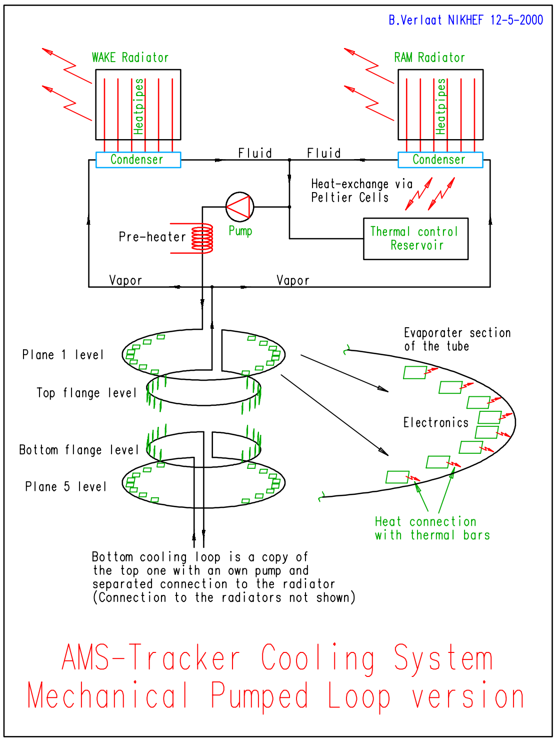

Figure 22. MPL Concept for Tracker Thermal Control

The detectors operate in a magnet field generated by a super-conductive magnet, which is responsible for curving the particle tracks necessary for charge identification. Its scientific goal is to detect anti-matter. The project leader is Nobel Prize laureate S. Ting of the Massachusetts Institute of Technology (MIT). The project is a joint between MIT and CERN (the European centre of nuclear research). The collaboration, supported by the US Department of Energy and NASA, includes worldwide 39 participating from academia and research institutes (Viertel, Capell, 1998). AMS-1, containing a heavy solid magnet instead a super-conductive magnet, was a demonstration flight on STS-91. Figure 21 depicts the AMS configuration, showing the various experiments. Contractors for thermal control are Lockheed Martin, CGS, NIKHEF, OHB and NLR. NLR is involved in the overall thermal control, the thermal control of the electronic boxes (crates), and (together with the University of Geneva and NIKHEF) the development of a carbon dioxide two-phase mechanically pumped two-phase loop for the Tracker experiment (Fig. 22).

CIMEX-3: NLR's Versatile Two-Phase Loop Experiment

The Convective Interfacial Mass Experiment CIMEX, an ESA Microgravity Application Promotion (MAP) project, consists of a group of four different experiments (Legros et al, 2000) to be carried out in the Fluid Science Laboratory (FSL) aboard ISS. CIMEX-3 is the NLR Versatile Two-Phase Loop Experiment: A multi-purpose loop with a mechanically and a capillary pumped option, different types of evaporators (capillary and swirl), and the possibility to operate while using different working fluids (Delil, Woering, 2000). The loop schematic is depicted in figure 23.

