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National Aerospace Laboratory NLR

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CIMEX-3, a Versatile Two-Phase Loop Experiment on ISS

The rationale behind the experiment and its relation to other CIMEX experiments

A.A.M. Delil

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This report presents the background of a presentation on CIMEX-3 held at the Two-Phase 2000 Workshop at ESTEC, Noordwijk, The Netherlands, 6-7 july 2000, and of a presentation held on CIMEX at the ESA First International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology, Sorrento, Italy, 10-15 September 2000.

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Summary

This technical publication concerns CIMEX-3: The NLR Versatile Two-Phase Loop Experiment to be executed in the Fluid Sciences Laboratory (FSL) of the International Space Station (ISS).

It consists of two parts:

PART I:
An overview article on the rationale behind the CIMEX-3 experiment: The article justifies (supported by an appreciable set of references) why such an experiment is to be carried out, by discussing its historical background, its objectives and its preliminary configuration. It is shown that CIMEX-3 is not intended only as an experiment to get a better knowledge of the physics of two-phase flow and heat transfer, but that it basically constitutes the logical step forward in the more than 15 years of worldwide (NASA, ESA, NASDA and CNES sponsored) research for developing reliable two-phase thermal control systems for many future spacecraft.

PART II:
The article of the CIMEX (overall) presentation held at the ESA First International Symposium on Microgravity Research & Applications in Physical Sciences and Biotechnology in Sorrento, Italy, 10-15 September 2000.

Contents

(38 pages in total)

List of Acronyms

3D	3-Dimensional
ALPHA	American Liquid Heat Pipe with Ammonia
ATLID	ATmospheric LIDAR
BTU	Cottbus University of Technology
CAPL	Capillary Pumped Loop
CCD	Charge Coupled Device
CCLP	Cryogenic Capillary Pumped Loop
CIMEX	Convective Interfacial Mass EXperiment
CIMEX-3	CIMEX two-phase flow component
CNES	Centre Nationale d' Etude de L'Espace
COM2PLEX	COMbined 2 Phase Loop Experiment
CPL	Capillary Pumped two-phase Loop
EOS-AM	American Earth Observation Satellite
ESA	European Space Agency
EU	European Union
FOTON	Russian satellite, derived from the Vostok family of retrievable capsules
FSL	Fluid Science Laboratory
HELPD	High-Effective Low Pressure Drop
ICOPAC	Interfacial COnvection and PhAse Change
IR	Infra Red
ISS	International Space Station
ITEL	Interfacial Turbulence in Evaporating Liquids
IUSTI	Université de Provence
LHP	Loop Heat Pipe
LHPFX	Loop HeatPipe Flight eXperiment
LIDAR	Light Intensification Detection and Ranging
MAP	Microgravity Application Promotion
MASER	Material Science Experiment Rocket
MBIS	Marangoni Benard Instability with Soret effect
MPL	Mechanically Pumped two-phase Loop
NASA	National Aeronautics and Space Administration
NASDA	National Space Development Agency
NLR	Nationaal Lucht- en Ruimtevaartlaboratorium (National Aerospace Laboratory)
OBZOR	Russian spacecraft
SABCA	Société Anonyme Belge de construction Aéronautiques
SSC	Swedish Space Corporation

STENTOR	Satellite Technologique pour Experimenter des Nouvelles Techniques en ORbite
TEEM	Two-phase flow Extended Evaluation in Microgravity
TLC	Temperature sensitive Liquid Crystals
TPF	Two-phase Flow
TPX	Two-Phase eXperiment
TUD	Technische Universität Darmstadt
ULB-MRC	Université Libre de Bruxelles
Ulg	Université de Liège
VQS	Vapour Quality Sensor

PART I

THE RATIONALE BEHIND CIMEX-3

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ABSTRACT

The rationale behind the CIMEX-3 experiment is explained. It is justified (supported by many references) why such an experiment shall be carried out, by discussing its historical background, its objectives and its preliminary configuration. It is shown that CIMEX-3 is not intended only as an experiment to get a better knowledge of the physics of two-phase flow and heat transfer, but that it basically constitutes the logical step forward in the more than 15 years of worldwide (NASA, ESA, NASDA and CNES sponsored) research for developing reliable two-phase thermal control systems for many future spacecraft missions.

FORWARD

The Convective Interfacial Mass Experiment CIMEX, an ESA Microgravity Application Promotion (MAP) project, consists of four different experiments to be carried out in the Fluid Science Laboratory (FSL) aboard the International Space Station ISS. A detailed overview of CIMEX - describing the various, strongly inter-related, goals of the project experiments - is given in reference 1 (incorporated in this report, minimally adapted, as PART II). Figure 1, taken from this reference, shows the CIMEX project structure.

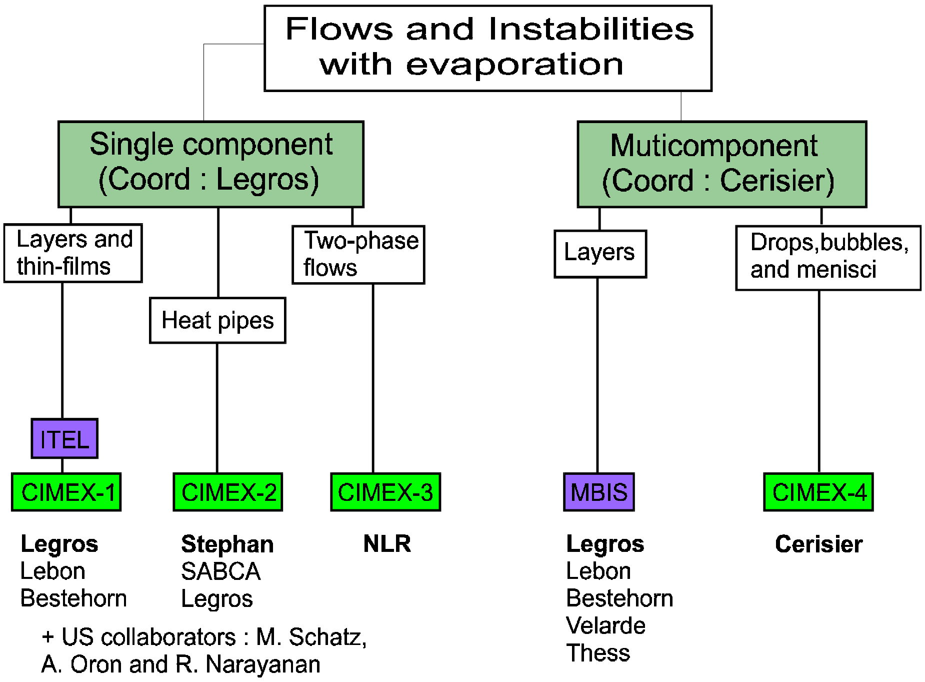

Figure 1. *CIMEX Programme: Micro-g Experiments, Foreseen for ISS, are CIMEX-1 to 4*

One of the constituents is CIMEX-3, NLR's 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. The loop schematic is depicted in figure 2.

