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Aerospace-related fluid physics, heat transfer, and thermal control research at the NLR Space Division

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AEROSPACE-RELATED FLUID PHYSICS, HEAT TRANSFER, AND THERMAL CONTROL RESEARCH AT THE NLR SPACE DIVISION

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ABSTRACT

Including the information published earlier [1], the aerospace-related fluid physics, heat transfer and thermal control research carried out by the NLR Space Division can be summarised by:

- Thermal conductivity investigations.
- Design and manufacture of a test rig for measuring the thermal conductance of axially loaded rotating bearings in vacuum.
- Thermal modelling of various rotating space mechanisms and the compilation of a handbook to model such mechanisms.
- Thermal performance of MLI blankets.
- Constant and variable conductance heat pipes, electro-osmotic heat pipe.
- Radiation heat transfer.
- Movable thermal joints and flexible thermal links.
- Thermal analysis and design.
- Two-phase heat transport systems: Their thermal- gravitational modelling and scaling, control methods/ algorithms. Two-phase test rigs development, components testing and calibration.
- Thermal modelling of the ESA ATLID two-phase laser head thermal control system breadboard, and the ESA capillary pumped loop engineering model.
- Development of the ESA high-efficiency low pressure drop two-phase condenser.
- Adapting liquid flow metering assemblies for use in space.
- Development of accurate ultrasonic flow meter for propellants.
- TPX I: In-orbit two-phase experiment and TPX II, a re-flight of the modified two-phase experiment (parallel thermally unbalanced condensers configuration, high pumping power sintered nickel evaporators, upgraded controllable valve).
- Loop heat pipe flight experiment.
- Flexible external insulation blanket permeability.
- Self regulating heaters.
- ESA Thermal Analyzer & Fluid Heat Transfer Solver Upgrade.
- Thermal modelling of laser heads, glove-boxes, the phased-array universal synthetic aperture radar structure, European co-operation for long-term in defence programme synthetic aperture radar antennae, avionics racks and components.
- Meteosat Second Generation propellant gauging. Experimental determination of the dielectric properties of propellants.
- Future European Space Transportation Investigations Program. Sänger aerospace plane thermal design activities.
- Critical and novel issues, AMS-2 and CIMEX-3.
- Pulsating two-phase loops and other pulsating/ oscillating heat transfer devices.
- Small dedicated satellites: Wetsat & Sloshsat-Flevo.
- Instrumentation for microgravity research.

DETAILING

The detailing is a complete overview of all relevant research activities. The presentation will highlight a selection of the most interesting and innovating issues (as it is listed in the Appendix).

Thermal conductivity

Equipment has been built to measure the thermal conductivity of anisotropic materials. Measurements, carried out in the NLR thermal vacuum chamber, confirm the model developed at NLR for the thermal conductivity of metallic honeycomb sandwich panels for space applications [2, 3]. Carbon fibre reinforced plastic sheet containing materials were investigated also [4, 5].

Under contract with Fokker Aircraft, the equipment was used to determine the thermal resistances of the hinges between the solar panels and structure of the Astronomical Netherlands Satellite [6].

Further investigations concern contact conductance (bolted joints, effects of interface filters) and the thermal resistance induced by sheet material deformation [7].

A test rig for rotating loaded bearings in vacuum

To obtain reliable results in the thermal design of space-borne mechanisms, it is important to know the thermal conductance and generated friction heat of rotating bearings in vacuum.

Under European Space Agency (ESA) contract, NLR designed and built a test rig to measure the above quantities. This test rig, still operational at the European Space Tribology Centre in Risley

(UK), accommodates three different bearing sizes (90 mm OD/55 ID, 42 OD/20 ID, 16 OD/5 ID), operated with and without lubricant. The thermal conductance of the rotating bearing is obtained by measuring the heat flux through and temperature drop across the bearing. The generated friction heat is obtained from friction torque and rotation speed measurements.

Typical test rig specifications are:

- A rotation speed adjustable from 1 to 2500 rpm.
- A pre-load ranging from 0 to 5 kg in 50 g steps.
- Inner and outer race temperatures variable between -20 and +60 °C and +20 and +70 °C respectively.

Details on the rig and measuring techniques is given in [8, 9].

Thermal modelling of rotating space mechanisms

Also for ESA a handbook has been compiled for the thermal modelling of space mechanisms [10]. The handbook presents a literature survey, step-by-step procedure, data compilations of material properties, etc. It also contains the theory basic to the thermal modelling procedure chosen. This procedure is illustrated by the results of calculations on a high speed mechanism, the reaction wheel of the Astronomical Netherlands Satellite, on a medium speed mechanism, Dornier's antenna despin mechanism, and on a low speed mechanism, Marconi's solar paddle drive.