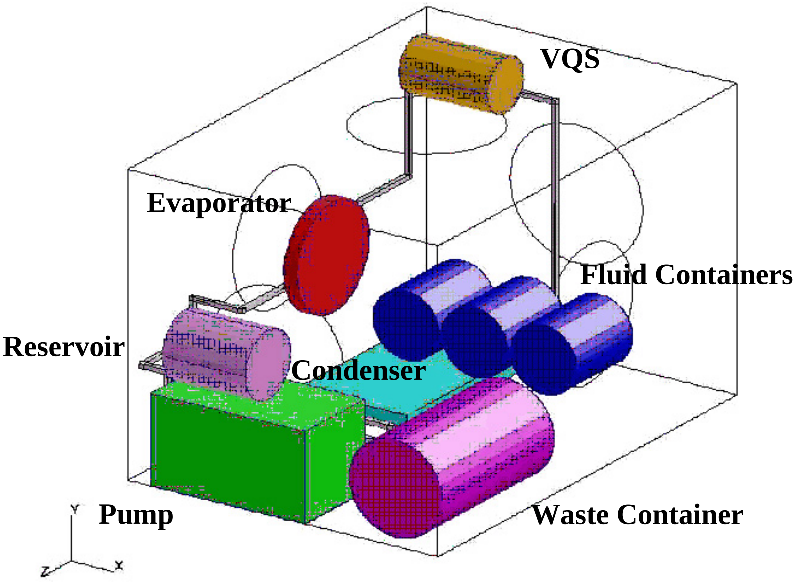

Figure 23. CIMEX-3: NLR's Versatile Two-Phase Loop

Primary objectives of CIMEX-3 loop are to study micro-g two-phase flow and heat transfer issues, by developing transparent (Swirl) Evaporators and High Efficiency Low Pressure Drop Condensers, measuring void/mass fraction in the adiabatic line for VQS calibration, flow pattern characterisation and creation of flow pattern maps, and viability demonstration of Mechanically and Capillary Pumped two-phase Loops, using different working fluids or mixtures. In addition the CIMEX-3 loop may accommodate other CIMEX experiments, e.g. 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.

REFERENCES

Allen, J.S., Hallinan, K.P., Lekan, J., "A Study of the Fundamental Operation of a Capillary Driven Heat Transfer Device in Both Normal and Low Gravity, Part I. Liquid Slug Formation in Low Gravity", *AIP Conf. Proc. 420, Space Technology & Applications International Forum*, Albuquerque, USA, 1998, pp. 471-477; Part II. Effect of Evaporator Meniscus Oscillations", *AIP Conf. Proc. 458, Space Technology & Applications International Forum*, Albuquerque, USA, 1999, 811-817.

Amadieu, M. et al., "Development of a Deployable Radiator using a LHP as Heat Transfer Element", *ESA SP400, Proc. 6th European Symp. on Space Environmental Control Systems*, Noordwijk, Netherlands, 1997, 283-288.

Antar, B.N., Collins, F.G., "Flow Boiling in Low Gravity Environment", *AIChE Symp.Series 310, Heat Transfer - Houston 1996*, Houston, USA, 1996, 32-44.

Antoniuk, D., Nienberg, J., "Analysis of Salient Events in the Two-Phase Thermal Control Flight Experiment", SAE 981817, 28th Int. Conf. on Environmental Systems, Danvers, USA, 1998.

Bienert, W., Wolf, D., "Temperature Control with Loop Heat Pipes: Analytical Model and Test Results", *9th Int. Heat Pipe Conf.* Albuquerque, USA, 1995. 981-988.

Bienert, W.B., Baker, C.L., Ducao, A.S., "Loop Heat Pipe Flight Experiment", SAE 981580, 28th Int. Conf. on Environmental Systems, Danvers, USA, 1998.

Borodkin, A.A., Kotlyarov, E.Yu, Serov, G.P., "Evaporation-Condensation Pump for Providing of Working Fluid Circulation in