Primary objectives of the CIMEX-3 experiment 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 vapour quality sensor (VQS) calibration, flow pattern characterisation and creation of flow pattern maps, and the viability demonstration of Mechanically and Capillary Pumped two-phase Loops (MPL & CPL), using different working fluids or mixtures. The justification for studying the different abovementioned topics is elucidated in the following sections.

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.

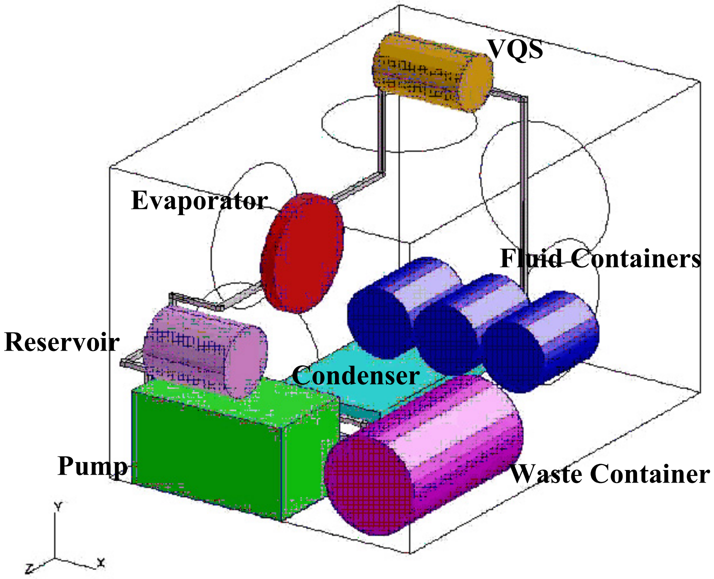

***Figure 2**. CIMEX-3: NLR's Versatile Two-Phase Loop*

TYPICALITIES OF TWO-PHASE FLOW AND HEAT TRANSFER

Two-phase flow is the simplest case of multiphase flow, the latter being the simultaneous flow of different phases (states of matter): gas, liquid and solid. The nature of two-phase flow in spacecraft thermal control systems is single-component, meaning that the vapour and the liquid phase are of the same chemical substance. If the phases consist of different chemical substances, e.g. in air-water flow, the flow is called two-phase two-component flow. The hydraulics of two-phase, single-component and two-component flows is described by almost the same equations, as long as diffusion due to concentration gradients can be neglected. Results of calculations and experiments in one system can be used in the other, as long as they pertain to flow phenomena only, hence if there is no heat transfer.

Heat transfer in a two-phase two-component system has a relatively simple impact on the system behaviour. Only the physical (material) properties of the phases are temperature dependent. Two-phase single-component systems are far more complicated, because the heat transfer and the temperature cause (in addition to changes of the physical properties of the phases) mass exchanges between the phases, by evaporation, flashing and condensation. Consequently, complicated two-phase single-component systems cannot be properly understood by using modelling and experimental results of simpler two-phase two-component systems. Two-phase single-component systems, like the liquid-vapour systems in spacecraft thermal control loops, require their own very complicated mathematical modelling and also dedicated two-phase single-component experiments.

Liquid-vapour flows obey all basic fluid mechanics laws, but their constitutive equations are more numerous and complicated than the equations for single-phase flow. The complications are due to the fact that inertia, viscosity and buoyancy effects can be attributed to the liquid and to the vapour phase, and also to surface tension effects. An additional, but major complication is the spatial distribution of liquid and vapour, being the flow pattern.

Figure 3 schematically depicts the various flow patterns occurring in a vertical tube evaporator: the entering pure liquid gradually changes to the exiting pure vapour flow, via the main (morphological) patterns for bubbly, slug (or plug), annular and mist (or drop) flow.

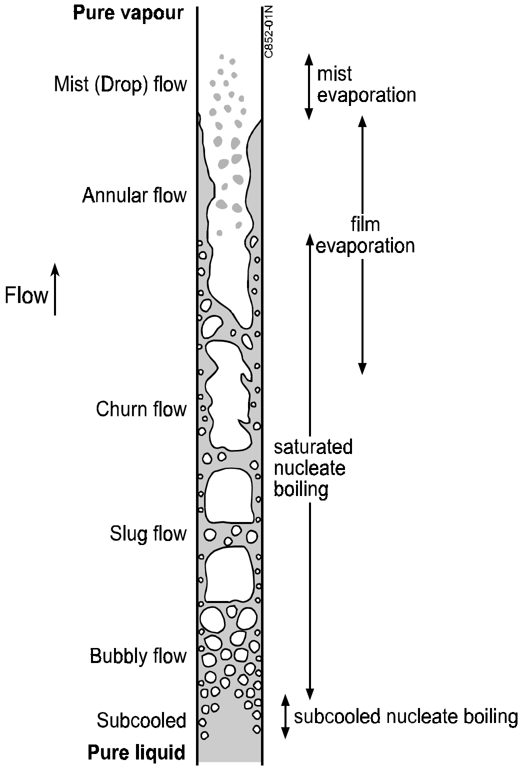

Figure 3. *Flow Patterns and Boiling Mechanisms for Up-Flow in a Vertical Line on Earth*

The hybrid flow patterns, bubbly-slug, slug-annular (churn), and annular-wavy-mist, can be considered as transitions between main patterns. The behaviour in a horizontal evaporator on earth is depicted in figure 4. Figure 5 gives the patterns in a horizontal condenser tube for high and low liquid loading.