Multilayer insulation blankets

Models describing the thermal performance of evacuated multilayer insulation blankets are usually based on the simple addition of the three mutually interacting modes of energy transfer: radiation between the shields, solid conduction via the components and their interfaces and gas conduction in the interstices, determined by residual gas pressure, outgas and the way the outgas products migrate through the blanket.

Blankets for spacecraft applications are usually made of perforated shields allowing fast depressurisation during the spacecraft launch. Perforations impair the insulation quality of a blanket, as perforations increase the effective shield emissivity (hence radiation transfer) and allow broadside pumping: Outgas products migrate via perforatios from interstice to interstice accumulating until they eventually escape at the blanket boundary.

Earlier reported models [11-13] concern either purely broadside-pumped blankets or purely edge-pumped blankets (of non-perforated shields, where the outgas products can escape only at the edges of the interstices). The pumping in most blankets for spacecraft is simultaneously edge and broadside. [13] presents the NLR model to account for this hybrid pumping.

A test apparatus was built to experimentally verify the models [13, 14]. There is good agreement between experiment and theory.

Heat pipes

Constant conductance heat pipe work consisted of a compilation of constant conductance heat pipe design data [15], performance measurements, filling procedures, the impact of filling ratio on the transport properties, and the impact of working fluid dissociation.

Considerable effort has been spent on the modelling and manufacture of an electro-osmotic heat pipe, a heat pipe with a feedback controlled pumping section, based on the phenomenon of electro-osmosis [16-18]. Unfortunately the realisation of such a heat pipe turned out to be unsuccessful since polarisation effects and dissociation of the working fluid impair a proper long-term performance, a problem for which no proper solution was found.

NLR also developed a transient thermal model for gas-loaded variable conductance heat pipes. This model can be easily implemented in existing general thermal analyzer computer programs. It is more generally valid than the Edwards/Marcus-model [19], commonly accepted in variable conductance heat pipe research, since the NLR model accounts for inertial and frictional effects of the moving vapour [20-24]. Consequently it predicts different transport and control behaviour, especially within the low vapour pressure operating range (typical for liquid metal heat pipes), start-up operation, and control. [24] presents a detailed analysis of the considerable limitations of performance and control predicted by the NLR model for a methanol variable conductance heat pipe built for experimental model validation.

An automated heat pipe test rig has been designed/ manufactured to perform the validation experiments [25].

Radiation heat transfer

Apart from thermal emissivity and solar absorptivity measurements, NLR investigated the modelling of radiation heat transfer in a magnetohydrodynamic generator channel, within the the Netherlands MHD power generation project [26].

Movable thermal joints

Within ESA's Columbus Polar Platform development, NLR studied thermal joints for deployable/ steerable radiators [27, 28]. Various options were traded. New ideas, the rotatable radial heat pipe and the movable oscillating hydrodynamic thermal joint, were proposed.

A continuously rotatable thermal joint for steerable radiators, currently under test [29, 30], is being patented.

Thermal analysis and design

Thermal modelling and design work for Columbus Resources Module [31] and Polar Platform [32, 33] was done for Fokker.

Two-phase heat transport systems

Two-phase work at NLR includes:

- A trade study on vapour quality sensors for spacecraft two-phase heat transport systems, measuring the relative vapour mass content of a flowing two-phase mixture [34, 35]. Design and manufacture of vapour quality sensors for the test bed developed the European Space Agency within the Two-Phase Heat Transport Systems-Critical Components study [36-41].
- Development of control algorithms, considered also a critical component within this study. Preliminary evaluation of control methods for the mechanically pumped two-phase heat transport systems engineering model, including development and analysis of dynamic models for its vapour pressure control loop [42-44].