Two-Phase Heat Transferring System", SAE 951508, 25th Int. Conference on Environmental Systems, San Diego, USA, 1995.
Butler, D., "Overview of CPL & LHP Applications on NASA Missions", *AIP Conf. Proc. 458, Space Technology & Applications International Forum*, Albuquerque, USA, 1999, 792-799.
Butler, D., Ottenstein, L., Ku, J., "Flight Testing of the Capillary Pumped Loop Flight Experiments", SAE 951566, 25th Int. Conf.on Environmental Systems, San Diego, USA, 1995.
Carey, P. Van, "*Liquid-Vapor Phase-Change Phenomena*", Hemisphere Publishing Company, Washington DC, USA, 1992.
Chen, I. et al, "Measurements & Correlation of Two-Phase Pressure Drop under Microgravity Conditions", *J. Thermophysics*, **5**, 1991, 514-523.
Colin.C., Fabre, J., Dukler,A., "Gas-Liquid Flow at Microgravity Conditions", *Int. J. Multiphase Flow*, **17**, 1991, 533-544.
Collier, J.G., "*Convective Boiling and Condensation*", McGraw-Hill, Maidenhead, UK, 1972.
Crowley, C.J., Sam, R.G., "Microgravity Experiments with a Simple Two-Phase Thermal System", *AIP Conf. Proc.910116, Space Technology & Applications International Forum*, Albuquerque, USA, 1991, 1207-1213.
Cullimore, B., "CPL Application Guide", SAE 932156, *23rd Int. Conf. on Environmental Systems*, Colorado Springs, USA, 1993.
Cullimore, B., Nikitkin, M., "CPL and LHP Technologies: What are the differences, What are the similarities?", SAE 981587, *28th Int. Conf. on Environmental Systems,* Danvers, USA, 1997.
Cykhotsky, V.M., et al., "Development and Analyses of Control Methods of the International Space Station Alpha Russian Segment Thermal Control System Parameters", *AIP Proc. 458, Space Technology & Applications International Forum*, Albuquerque, USA, 1999, 848-853.
Dam, A.A. ten, Berg, J.I. van den, "Numerical simulation of a condenser in two-phase heat transport systems, a feasibility study", NLR TP 92081, 1992.
Da Riva, I., Sanz. A, "Condensation in Ducts", *Microgravity Science and Technology*, **4,** 1991, 179-187.
Delil, A.A.M., "A Sensor for High-Quality Two-Phase Flow", NLR MP 88025, *16th Int. symposium on Space Technology and Science*, Sapporo, Japan, 1988, 957-966.
Delil, A.A.M., "Two-Phase Heat Transport Systems for Spacecraft – Scaling with Respect to Gravity", NLR-TP-89127, SAE 891467, 19th Int. Conf. on Environmental Systems, San Diego, 1989, *SAE Trans. J. Aerospace*, **98**, 1989, 554-564.
Delil, A.A.M., "Thermal Gravitational Modelling and Scaling of Two-Phase Heat Transport Systems: Similarity Considerations and Useful Equations, Predictions Versus Experimental Results", NLR-TP-91477, *Proc. 1st European Symp. Fluids in Space,* Ajaccio, France, 1991, ESA SP-353, 579-599.
Delil, A.A.M., "Two-Phase Heat Transport Systems for Space: Thermal Gravitational Modelling and Scaling Predictions Versus Results of Experiments", *ASME-JSME Forum Microgravity Fluid Flow, Portland*, USA, 1991, ASME-FED- 111, 21-27.
Delil, A.A.M., "Thermal Scaling of Two-Phase Heat Transport Systems for Space: Predictions versus Results of Experiments", NLR-TP-91477, *Proc. 1991 IUTAM Symp on Microgravity Fluid Mechanics*, Bremen, Germany, 1991, 469-478.
Delil, A.A.M., "Gravity Dependence of Pressure Drop and Heat Transfer in Straight Two-Phase Heat Transport System Condenser Ducts, NLR-TP-92167 SAE 921168, 22nd Int. Conf. Environmental Systems", Seattle, USA, 1992, *SAE Trans, J. Aerospace,* **101**, 1992, 512-522.
Delil, A.A.M., "Gravity Dependent Condensation Pressure Drop and Heat Transfer in Ammonia Two-Phase Heat Transport Systems", NLR-TP-92121, AIAA 92-4057, National Heat Transfer Conf., San Diego, 1992.
Delil, A.A.M., "TPX for In-Orbit Demonstration of Two-Phase Heat Transport Technology - Evaluation of Flight & Postflight Experiment Results", NLR-TP-95192, SAE 95150, 25th Int. Conf. on Environmental Systems, San Diego, USA, 1995.
Delil, A.A.M. et al., "Sensors and Components for Aerospace Thermal Control, Life Science and Propellant Systems", NLR TP 97504, *AIP Proc. 387, Conf. on Applications of Thermophysics in Microgravity, Space Technology & Applications Int. Forum,* Albuquerque, USA, 1997.
Delil, A.A.M., Dubois, M., Supper, W., "The European Two-Phase Experiments: TPX I & TPX II", NLR TP 97502 U, *Proc. 10th International Heat Pipe Conference*, Stuttgart, Germany, 1997.
Delil, A.A.M., "On Thermal-Gravitational Modelling, Scaling and Flow Pattern Mapping Issues of Two-Phase Heat Transport Systems", NLR-TP-98268, SAE 981692, 28th Int. Conf. on Environmental Systems, Danvers, USA, 1998, *SAE Trans. J. Aerospace*, **107**, 1998.
Delil, A.A.M., "Aerospace Heat and Mass Transfer Research for Spacecraft Thermal Control Systems Development", NLR-TP-98170", *Heat Transfer 1998*, *Proc. 11th Int. Heat Transfer Conf*., Kyongju, Korea, 1998, **1**, Keynotes, 239-260.
Delil, A.A.M., "Unsolved Aerospace Heat & Mass Transfer Research Issues for the Development of Two-Phase Thermal Control Systems for Space", *Proc. Int. Workshop Non-Compression Refrigeration & Cooling*, Odessa, Ukraine, 1999, 21-42.
Delil, A.A.M., "Thermal-Gravitational Modelling, Scaling and Flow Pattern Mapping Issues of Two-Phase Heat Transport Systems", *AIP Conf. Proc. 458, Space Technology & Applications Int. Forum*, Albuquerque, USA, 1999, 761-771.
Delil, A.A.M., "Some Critical Issues in Developing Two-Phase Thermal Control Systems for Space", NLR-TP-99354, *Proc. 11th Int. Heat Pipe Conf.*, Tokyo, Japan, 1999, **3**, Keynote and Invited Lectures, 61-79.
Delil, A.A.M., "Microgravity Two-Phase Flow and Heat Transfer", NLR-TP-99429, *Chapter 9 of Fluid Physics in Microgravity,* (Monti, R., Ed.), Overseas Publishing Associates, Reading UK, 2000.
Delil, A.A.M., "Extension of Thermal-Gravitational Modelling & Scaling of Two-Phase Heat Transport Systems to Super-Gravity Levels and Oscillating Heat Transfer Devices", Keynote Lecture, *Proc. 6th Int. Heat Pipe Symp.*, Chiang Mai, Thailand, 2000.and *ESA Proc. Two-Phase 2000 Workshop*, Noordwijk, Netherlands, 2000.
Delil, A.A.M., "Thermal-Gravitational Modelling and Scaling of Heat Transport Systems for Applications in Different Gravity Environments: Super-Gravity Levels & Oscillating Heat Transfer Devices", NLR-TP-2000-213, SAE-2000-01-2377, *Proc. 30th Int. Conf. on Environmental Systems & 7th Europ. Symp. Space Environmental Control Systems*, Toulouse, France, 2000.
Delil, A.A.M., "Issues of Various Two-Phase Heat Transfer Devices in Gravity Environments Ranging from Micro-Gravity to Super-Gravity", NLR-TP-2000-612, 2000.
Delil, A.A.M., Woering, A.A.,"CIMEX-3: A Versatile Two-Phase Loop Experiment on ISS", NLR-TP-2000-702, *ESA Proc. Two-Phase 2000 Workshop*, Noordwijk, Netherlands, 2000.
Delil, A.A.M., "Fundamentals of Gravity Level Dependent Two-Phase Flow and Heat Transfer - A Tutorial", *AIP Conf. Proc., Space Technology & Applications International Forum*, Albuquerque, USA, 2001.
Delil, A.A.M., "Thermal-Gravitational Modelling and Scaling of Two-Phase Heat Transport Systems from Micro-Gravity to Super-Gravity Levels", *AIP Conf. Proc., Space Technology & Applications International Forum*, Albuquerque, USA, 2001.