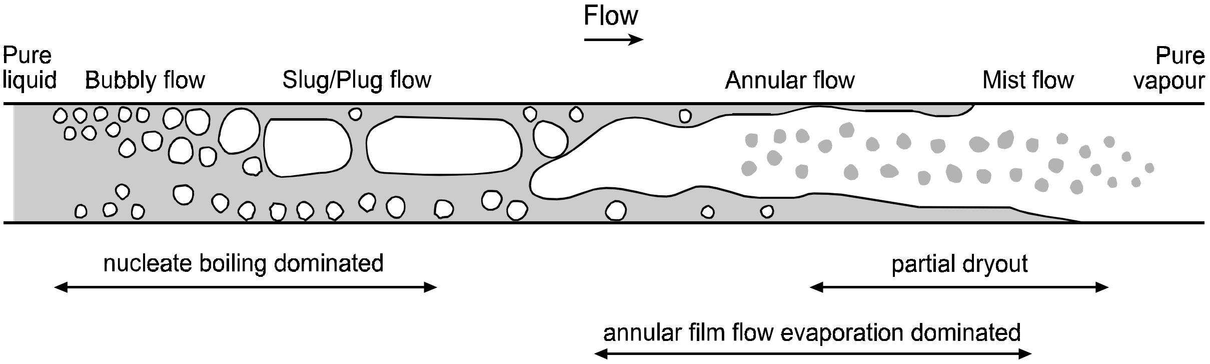

Figure 4. *Horizontal Evaporator Line on Earth*

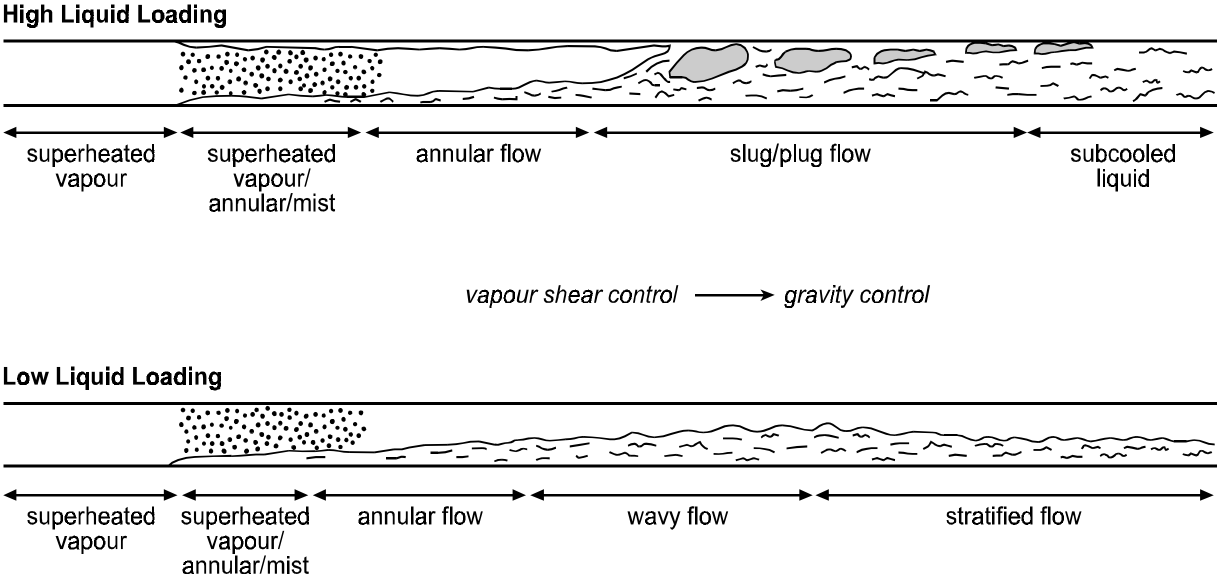

Figure 5. *Horizontal Condenser Line on Earth*

The above figures clearly illustrate the stratification induced by gravity, leading to non-symmetric flow patterns. The problem is that each flow pattern (regime) requires its own thermal/mathematical modelling. In addition, transitions from one pattern to another are to be modelled also. Within a particular regime, further refinement of the modelling can be based on additional criteria: The relative magnitudes of the various forces or the difference between laminar and turbulent flow. Figure 6 (taken from reference 2) presents a qualitative picture of the interfacial friction factor as a function of the liquid fraction of a flowing two-phase mixture. It illustrates clearly the conditions for transitions between the different flow patterns.

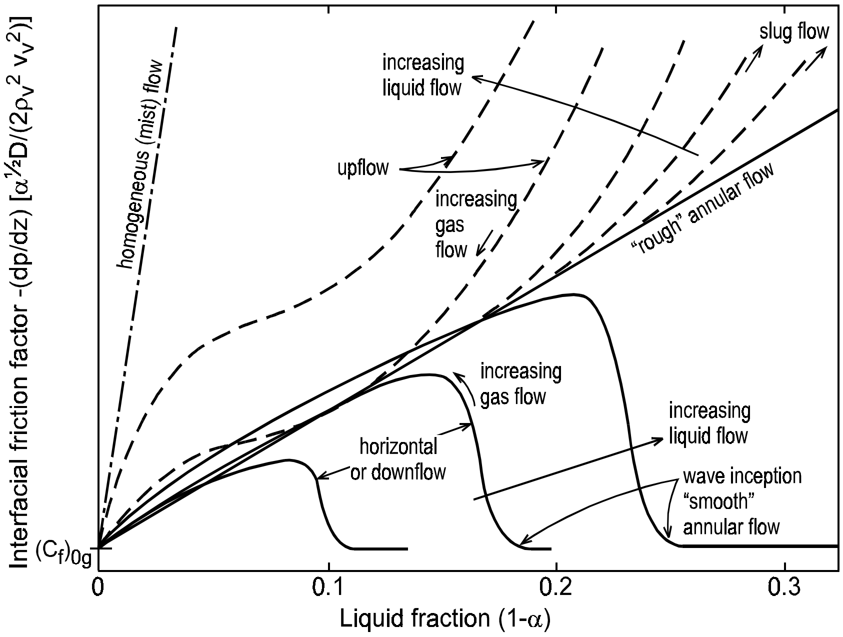

Figure 6. Apparent Friction for Some Flow Patterns (Ref. 2)

VIABILITY DEMONSTRATION & DEVELOPMENT OF NOVEL COMPONENTS

The main driver behind the research on two-phase flow and heat transfer in micro-g is the need for thermal control systems for future large spacecraft, which have to transport large amounts of dissipated power (say hundreds of kW) over large distances (say 100 meters). Though conventional single-phase systems (based on the caloric heat 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 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. A very important near-future two-phase heat transport system application is the two-phase thermal control system of the Russian segment of the International Space Station (Refs. 3-5).