- The design & manufacture of a 5 kW automated mechanically pumped two-phase freon test loop to calibrate vapour quality sensors [45].
- Thermal scaling with respect to gravity to properly predict the low-gravity performance of a two-phase heat transport system and its components using results of experiments on earth with, fluid to fluid and geometric, scale models [46-53].
- Design/manufacture/operation of an automated mechanically pumped two-phase ammonia test loop for calibration of the vapour quality sensors for a capillary pumped two-phase ammonia system, which is the Dutch/Belgian two-phase experiment (TPX I) that has flown, in the ESA In-Orbit Technology Programme, as Get Away Special G557 aboard Space Shuttle (STS60), early February 1994 [54-62].
- Two-phase heat transport component testing [63].
- TPX II: The re-flight of a modified two-phase experiment, with parallel condensers, high pumping power evaporators, improved liquid flow meters and Swalve, as Get Away Special G467 on a Space Shuttle flight end 1998 [64-66].
- Contributing to the concept, thermal/structural design, flight scenario, testing and experiment evaluation of the loop heat pipe flight experiment, a hitchhiker experiment on Space Shuttle flight (STS87), November 1997 [67-69]. This experiment was conducted by a team led by Dynatherm, consisting of the Naval Research Laboratory, NASA GSFC and the Center for Space Power, Hughes Space & Communications, the Center for Commercial Development of Space, US Air Force Wright & Phillips Laboratories, BMDO, and NLR.
- Development of ESA's high efficiency, low pressure drop condenser, with Daimler Benz Aerospace, Bradford Engineering, TAIS and Swales as subcontractors [70-72].
- The ESA study on "spatialisation" of flow metering assemblies with subcontractors SPPS Suisse/Bradford Engineering and the Société Anonyme Belge de Construction Aéronautique [73].
- Thermal modelling and design of the atmospheric LIDAR laser head thermal control breadboard, for MMS-UK [74].
- Thermal modelling and design of ESA's capillary-pumped loop engineering model [75, 76], for MMS-UK.
- Development of a two-phase thermal control system for a phased array radar module [77].

Miscellaneous

Other activities for ESA and other customers are:

- Sänger-related thermal research proposed for the two-stage to orbit space plane and the hot structure test facility, in the ramjet technology demonstration programme [78].
- Flexible external insulation blanket permeability testing [79].
- Testing of self-regulating heaters, designed to maintain their substrate temperature, by using their intrinsic material properties instead of external thermostats [80].
- ESA's flexible thermal link development for Dornier [81, 82].
- The Meteosat Second Generation Unified Propulsion System - Gauging Sensor Unit: the NLR/Bradford development of level gauges for spin-stabilised spacecraft propellant tanks, derived from the earlier developed NLR vapour quality sensor [29, 30, 83]. Work is done for ESA on the experimental determination of dielectric properties of propellants MON & MMH [84, 85] and, with Bradford, on the development of an ultrasonic flow meter for propellants. Current investigations concern the development of propellant level sensors for 3-axis stabilised spacecraft.

Thermal modelling

These modelling activities pertain to:

- The ESA Thermal Analyzer upgrading, focusing on the fluid dynamics part of the Fluid Heat Transfer Solver: The replacement of the current homogeneous flow model by physically more realistic models for two-phase flow [86].
- Detailed thermal modelling of a laser head [87].
- Thermal modelling of glove-boxes for ISS, of the structure of the phased array universal synthetic aperture radar [88], and of the heat load on ALADIN in an arbitrary ISS-related orbit [89].
- The European co-operation for long-term in defence programme [90-95]. Research and technology project 4: the Modular Avionics Harmonisation Study, thermal modelling of components/avionics racks, and the impact of high thermal load on environmental control systems and project 9: Advanced space synthetic aperture radar sensor technology, thermal design/model of synthetic aperture radar antennae.
- Future European Space Transportation Investigations Program.

Critical & novel two-phase issues, AMS and CIMEX

An inventory of critical research items has been produced, especially pertaining to problems/unresolved issues in the field of aerospace heat transfer, resulting in various publications related to extension of gravity levels [96 to 103].

AMS-2 is a 4-5 years lasting international experiment on the International Space Station ISS. It is a particle detector for high-energy cosmic rays, consisting of several sub-detectors. Its scientific goal is to detect anti-matter. NLR is involved in the overall thermal control, the thermal control of electronics, and the development of an novel carbon dioxide two-phase MPL for the Tracker experiment [104-105]. The latter loop is intended also to perform fundamental two-phase research experiments during time slots when the particle detectors will be set inactive.

CIMEX-3, NLR's Versatile Two-Phase Loop Experiment, planned to be executed (in ESA's MAP programme) in the Fluid Physics Laboratory on ISS [106], is a multi-purpose two-phase heat transport 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. Detailed discussions on the rationale behind the experiment [107] illustrate that the objectives of CIMEX-3 are:

- To study micro-g two-phase flow and heat transfer issues, via transparent (swirl) evaporators and high efficiency low pressure drop condensers.
- To measure the void/mass fraction in the adiabatic line for vapour quality sensor (VQS) calibration.

- Flow pattern characterisation, creation of flow pattern maps.
- The viability demonstration of Mechanically and Capillary Pumped two-phase Loops (MPL & CPL), using different working fluids or mixtures.