Delil, A.A.M., “Modelling and Scaling of Oscillating or Pulsating Heat Transfer Devices Subjected to Earth Gravity and to High Acceleration Levels”, *AIP Conf. Proc., Space Technology & Applications International Forum*, Albuquerque, USA, 2001.

Fore, L.B., Witte, L.C., McQuilen, J.B., “Microgravity Heat Transfer and Pressure Drop in Gas Liquid Mixtures: Slug and Annular Flow”, *AIChE Symposium Series 310, Heat Transfer- Houston* 1996, Houston, USA, 1996, 45-51.

Grigoriev, Y.I., et al., “Two-Phase Heat Transfer Loop of Central Thermal Control System of the International Space Station Alpha Russian Segment”, *AIChE Symposium Series 310, Heat Transfer - Houston 1996*, Houston, USA, 1996, 9-18.

Hagood, R., “CCPL Flight Experiment: Concepts through Integration”, SAE 981694, 28th International Conference on Environmental Systems, Danvers, USA, 1998.

Hamme, T.A., Best, F.R., “Gravity Dependent Flow Regime Mapping”, *AIP Conf. Proc. 387, Space Technology & Applications International Forum*, Albuquerque, USA, 1997, 635-640.

Huckerby, C.S., Rezkallah, K.S., “Flow Pattern Observations in Two-Phase Gas-Liquid Flow in a Straight Tube under Normal and Microgravity Conditions”, *Proc. 1992 AIChE Heat Transfer Conference*, San Diego, USA, 139-147.

Issacci, F., Wang, C.S.H., Dhir, V.K., “Boiling Heat Transfer and Two-Phase Flow in Microgravity: A Review”, *Proc. 30th National Heat Transfer Conference, Portland*, USA, 1995, ASME-HTD-305, 3-14.

