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Bearings	Mathematical models	Thermal conductivity
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Heat pipes	Performance prediction	Thermophysical properties
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Insulation	Spacecraft design	

ABSTRACT
A survey of aerospace-related thermophysical research carried out by the National Aerospace Laboratory NLR is given. Brief descriptions of a variety of subjects are followed by an extensive list of references.

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AEROSPACE RELATED THERMOPHYSICAL EXPERIENCE OF THE NLR SPACE DIVISION

by

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AEROSPACE RELATED THERMOPHYSICAL EXPERIENCE OF THE NLR SPACE DIVISION

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Aerospace-related thermophysical research carried out by the NLR Space Division concerns (Ref. 1):

- Thermal conductivity investigations.
- The design and manufacture of a test rig for measuring the thermal conductance of loaded rotating bearings in a vacuum environment.
- The thermal modelling of various rotating space mechanisms and the compilation of a handbook for the modelling of such mechanisms.
- The thermal performance of multilayer insulation blankets.
- Constant and variable conductance heat pipes.
- Radiation heat transfer.
- Moveable thermal joints and flexible thermal links.
- Thermal analysis and design.
- Two-phase heat transport systems, including their thermal gravitational modelling and scaling. Test rigs development and two-phase components testing and calibration. Control methods and algorithms.
- Thermal Modelling of the ATLID Two-Phase Laser Head Thermal Control System Breadboard.
- Development of a high-efficiency low pressure drop two-phase condenser.
- Spatialisation of liquid flow metering assemblies.
- TPX: in-orbit Two-Phase eXperiment and TPX II, a reflight of a modified TPX (parallel condensers configuration, high pumping power sintered nickel evaporators, upgraded Swalve, etc.).
- Loop Heat Pipe Flight eXperiment.
- FEI blanket permeability.
- Self regulating heaters.
- ESATAN/FHTS modelling upgrade.
- Thermal modelling of laser heads, gloveboxes, PHARUS structure, EUCLID SAR antennae and avionics racks and components.
- MSG propellants gauging.
- FESTIP and Sänger aerospace plane thermal design activities.
- Wetsat and Sloshsat.
- Instrumentation for microgravity research.

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 (Refs. 2, 3). Carbon fibre reinforced plastic sheet containing materials were investigated also (Refs. 4, 5).
Under contract with Fokker Aircraft Industry, the equipment was used to determine the thermal resistances of the hinges between the solar panels and structure of the Astronomical Netherlands Satellite (Ref. 6).
Further investigations concern contact conductances (bolted joints, effects of interface filters, etc.) and the thermal resistance induced by sheet material deformation (Ref. 7).

A test rig for rotating loaded bearings in vacuum

In order 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 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 (U.K.), 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 that can be adjusted between 1 and 2500 rpm.
- A pre-load ranging from 0 to 5 kg in 50 g steps.
- Inner and outer race temperatures can be varied between -20 and +60 °C and +20 and +70 °C respectively.

Detailed information on the rig and the measuring techniques can be found in the referênces 8 and 9.

Thermal modelling of rotating space mechanisms

Also under ESA contract, a handbook has been compiled for the thermal modelling of space mechanisms (Ref. 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 performed on a high speed mechanism, i.e. the reaction wheel of the Astronomical Netherlands Satellite, a medium speed mechanism, i.e. the Dornier antenna despin mechanism, and a low speed mechanism, i.e. the Marconi MSDS 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 launch of the spacecraft. Perforations impair the insulation quality of a blanket, because the perforation holes increase the effective shield emissivity (hence the radiation transfer) and the holes allow for broadside pumping, viz. the outgas products migrate via the holes, from interstice to interstice gradually accumulating until they eventually escape at the blanket boundary.

Earlier reported models (Refs. 11 to 13) concern either purely broadside-pumped blankets or purely edge-pumped blankets (of nonperforated 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. Reference 13 presents the model developed at NLR to account for this hybrid pumping.

A test apparatus was built to experimentally verify the models (Refs. 13, 14). Reference 14 reports the good agreement between the experimentally and theoretically determined performances.

Heat pipes

Constant conductance heat pipe work at NLR consisted of a compilation of constant conductance heat pipe (CCHP) design data (Ref. 15), performance measurements, filling procedures, the influence of the filling ratio on the transport properties, and the impact of dissociation of the working fluid.

Considerable effort has been spent on the modelling and manufacture of an electro-osmotic heat pipe (EOHP), a heat pipe with a feedback control section based on the phenomenon of electro-osmosis (Refs. 16 to 18). Unfortunately the realisation of an EOHP 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 could be found.

NLR also developed a transient thermal model for gas-loaded variable conductance heat pipes (VCHP). This model is easily implementable in existing general thermal analyzer computer programs. It is more generally valid than the Edwards/Marcus-model (Ref. 19), commonly accepted in VCHP research, since the NLR model accounts for inertial and frictional effects of the moving vapour (Refs. 20 to 24). Consequently it predicts different transport and control behaviour, especially within the low vapour pressure operating range (typical for liquid metal CCHP and VCHP), startup operation, and control. Reference 20 presents a detailed analysis of the considerable limitations of performance and control predicted by the current NLR model for a methanol VCHP built for the experimental validation of the model. An automated heat pipe test rig has been designed and manufactured to carry out the validation experiments (Ref. 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 (Ref. 26). This work was carried out within the framework of the Netherlands MagnetoHydroDynamic power generation project.