The stations can be arranged in a series, a parallel or a hybrid configuration. The series configuration is the simplest. 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. An example of a parallel concept is ESA's Two-Phase Heat Transport System (Refs. 6-8). However, 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 (Refs. 8-14).

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 systems can be distinguished (Fig. 7): The western-heritage Capillary Pumped Loop CPL (Refs. 15-17) and the Russian-heritage Loop Heat Pipe LHP (Refs. 18-21). Active loop set-point temperature control can be 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).

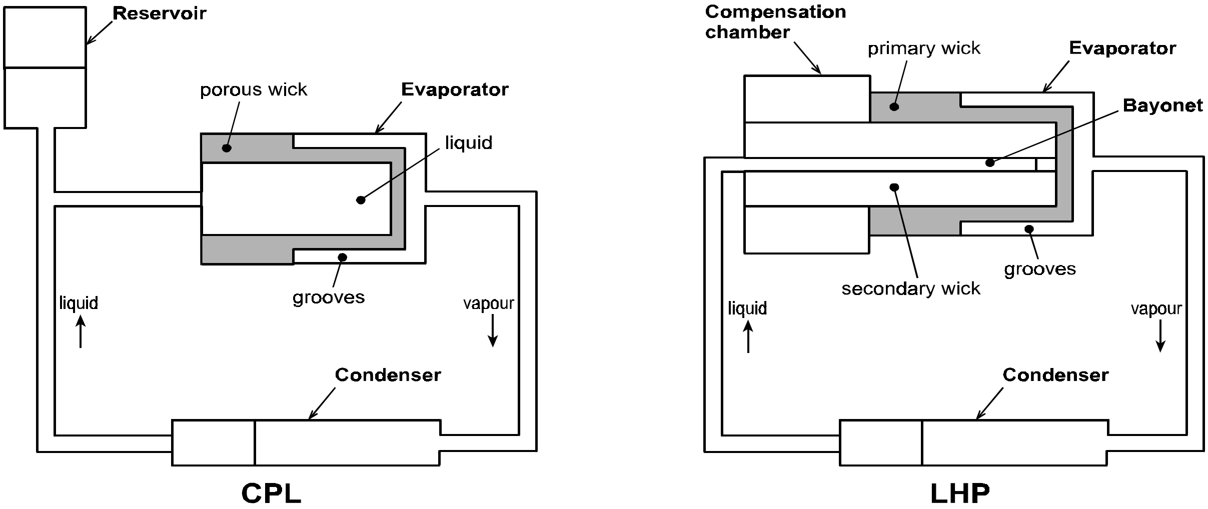

Figure 7. *Schematics of Capillary Pumped Loop (CPL) and Loop Heat Pipe (LHP)*

Because of performance advantages and unique operational characteristics (Ref. 22) CPL's and LHP's are planned for several future spacecraft missions These are not only low-orbit or geo-synchronous satellites, but include also missions to planets (Ref. 23). Examples are the American Earth Observation Satellite EOS-AM, the European Atmospheric LIDAR earth observation spacecraft ATLID (Ref. 24), the French technology demonstration satellite STENTOR, the Russian spacecraft OBZOR, the Hubble Space Telescope retrofit mission, the Hughes 702 satellites (Ref. 25), and other commercial geo-synchronous communication satellites.

Since two-phase flow and heat transfer is essentially different in earth gravity, lunar gravity, martial gravity and micro-gravity, two-phase heat transport system technology has to be demonstrated in space. Therefore several in-orbit experiments were carried out: Two-Phase eXperiment TPX I (Refs. 26-28), NASA's CApillary Pumped Loop experiments CAPL 1&2 (Ref. 29), the Loop Heat Pipe Flight eXperiment LHPFX (Ref. 25), the all US Loop Heat Pipe with Ammonia ALPHA, the Cryogenic Capillary Pumped Loop CCLP (Ref. 30), and the Two-Phase Flow experiment TPF (Refs. 31, 32). Others were planned and were (to be) done on other flights: TPX II (Ref. 28), CAPL 3 (Ref. 33), STENTOR (Ref. 34), Two-phase flow Extended Evaluation in Microgravity TEEM (Ref. 35), Granat (Ref. 36) and ESA's COM2PLEX (Ref. 37).

Development supporting, scientific experiments were also carried out in the last decade, within research programmes concentrating on the physics of two-phase flow and heat transfer in microgravity (e.g. Ref. 38). Some experiments were done in drop towers (e.g. Ref. 39) or during Microgravity Science Laboratory missions on the Space Shuttle (Ref. 40). Many others were executed during low-gravity aircraft flights (Refs. 41-55). 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, may be useful, but are certainly less relevant for two-phase heat transport loops.

In summary: Though the in-orbit technology demonstration experiments TPX I, CAPL 2, TPF, ALPHA and CCPL in principal proved the viability two-phase technology for thermal control systems for space, many questions remained unanswered. Since drop tower and low-g aircraft experiments are only indicative (and in many cases less relevant as they concern most frequently two-phase two-component flow instead two-phase single-component flow), there is a strong need for long duration micro-g experimenting. CIMEX-3; The versatile two-phase loop offers ample possibilities for such experimental research, including development and micro-g calibration of components, like vapour quality sensors, flow meters, and novel evaporators and condensers (Refs. 8-14, 27, 28, 56-60).