Pulsating/Oscillating Heat Transfer Devices

The research [108- 112] concentrates on pulsating/ oscillating heat transfer devices, being of interest for applications in spacecraft thermal control in microgravity, in planetary partial gravity and supergravity environments, and in hypergravity acceleration levels in rotating spacecraft or manoeuvring combat aircraft [110]. Different aspects of various heat transfer devices in gravity environments ranging from micro-gravity to super-gravity are discussed. Based on an overview is of world-wide activities and the state of the art of pulsating and oscillating heat transfer device research and an assessment of commonality and difference. a baseline philosophy was defined for modelling and comparison of experimental data, in order to anticipate an easy comparison with the results of ongoing and future research activities. Several test set-ups were built, including a versatile one [113-114], allowing variation of almost all relevant parameters: Working fluid and fill charge, power, transport length, inclination with respect to the gravity vector, and the possibility to choose either the dead-end pulsating or the closed-loop oscillating configuration.

Small satellites: "Wetsat" and "Sloshsat Flevo"

A definition study was completed on Wetsat: a small spacecraft to collect data on heat and mass transport by evaporation and condensation across an annular spherical gap. Various force fields have been introduced: an electrical radial field and centrifugal fields from spacecraft spin [115].

Because of insufficient support efforts were redirected to the definition of a spacecraft to investigate dynamics of onboard liquid. After a successful precursor, the Wet Satellite Model that flew 7 minutes following a rocket launch. Its follow-up Sloshsat is currently planned for Space Shuttle launch in 2002. The Sloshsat payload, a 80 litres tank with 33 litres of water. The location of the water in the tank is determined by the Coarse Sensor Array, a uniform distribution of 137 platinum ring electrodes embedded in the tank wall [116]. The capacitance between 270 electrode pairs provides liquid height information. Prediction of the dynamics and development of the control algorithms for the spacecraft are being generated with the Sloshsat Motion Simulator. This original development at NLR is operated in the EUROSIM software environment. Further activities [117-127] finally resulted in the flight hardware, being manifested to be launched from the Shuttle.

Instrumentation for microgravity research

With the Spanish Laboratory Lamf/ETSIA NLR carried out work, within the European Space Agency High Temperature Facility Technology Study, on combustion experiment instrumentation [128], focusing on flow field mapping in opaque liquids [129, 130].

Activities within the European Space Agency Fluid Physics Instrumentation Study [131] led to the Prototype Optical Diagnostic Instrument [132], a precursor to the European Space Agency Fluid Science Laboratory Facility Development Study [133], used for thermophysical & fluid physics diagnostics [134].

Other investigations concern microscopy [135], optical diagnostics of crystal growth [136], optical detection methods for biochemical sample analysis [137], and the development of a biomass sensor [138, 139].

CONCLUDING REMARKS

In conclusion it can be said that the research done concerns all aspects of aerospace thermal control system technology, i.e.:

- All heat transfer modes: Radiation, convection, conduction.
- Development of both passive and active thermal control components, heat transport loops and other (sub-)systems, and full-scale flight systems.
- Design from component to satellite level.
- All kinds of two-phase heat transfer devices: CCHP, VCHP, LHP, CPL, MPL, VDHTD, Oscillating/Pulsating HP, etc.
- Thermal modelling and the experimental verification of the modelling results.
- Thermal/gravitational scaling of two-phase flow and heat transfer in gravity environments for microgravity spacecraft applications, for reduced gravity applications in Moon and Mars thermal control systems, and for hypergravity applications in spinning satellites, combat aircraft and supergravity planetary environment.
- Development and execution of in-orbit experiments.

It is obvious that the research activities continuously change as they have to follow the needs resulting from more and more demanding requirements for developing novel, very advanced spacecraft with extremely long lifetimes.

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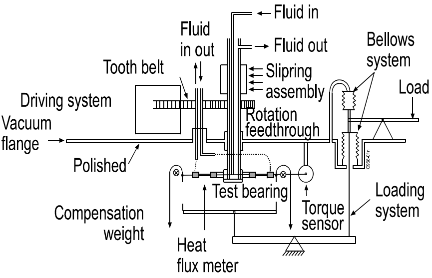
APPENDIX

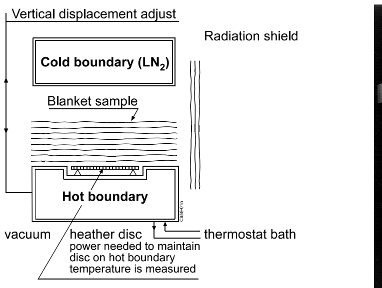
The presentation focuses particularly on the following issues (Some relevant figures are given in the following three pages):