Moveable thermal joints

Within the framework of the ESA Columbus Polar Platform development, NLR studied - as subcontractor of Fokker Space & Systems - the possibility of a thermal joint for a deployable or steerable radiator for the Polar Platform (Refs. 27, 28). Various options were traded. New ideas, the rotatable radial heat pipe and the moveable oscillating hydrodynamic thermal joint, were proposed. A continuously rotatable thermal joint for steerable radiator applications, currently under test, is being patented.

Thermal analysis and design

Fokker Space & Systems subcontracted to NLR thermal modelling and design work for ESA's Columbus Resources Module (Ref. 29) and Polar Platform (Refs. 30, 31).

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 (Refs. 32, 33).
- The design manufacture of vapour quality sensors for the test bed developed within the ESA Two-phase heat Transport Systems-Critical Components study (Refs. 34 to 39).
- The development of control algorithms, considered to be also a critical component of the aforementioned ESA study (Refs. 34, 35). Preliminary evaluation of control methods for the ESA mechanically pumped TPHTS Engineering Model, including development and analysis of dynamic models for its vapour pressure control loop (Refs. 40 to 42).
- The design & manufacture of a 5 kW automated

mechanically pumped two-phase freon test loop to calibrate quality sensors for the ESA test bed (Ref. 43).
- 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 (Refs. 44 to 50).
- The design, manufacture and 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 that has flown, within the ESA In-Orbit Technology Programme, as Get Away Special G557 aboard STS 60 early February 1994 (Refs. 51 to 59).
- Testing of two-phase heat transport components (Ref. 60).
- The reflight of a modified TPX (parallel condensers, high pumping power evaporators, improved liquid flowmeters and Swalve), as Get Away Special G465 in a space shuttle flight, mid 1997.
- Contributing to the concept, thermal/structural design, flight senario, testing and experiment evaluation for LHPFX, the Loop Heat Pipe Flight eXperiment on the Wake Shield Facility during a shuttle flight, end 1996 (an experiment of a team led by Dynatherm, consisting of DTX, the Naval Research Laboratory, the Center for Space Power of Texas A&M, Hughes Space & Communications, the Center for Commercial Development of Space and NLR).
- The development of a high efficiency, low pressure drop, two-phase condenser for ESA, with DASA/ERNO and Bradford Engineering as subcontractors (Refs. 61, 62).
- The ESA study on spatialisation of a flow metering assembly, with SABCA and Bradford Engineering as subcontractors (Ref. 63).
- Thermal modelling and design of the ATLID laser head thermal control breadboard, for MMS UK, together with Bradford Engineering (Ref. 64).

Miscellaneous

Additional activities for ESA and other customers also concern:
- Sänger-related thermal research proposed for the two-stage to orbit spaceplane and the HOt Structure Test facility (HOST), within the Ramjet Technology Demonstration Programme (Ref. 65).
- FEI blanket permeability measurements (Ref. 66).
- Testing of self regulating heaters, designed to maintain their substrate temperature, by using their intrinsic material properties instead of external thermostats (Ref. 67).
- Development of a novel flexible thermal link for ESA, as subcontractor of Dornier (Refs. 68, 69).
- The Meteosat Second Generation Unified Propulsion System Gauging Sensor Unit: the NLR/Bradford Engineering development of level gauges for MSG propellant tanks, derived from the earlier developed NLR vapour quality sensor.

Thermal modelling

Activities pertain to:
- ESATAN upgrading focusing on the fluid dynamics part of FHTS: the replacement of the current homogeneous flow model by advanced, physically more realistic models for two-phase flow (Ref. 70).
- Detailed thermal modelling of a laser head.
- Thermal modelling of glove boxes (e.g. for Space Station) and of the structure of PHARUS, the PHased ARray Universal Synthetic aperture radar (Ref. 71).
- The EUropean Cooperation for Long-term In Defence (EUCLID) programme, Research and Technology Projects RTP 4, Modular Avionics Harmonisation Study, Thermal modelling of components/avionic racks, Impact of high thermal load on environmental control system (Ref. 72) and RTP 9, Advanced space SAR sensor technology, Thermal design/model of SAR antennae.
- Thermal modelling within the framework of FESTIP, the Future European Space Transportation Investigations Program.

Wetsat and Sloshsat

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 were to be introduced: an electrical radial field and centrifugal fields from spacecraft spin (Ref. 73).
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, work is in progress on Sloshsat, planned for STS launch, April 1998 (Ref. 74).
The Sloshsat payload, a 80 litres tank with 33 litres of water. The water location in the tank is determined by the Coarse Sensor Array, a uniform distribution of 137 circular electrodes on the tank wall. The capacitance between 270 electrode pairs provides liquid height information.

Instrumentation for micro-gravity research

Together with Lamf/ETSIA NLR carried out work, within the ESA High Temperature Facility Technology Study, on combustion experiment instrumentation (Ref. 75) and on flow field mapping in opaque liquids (Refs. 76, 77).
Activities within the ESA Fluid Physics Instrumentation Study (Ref. 78) led to PODI, the Prototype Optical

Diagnostic Instrument (Ref. 79), a precursor to the ESA Fluid Science Laboratory Facility Development Study (Ref. 80), being used for thermophysical and fluid physics diagnostics (Ref. 81).
Other investigations concern microscopy (Ref. 82), optical diagnostics of crystal growth (Ref. 83) and optical detection methods for biochemical sample analysis (Ref. 84).

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