BETTER UNDERSTANDING OF PHYSICAL PHENOMENA

Various textbooks on two-phase flow and heat transfer (Refs. 2, 61-63) derive and discuss in detail the constitutive (conservation) equations for the various (main) flow patterns, focusing on one-dimensional liquid-vapour (or gas) flow. Such one-dimensional models, especially those for homogeneous (bubbly and mist) flow, slug and annular vertical downward flow in lines of circular cross section, are relevant for the various aerospace-related two-phase issues, as non-terrestrial gravity conditions in various space environments are circular symmetric also. By writing these equations in dimensionless form, one can identify dimensionless numbers (groups of fluid properties and dimensions) that determine two-phase flow and heat transfer. Such numbers are very useful for similarity considerations in thermal-gravitational scaling exercises and (anticipating a later section) for the creation of flow pattern maps. An alternative way to derive these dimensionless numbers is by dimension analysis, a useful baseline for similitude in engineering approaches, discussed in special textbooks (Ref. 64). It is remarked that the discussions here are restricted to lines, which have a circular cross-section: The problem therefore is circle-symmetric, one-dimensional. The homogeneous flow model is based on homogeneous mixture properties and on zero slip between the phases (equal velocities of both phases). The annular flow model, considering the two phases to move separately with different velocities, is valid in the adiabatic two-phase thermal control system lines, in almost the entire condenser, and also - in the case of (swirl) tube evaporators - in evaporator lines.

Two issues will be briefly discussed here: They pertain to the thermal-gravitational modelling and scaling philosophy/approach and results obtained, and to gravity level dependent annular flow condensation. For all details on these two issues, it is referred to the many papers and journal articles published before (Refs. 65-80), and the references list in the review paper (Ref. 81).

Thermal-Gravitational Modelling and Scaling Issues

Development supporting theoretical work like thermal-gravitational modelling and scaling of two-phase heat transport systems is being done to get better understanding of the impact of gravitation level on two-phase flow and heat transfer phenomena, to provide means for comparison and generalisation of data, to develop tools to design space-oriented two-phase loops (components), based on terrestrial tests, and to reduce costs. Scaling of physical dimensions is of major interest in the process industry: large-scale industrial systems are studied using reduced scale laboratory systems. Scaling of the working fluid is of principal interest in the power industry: large industrial systems, characterised by high heat fluxes, temperatures, and pressures, are translated in full size systems operating at more attractive lower temperature, heat flux and pressure. The main goal of thermal-gravitational of space-related two-phase heat transport systems is to develop reliable spacecraft systems, whose reduced gravity performance can be predicted using results of experiments with scale models on earth. Scaling spacecraft systems can be useful also for in-orbit technology demonstration, e.g. the performance of spacecraft heat transport systems can be predicted based on the outcomes of in-orbit experiments on model systems with reduced geometry or different working fluid. Also in-orbit experiments are defined to isolate phenomena to be investigated, e.g. excluding gravity-induced disturbing buoyancy effects on alloy melting, diffusion and crystal growth, for a better understanding of the phenomena. The magnitude of the gravitational scaling varies with the objectives from 1 g to 10^{-6} g for terrestrial scaling of orbiting spacecraft, to 0.16 g on Moon and 0.4 g on Mars s, and to super-g on larger planets.

It is remarked that (worldwide) only NLR is carrying out such thermal-gravitational scaling of two-phase systems. The fact that all papers from NLR with respect to this subject, haven been selected (via peer reviews) for journals and transactions, at least suggests the uniqueness/importance of the activity. The approach is based on dimension analysis and similarity considerations, which led to the identification of 18 dimensionless numbers (called π-numbers) relevant for thermal gravitational scaling of mechanically and capillary pumped two-phase loops. This set of 18 π-numbers, "the most complete set for two-phase flow" (Ref. 82), is listed in the table below.

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			
$\pi_1 = D/L$ = 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			•	/•	•
$\pi_{10} = Pr_l = (\mu Cp/\lambda)_l$		•	•		•
$\pi_{11} = Nu_l = (hD/\lambda)_l$ = 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			•	/•	•
$\pi_{16} = Ma = v/(\partial p/\partial \rho)^{1/2}_s$			•	•	•
$\pi_{17} = (h/\lambda_l)(\mu_l^2 g)^{1/3}$			•		•
$\pi_{18} = L^3 \rho_l^2\ g\ h_{lv}/\lambda_l \mu_l (T-T_o)$			•		•

Considering only the identity of Morton number and the identity of We/Fr for prototype and scale model (referring for details on this scaling exercises to the references mentioned), the following conclusions can be drawn from the figures 8 and 9, showing the temperature dependence of the groups $g.Mo_l = \rho_l.\sigma^3/\mu_l^4$ and $(\sigma/\rho_l)^{½} = D.g^{½}/(We/Fr)^{½}$:

- First, scaling at the same gravity level means a fixed $gMo = \rho_l\sigma^3/\mu_l^4$-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.
- Second, figure8 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 $\rho_l \sigma^3/\mu^4_l = 2.10^{12}$ m/s^2) is about 0.4.

- Third, 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).
- Fourth, 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.

In conclusion it can be said that verification of the results of the above thermal-gravitational scaling approach is one of the CIMEX-3 objectives.