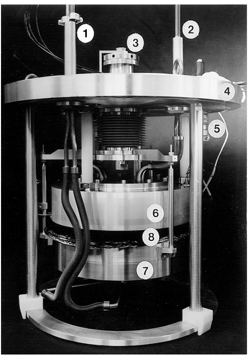
- Thermal conductance of loaded rotating bearings in vacuum.
- The thermal performance of multilayer insulation blankets.
- VCHP modelling and the modelling results.
- The results of the similarity (π-numbers) approach for the thermal/gravitational scaling of two-phase systems for micro-gravity, reduced-gravity, and hyper-gravity applications in aerospace.
- Constitutive equations for annular two-phase flow and heat transfer, predictions for condensation.
- ATLID and HELPD condensers, CLEM.
- In-orbit technology demonstration: TPX & LHPFX.
- Two-phase flow pattern aspects.
- Oscillating/pulsating heat transfer devices.
- The AMS-2 Tracker mechanically pumped two-phase CO_2 thermal control loop.
- CIMEX-3: Versatile two-phase loop experiments on ISS.

Test Rig to Measure the Thermal Conductance of Rotating Bearings (in Vacuum)



MLI Blanket Test Rig





1. Feedthrough hot liquid
2. Feedthrough cold liquid
3. Vertical displacement adjust
4. Vacuum flange
5. Feedthrough themocouples
6. Cold boundary
7. Hot boundary
8. Blanket sample

Dimension Analysis & Similarity Considerations

π-number relevance for thermal-gravitational scaling of two-phase loops

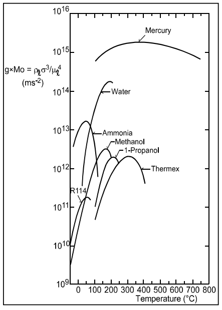
	Liquid Parts		Evaporators Swirl & Capillary	Non-liquid Lines Vapour/2-Phase	Condensers
	Adiabatic	Heating/Cooling			
$\pi_1 = D/L$ = geometry	•	•	•	•	•
$\pi_2 = Re_l = (\rho v D/\mu)_l$ = inertia/viscous	•	•	•	•	•
$\pi_3 = Fr_l = (v^2/gD)_l$ = inertia/gravity	•	•	•	/•	•
$\pi_4 = Eu_l = (\Delta p/\rho v^2)_l$ = pressure head/inertia	•	•	•	•	•
$\pi_5 = \cos \nu$ = orientation with respect to g	•	•	•	/•	•
$\pi_6 = S$ = slipfactor $= v_v/v_l$			•	•	•
π_7 = density ratio $= \rho_v/\rho_l$			•	•	•
π_8 = viscosity ratio $= \mu_v/\mu_l$			•	•	•
$\pi_9 = We_l = (\rho v^2 D/\sigma)_l$ = inertia/surface tension			•	/•	•
$\pi_{10} = Pr_l = (\mu Cp/k)_l$		•	•		•
$\pi_{11} = Nu_l = (hD/k)_l$ = convective/conductive		•	•		•
$\pi_{12} = k_v/k_l$ = thermal conductivity ratio			•		•
$\pi_{13} = Cp_v/Cp_l$ = specific heat ratio			•		•
$\pi_{14} = \Delta H/h_{lv}$ = enthalpy number = X = quality		•	•	•	•
$\pi_{15} = Mo_l = (\rho_l \sigma^3/\mu_l^4\, g)$ = capillarity/buoyancy			•	/•	•
$\pi_{16} = Ma = v/(\partial p/\partial \rho)^{1/2}_s$			•	•	•
$\pi_{17} = (h/k_l)(\mu_l^2 g)^{1/3}$			•		•
$\pi_{18} = L^3 \rho_l^2\, g\, h_{lv}/k_l \mu_l (T-T_o)$			•		•

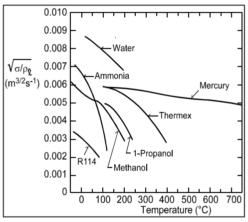
Consequences of Similarity Approach for Applications of Thermal-Gravitational Scaling

(for MPL/CPL/LHP/VPDL)

- ***Geometric or fluid to fluid scaling at same g-level , and from earth-g to the reduced g-levels of Mars & Moon***
- ***Hybrid scaling from earth-g to micro- g and super-g***
- ***Support of (CIMEX) experiments on to determine boiling and condensation trajectories in flow pattern maps***