Jayawardena, S.S., “Reduced Gravity Two-Phase Flow at Tee Junction”, *AIChE Symposium Series 310, Heat Transfer- Houston 1996*, Houston, USA, 1996, 68-72.

Kaya, T., Ku, J., “A Parametric Study of Performance Characteristics of Loop Heat Pipes”, SAE 99-01-2006, *Proc. 29th International Conference on Environmental Systems*, Denver, USA, 1999.

Kim, J.H., et al., “The Capillary Pumped Loop III Flight Demonstration, Description, and Status”, *AIP Conf. Proc. 387, Space Technology & Applications International Forum*, Albuquerque, USA, 1997, 623-628.

Kiseev, V.M., Zolkin, K.A., “The Influence of Acceleration on the Performance of Oscillating Heat Pipe”, *Proc. 11th Int. Heat Pipe Conference, Tokyo, Japan, 1999*, **2**, 154-158.

Ku, J., Yun, S, 1998, Design and Test Results of CAPL-3 Engineering Test Bed and Ground Test of CAPL-3 Flight Experiment, 28th Int. Conf. on Environmental Systems, Danvers, USA.

Ku, J., “Operational Characteristics of Loop Heat Pipes”, SAE 99-01-2007, *Proc. 29th International Conference on Environmental Systems*, Denver, USA, 1999.

Lebaigue, O., Bouzou, N., Colin, C., “Cyrène: An Experimental Two-Phase Ammonia Fluid Loop in Microgravity. Results of a Parabolic Flight Campaign”, SAE 981689, 28th International Conference on Environmental Systems, Danvers, USA, 1998.

Legros, J.C. et al., “Convection and Interfacial Mass Exchange (CIMEX)”, *ESA Proc. 'First International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology,* Sorrento, Italy, 2000.

Leontiev, A.I., et al., ”Thermophysics of Two-Phase Flows in Microgravity: Russian-American Research Project”, *AIP Conf. Proc. 387, Space Technology & Applications International Forum*, Albuquerque, USA, 1997, 541-546.

Lund, K.O., Baker, K.W., Weislogel, M.M., “The Vapor-Pressure Pumped Loop Concept for Space Systems Heat Transport”, *Proc. 1st Int. Conf. on Aerospace Heat Exchanger Technology 1993*, Palo Alto, USA, (Eds. Shah, R.K., Hashemi, A.), Elsevier, Amsterdam 1993, 45-55.

Maidanik, Y. & Fershtater, Y. & Goncharov, K., “Capillary Pump Loop for Systems of Thermal Regulation of Spacecraft”, ESA SP 324, *4th European Symp. on Space Environmental Control Systems*, Florence, Italy, 1991, 87-92.

Maidanik, Y.F., Solodovnik, N., Fershtater, Y.G., “Investigation of Dynamic and Stationary Characteristics of Loop Heat Pipe”, *Proc. 9th International Heat Pipe Conference Albuquerque*, USA, 1995, 1000-1006.

Mayinger, F., “*Strömung und Wärmeübergang in Gas-Flüssigkeits-Gemischen*”, Springer Verlag Wien, Austria, 1982.

McQuilen, J.B., Neumann, E.S., “Two-Phase Flow Research Using the Learjet Apparatus”, NASA TM-106814, 1995.

Miller-Hurlbert, K., “The Two-Phase Extended Evaluation in Microgravity Flight Experiment: Description and Overview”, *AIP Conf. Proc. 387, Space Technology & Applications International Forum*, Albuquerque, USA, 1997, 547-554.

Miller, K., et al., “Microgravity Two-Phase Pressure Drop Data in Smooth Tubing”, *AMD-174/FED-175, Proc. Symposium on Fluids Mechanics Phenomena in Microgravity*, ASME WAM, New Orleans, USA, 1993, .37-50.

Murphy, G., *Similitude in Engineering*, Ronald Press, New York, USA, 1950.

Orlov, A.A., et al., “The Loop Heat Pipe Experiment Onboard the Granat Spacecraft”, Proc. *6th European Symposium on Space Environmental Control Systems*, Noordwijk, Netherlands, ESA SP400, 1997, 341-353.

Oshinowo, T., Charles, M.E., “Vertical Two-Phase Flow, Flow Pattern Correlations”, *Can. J. Chem. Engng.*, **52**, 1974, 25- 35.