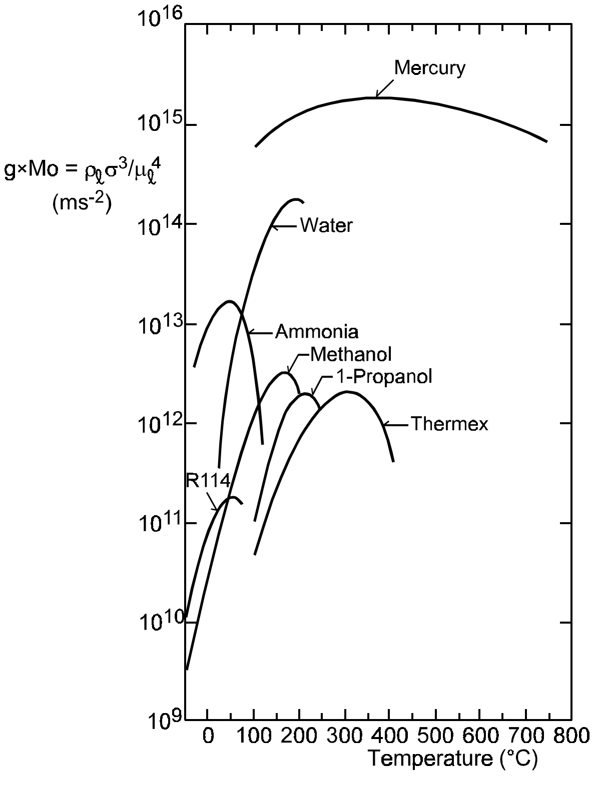

Figure 8. *$\rho_l.\sigma^3/\mu_l^4$ Versus Temperature for Six Fluids*

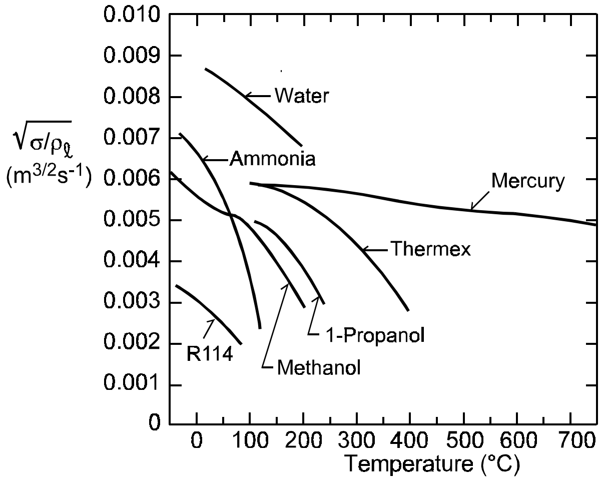

Figure 9. *$(\sigma/\rho_l)^{½} = Dg^{½}/(We/Fr)^{½}$ Versus Temperature*

Two-Phase Pressure Drop Issues

An important quantity (to be measured during two-phase flow experiments) is the pressure drop in adiabatic sections and in condensers: sections, being considered crucial for two-phase system modelling and scaling. The equations for annular flow pressure gradients in straight tube condensers and adiabatic lines, given and extensively discussed in literature (Refs. 65-80) are based on an elaborate journal article (Ref. 83). The total local (local position z-dependent) pressure gradient for annular flow is the sum of friction, momentum and gravity gradients. These constituents, calculated for ammonia at 25 °C and -25 °C are depicted in figure 10. The figure shows, that at 25 °C the gravity constituent overrules the sum of the two other constituents at vapour qualities below say 0.8. At -25 °C this overruling holds for vapour qualities below say 0.4. This confirms the statement, that say room temperature low-gravity behaviour can be simulated by terrestrial tests at far lower temperatures. Figure 11 shows curves, calculated (Refs. 66-68) assuming a constant 10^{-2}-g acting co-current with the flow, counter-current and perpendicular to the flow. As hydraulic changes in thermal systems are relatively slow, each measured value represents a mean of many low-g aircraft measurements (Ref. 84) at an average measured g-level of the order 10^{-2}-g. These measured data clearly lie within the boundaries of the calculated curves, which confirms the modelling.

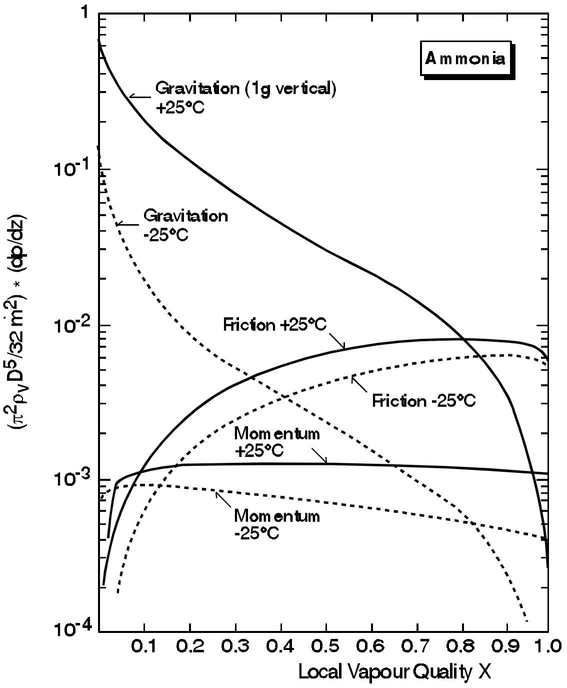

Figure 10. *Friction, Momentum and Gravity Gradients*

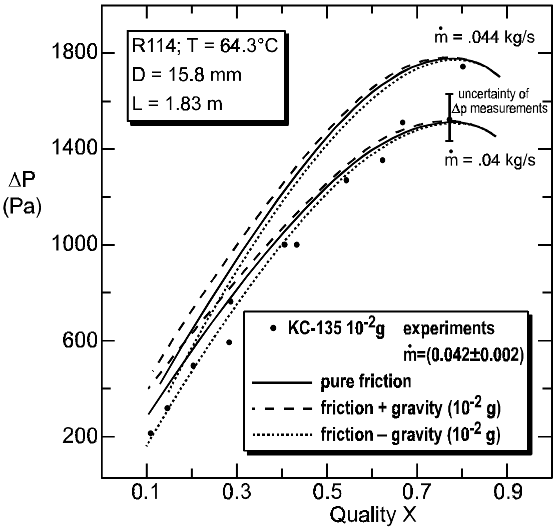

Figure 11. *Measured/Predicted Adiabatic Pressure Drops*

Modelling and calculations were extended from adiabatic to condensing flow in a straight duct (Refs. 69, 70) to investigate the impact of gravity level on the duct length required to achieve complete condensation. 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 (Ref. 85), 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 and parameter values defined in reference 85 were chosen as the baseline (power 1 kW, line diameter 16.1 mm, ammonia temperature 300 K and temperature drop to sink 10 K).

Figure 12 shows the vapour quality X along the condensation path (as a function of non-dimensional length z/D) for all gravity levels mentioned, including the curves of reference 85 for zero-g and horizontal condensation on earth, found in literature. From this figure 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. The findings of reference 85 can be considered as extremes.