$Mo \cdot g = \text{Ɉ}_l . \sigma^3/\mu_l^4$





$(\mathring{u}/\text{Ɉ}_l)^{½} = D.g^{½}.(We/Fr)^{-½}$

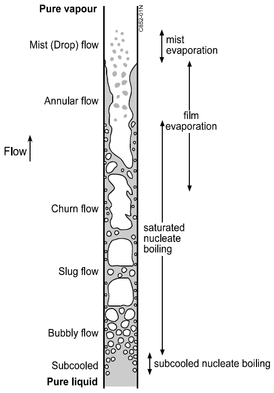
(Up-)Flow Patterns in Heated Circular Tube and Measurement Issues for CIMEX-3

Optical observation of two-phase flow patterns in the

- ***condenser***
- ***swirl tube evaporator***
- ***adiabatic section***

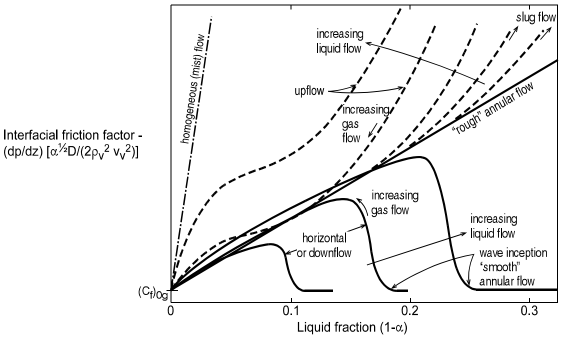
Instrumentation

- ***IR cameras for observing the condenser and the evaporator***
- ***CCD camera to observe the vapour line***
- ***Observing the vapour line by holographic interferometry***

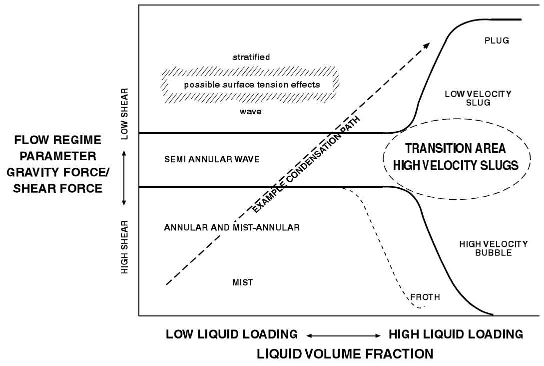


Flow Pattern Issues

Qualitative aspects of pressure gradient for various flow patterns



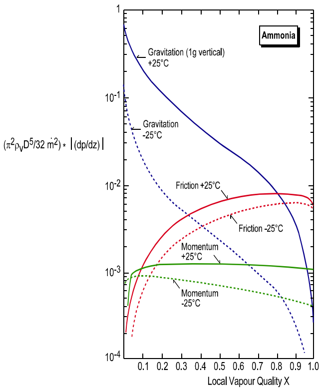
Flow Pattern Issues : Generalised Qualitative Two-Parameter Flow Regime Map for Horizontal Tube Condensation



Constitutive Equations for Annular Two-Phase Flow & Heat Transfer

- *Total Pressure Gradient* $(dp/dz)_t = (dp/dz)_f + (dp/dz)_m + (dp/dz)_g$
  - *friction* $(dp/dz)_f = -(32m^2/\pi^2 \rho_v D^5)(0.045/Re_v{}^{0.2})[X^{1.8}+5.7(\mu_l/\mu_v)^{0.0523}(1-X)^{0.47}X^{1.33}(\rho_v/\rho_l)^{0.261} +8.1(\mu_l/\mu_v)^{0.105}(1-X)^{0.94}X^{0.86}(\rho_v/\rho_l)^{0.522}]$
  - *momentum* $(dp/dz)_m = -(32m^2/\pi^2 \rho_v D^5)(D/2)(dX/dz)[2(1-X)(\rho_v/\rho_l)^{2/3} + 2(2X-3+1/X)(\rho_v/\rho_l)^{4/3} +(2X-1-ßX)(\rho_v/\rho_l)^{1/3} +(2ß-ßX-ß/X)(\rho_v/\rho)^{5/3} + 2(1-X-ß+ßX)(\rho_v/\rho_l)]$
  - *gravity* $(dp/dz)_g = (32m^2/\pi^2 \rho_v D^5)\{1-[1+(\rho_v/\rho_l)^{2/3}(1-X)/X]^{-1}\}[\pi^2 D^5 g (\cos\nu)(\rho_l-\rho_v)\rho_v/32m^2]$
- *Void - Quality Relation* $(1-\alpha)/\alpha = S(\rho_v/\rho_l)X/(1-X)$
- *Simplified Zivi-Correlation for Slip Factor* $S = (\rho_l/\rho_v)^{1/3}$
- *Condensation Heat Transfer* linear $X = 1 - z/L_C$ or more realistic $m.h_{lv}(dX/dz) = -h\pi D[T(z)-T_s]$
- $h = 0.018(\lambda_l \rho_l{}^{1/2} D^{1/2}/\mu_l)Pr_l{}^{0.65}|-(dp/dz)_t|^{1/2} + R(4\lambda_l/D)/\ln[1+(\rho_v/\rho_l)^{2/3}(1-X)/X])$ and $0 < R < 1$
- *Combination Yields* $F(dX/dz, X) = 0$ Č $X(z)$ & Δp_t by integrating $(dp/dz)_t dz$ from 0 to L_C