Ottenstein, L., Nienberg, J., “Flight Testing of the Two-Phase Flow Flight Experiment”, SAE 981816, 28th Int. Conf. on Environmental Systems, Danvers, USA, 1998.

Reinarts, T.R., Ungar, E.K., “Prediction of Annular Two-Phase Flow in Microgravity and Earth-Normal Gravity”, *AIChE Symposium Series 310, Heat Transfer - Houston 1996*, Houston, USA, 1996, 32-44.

Reinarts, T.R., Ungar, E.K., Butler, C.D., “Adiabatic Two-Phase Pressure Drop in Microgravity: TEMP2A-3 Flight Experiment Measurements and Comparison with Predictions”, AIAA 95-635, 33rd AIAA Aerospace Sciences Meeting, Reno, USA, 1995.

Rite, R.W., Rezkallah, K.S., “Heat Transfer in Two-Phase Flow Through a Circular Tube at Reduced Gravity”, *J. Thermophysics and Heat Transfer*, **8**(4), 1994, 702-708.

Soliman, M. & Schuster, J.R., Berenson, P.J., “A General Heat Transfer Correlation for Annular Flow Condensation”, *Trans. ASME C, J. Heat transfer*, 1968, **90,** 267-276.

Stenger, F.J., “Experimental study of water-filled capillary pumped heat transfer loops”, NASA X-1310, 1966.

Tamburini, P., “T-System”, “Proposal of a New Concept Heat Transport System”, *Proc. 3rd International Heat Pipe Conference*, Palo Alto, CA, USA, 1978, AIAA CP-784, 346-353.

Ungar, E.K., Mai, T.D., “The Russian Two-Phase Thermal Control System for the International Space Station”, *AIChE Symposium Series 310, Heat Transfer- Houston 1996*, Houston, USA, 1996, 19-24.

Viertel, G.M., Capell, M., “The Alpha Magnetic Spectrometer”, *Nuclear Instruments & Methods in Physics Research*, **A419**, 1998, 295-299.

Wallis, G.B., *One-dimensional Two-phase Flow*, McGraw-Hill, New York, 1969.

Wőlk, G., Dreyer, M., Rath, H.J., “Investigation of Two-Phase Flow in Small Diameter Non-Circular Channels under Low and Normal Gravity”, *AIP Proc.420, Space Technology & Applications International Forum*, Albuquerque, USA, 1999, 785-791.

Zhao, L., Rezkallah, K.S., “Gas-Liquid Flow Patterns at Microgravity Conditions”, *Int. J. of Multiphase Flow*, **19**, 1993, 751-763.

Zivi, S.M., "Estimation of Steady-State Void Fraction by Means of the Principle of Minimum Entropy Production", *Trans. ASME C, J. Heat Transfe*r, 1964, **86**, 247-252.

NOMENCLATURE

A	area (m^{2})
Bo	Bond number (-)
Boil	boiling number (-)
C	conductance (W/K)
Cp	specific heat at constant pressure (J/kg.K)
D	diameter (m)
Eö	Eötvös number (-)
Eu	Euler number (-)
Fr	Froude number (-)
g	(gravitational) acceleration (m/s^2)
H	enthalpy (J/kg)
h	heat transfer coefficient ($W/m^2.K$)
h_{lv}	latent heat of vaporisation (J/kg)
j	superficial velocity (m/s)
L	length (m)
Ma	Mach number (-)
Mo	Morton number (-)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number (-)
p	pressure (Pa = N/m^2)
Pr	Prandtl number (-)
Q	power (W)
q	heat flux (W/m^2)
Re	Reynolds number (-)
T	temperature (K or °C)
S	slip factor (-)
t	time (s)
v	velocity (m/s)
We	Weber number (-)
X	vapour quality (-)
z	axial or vertical co-ordinate (m)

Greek

α	vapour/void fraction (volumetric) (-)
Δ	difference, drop (-)
λ	thermal conductivity (W/m.K)
μ	viscosity ($N.s/m^2$)
ν	angle (with respect to gravity) (rad)
π	dimensionless number (-)
ρ	density (kg/m^3)
σ	surface tension (N/m)

Subscripts

a	acceleration, adiabatic, axial
c	condenser, cold, capillary
e	evaporator
f	friction
h	hot
g	gravitation
l	liquid
m	momentum, model
o	reference condition
p	prototype
s	sink
t	total
tp	two-phase
v	vapour
w	water