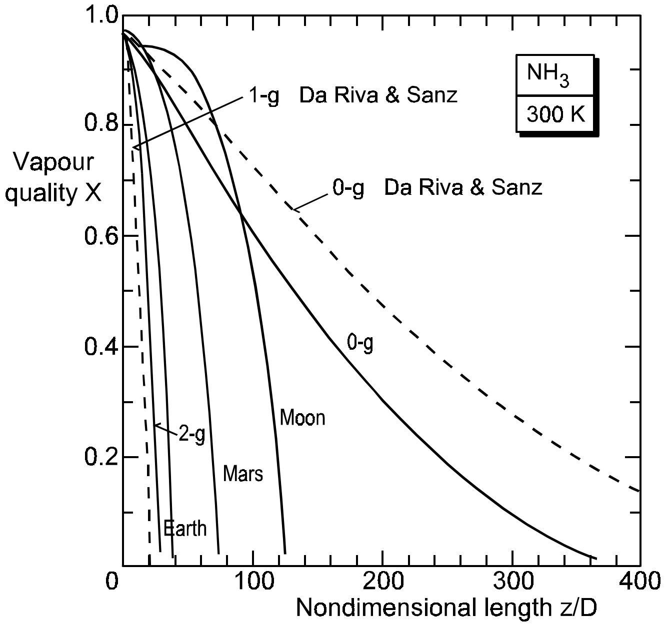

__Figure 12.__ Vapour Quality Along the 16.1 mm Duct for Ammonia at 300 K, 1 kW, for Different Gravity levels

To assess the impact of saturation temperature on condensation, similar curves were calculated for two other temperatures, 243 K and 333 K, and the same parameter values as used above (Refs. 69, 70). Calculations show that the full condensation length increases with the temperature for zero-g conditions, but decreases with temperature for the other gravity levels. This implies that the differences between earth gravity and low-g outcomes decrease with decreasing temperature, again confirming the statement that gravity impact is reduced in low temperature vertical downward flow.

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 (Refs. 69, 70) 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 g-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, 24.15 mm) at 300 K, gave the ratio of duct lengths L_c(m) needed for condensation under zero-g and one-g respectively (Refs. 69, 70). The ratio between 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. In other words, small line diameter systems are less sensitive to differences in gravity level as compared to larger diameter systems. This is confirmed by TPX I flight data (Ref. 27).

But it must be remarked that, since the model developed is valid for annular flow, it is worthwhile to investigate the impact of other flow patterns inside an evaporator or a condenser duct: Mist flow at high quality, slug and bubbly flow at low quality and wavy-annular-mist in between. It is to be investigated if an annular flow assumption leads towards slightly or substantially overestimated full condensation lengths.

In conclusion it can be said that experimental verification of outcomes of the modelling for condensing heat transfer is also a CIMEX-3 objective.

FLOW PATTERN ISSUES

Knowledge of the gravity level dependent two-phase flow regimes is crucial for modelling/designing two-phase heat transport systems for space, since flow patterns (or regimes) determine thermal hydraulic characteristics and the mathematical modelling of two-phase flow & heat transfer. Therefore it is clear that flow pattern (regime) maps are to be created, preferably in a non-dimensional format of figure 13 (Ref. 86).

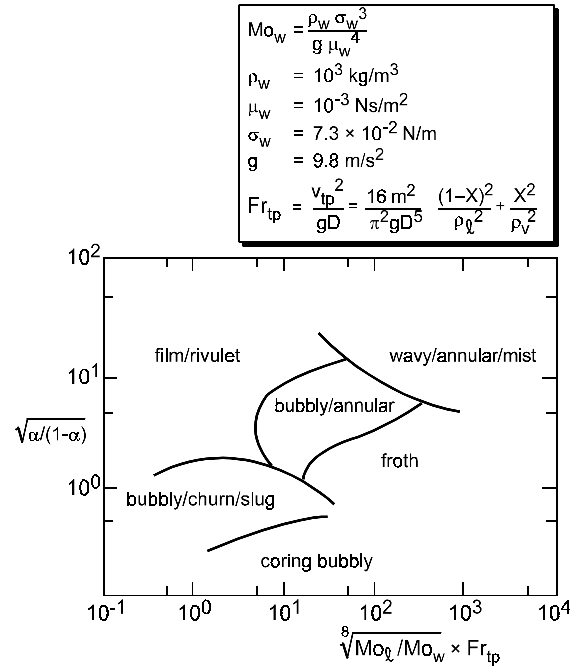

***Figure 23**. Normalised Flow Pattern Map for Vertical Down Flow*

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 (Ref. 42). The data was obtained at various g-levels, realised during numerous flights. The figures ($j_v = v_v.A_v/A$; $j_l = v_l.A_l/A$) clearly show the gravity level dependence 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 16 is a cross-section at 10^{-2}-g of the figures 14 and 15. Figure 17 shoes data of low-g aircraft experiment Cyrène, ammonia, 4.7 mm lines (Ref. 41). Figure 18 depicts a 0-g map derived from TPX I (ammonia, 4.9 mm line) VQS flight data (Ref. 27).