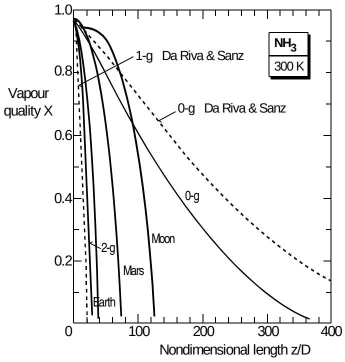
Pressure Gradient Constituents
Gravity-Assist & Anti-Gravity Issues



- *Impact of gravitation is smaller at lower temperature.*
- *Anti-g constituent overwhelms other gradients, below X=0.76 at 25 °C and X=0.38 at -25 °C.*
- *Annular liquid layer breaks/ falls back below these qualities.*
- *Shear-governed flow becomes (pulsating) slug, plug or churn flow, described by different equations and slip factors.*
- *Driving pressure (temperature) drops will strongly increase.*
- *(Anti-g) flow pattern maps are to be created.*

Gravity Dependent Condensation Lengths

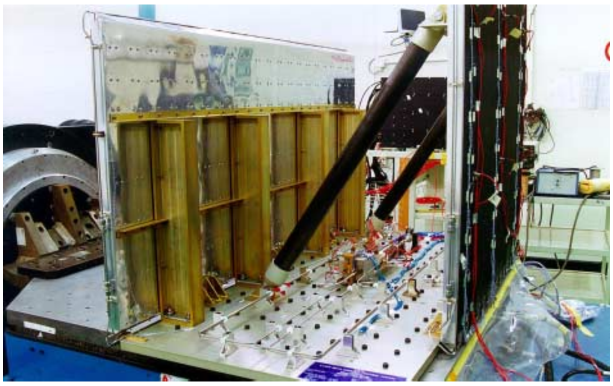
Vapour quality along the reference duct



- *Condensation lengths needed considerably increase with decreasing gravity.*
- *Differences between condensation lengths at different gravity levels become less pronounced with decreasing temperature and line diameter, increasing power, and heat transfer coefficient fine-tuning or enhancement. This coefficient, which varies along the condensation trajectory through the various flow patterns, is to be derived from experiments in different gravity environments.*

ATLID Two-Phase Heat Transport System

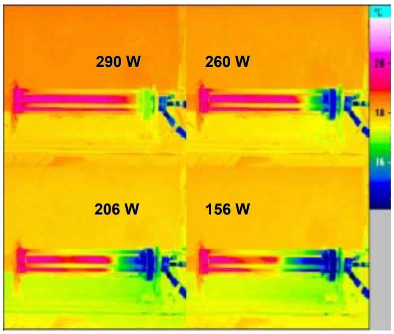
Hybrid CPL-LHP with Two Different Parallel Direct Condensers/Radiators (MMS, NLR,BE)



Breadboard Condenser IR Pictures to Verify Theoretical Predictions

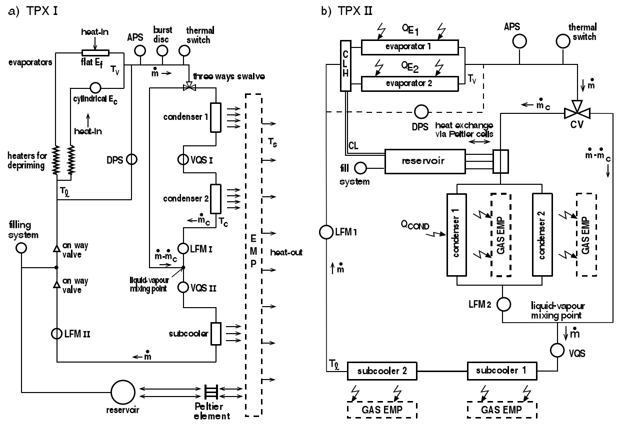
High Efficiency Low Pressure Drop Condenser

- ***Series configuration***
- ***Two-phase flow in annular tube***
- ***Liquid cooling in inner tube***

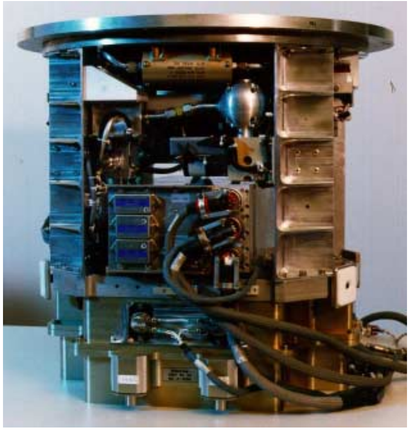


T_{vapour}=20.4 °C **$T_{coolant}$ = 14.5 °C**

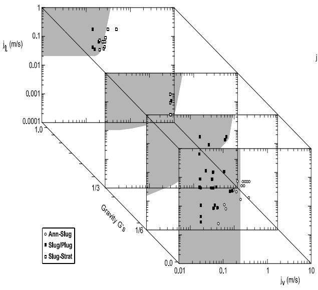
Schematics of TPX I & II



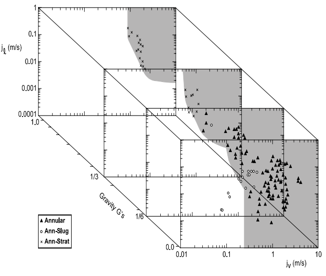
TPX I Flight Hardware



Flow Pattern Maps to be Created
for Gravity Levels from Micro- to Super-G



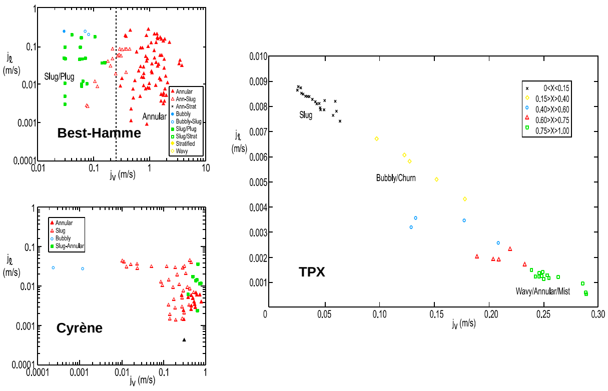
G-dependent 3-D slug-plug flow



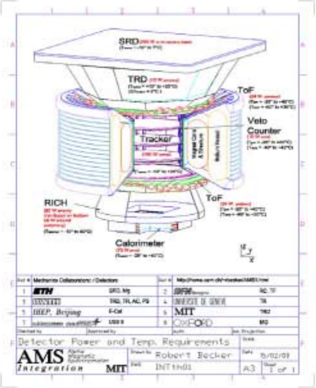
G-dependent 3-D annular flow

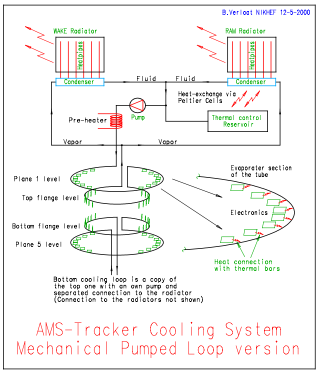
Partly Contradicting Low-G Flow Pattern Data

(Because of Different Line Diameters, Fluids or G-Levels?)



Alpha Magnetic Spectrometer on ISS
(Search for Anti-Matter, Dark & Lacking Matter)
Configuration & Tracker Two-Phase CO_2 MPL





Bottom cooling loop is a copy of the top one with an own pump and separated connection to the radiator (Connection to the radiators not shown)

AMS-Tracker Cooling System
Mechanical Pumped Loop version

CIMEX-3
Versatile Two-Phase Loop Baseline

Experiment objectives:

- *Development of (transparent) swirl evaporator and (HELPD) condenser*
- *Creation/characterisation of flow patterns and void/quality measurements in adiabatic transparent line to calibrate VQS and to create flow pattern maps*
- *Viability demonstration of mechanically pumped two-phase loop for different working fluids or mixtures*
- *Accommodating other CIMEX experiments to study the impact of Marangoni-convection on heat transfer and evaporation, micro-scale heat and mass transfer in single-groove structures, new heat pipe porous structures, and instabilities near drops and bubbles*