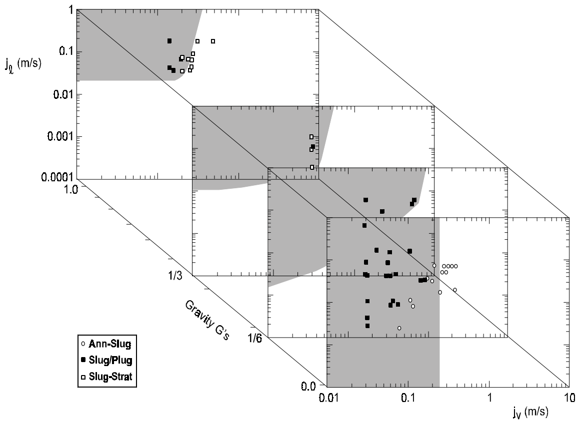

Figure 14. *G-Dependent 3-D Slug-Plug Flow Pattern Map*

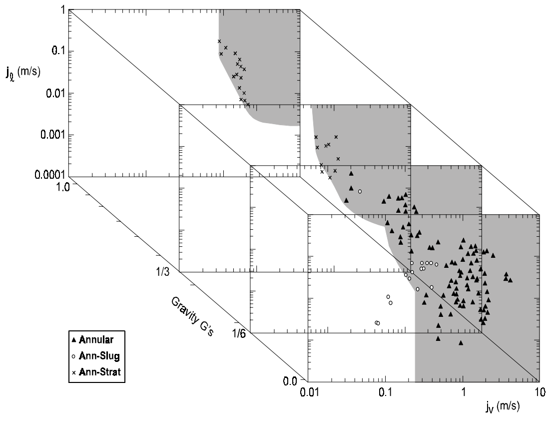

Figure 15. *G-Dependent 3-D Annular Flow Pattern Map*

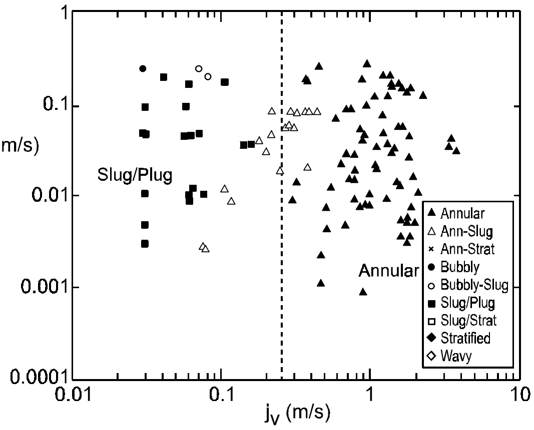

Figure 16. *0-G Cross-Section of 3-D Flow Pattern Maps*

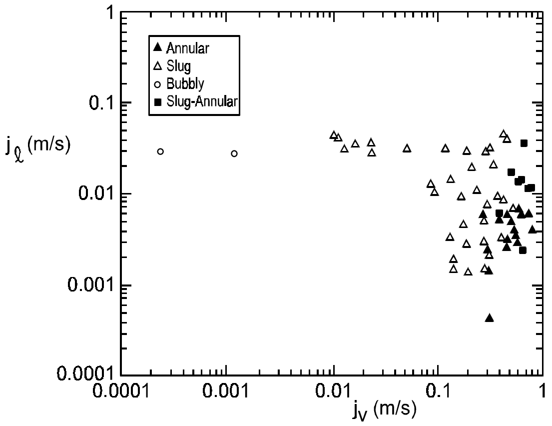

Figure 17. *Cyrène Flow Pattern Map Data*

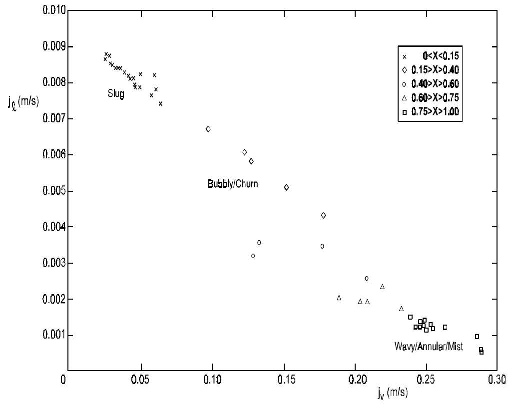

Figure 18. *Flow Patterns According TPX I VQS Data*

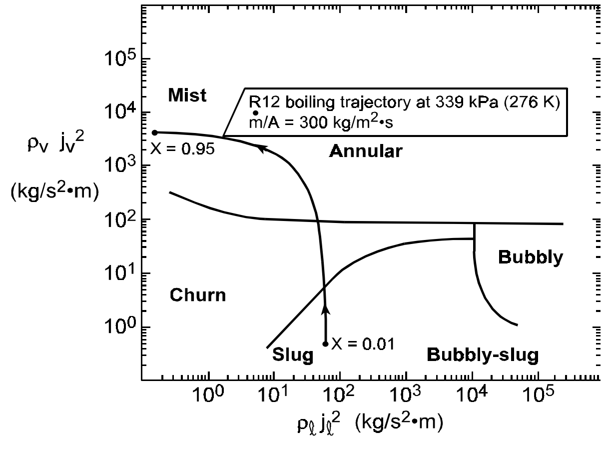

Figure 19. *Flow Pattern Map for Vertical Down Flow*

The experimental data in the figures partly contradict each other. A comparison suggests that the transition to annular flow occurs in these three systems more or less at the same j_v-value 0.2-0.25 m/s, but at different j_l-values. This can be caused either by the different working fluids (R12/ammonia/ammonia) or the different inner line diameter (10.5 mm/4.7 mm/4.9 mm). More data are to be gathered to draw final conclusions on the actual cause. Anyhow, it can be said that the above illustrates that a lot of work has to be done before adequate flow pattern or flow regime maps will be produced and will become mature. Such maps preferably have to be in the normalised format of figure 13 or in the very good alternative three-dimensional j_v - j_l - g format, given in the figures 14 and 15 (and their two-dimensional cross sections, as depicted in the figures 16 to 18). The maps can then be used to determine by iteration, via the flow pattern dependent constitutive equations for two-phase flow and heat transfer, the actual trajectories of condensing or evaporating/boiling flow, as schematically drawn in figure 19 in the alternative format $\rho_v j_v^2$ versus $\rho_l j_l^2$ (Ref. 63). This iterative approach will lead to an accurate determination of the pressure drops in the various sections and of heat transfer in evaporators and condensers of two-phase heat transport systems.

In summary: A very important CIMEX-3 objective is the creation of two-phase flow pattern maps for various fluids at different temperatures and line diameters.

CONCLUSION

The CIMEX-3 objectives discussed are:

- To prove the viability of Mechanically and Capillary Pumped two-phase Loops (MPL & CPL), using different working fluids or mixtures.
- To verify NLR's unique thermal-gravitational scaling approach.
- To experimentally verify the outcomes of the modelling for condensing heat transfer.
- The creation of two-phase flow pattern maps for various working fluids at different temperatures and line diameters.
- To develop and calibrate in micro-g components, like vapour quality sensors, flow meters, and novel evaporators and condensers.
- To accommodate (as an extra) 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.

These objectives obviously cover the various needs to obtain a vast amount of currently lacking information, which is essential to get a better understanding of the physics of two-phase flow and heat transfer phenomena in different gravity environments, and to get the knowledge and data required for the proper design of reliable two-phase thermal control systems for many future spacecraft, based on the results of experiments on earth.

NOMENCLATURE

A	area (m^2)
Boil	boiling number = $\Delta H/h_{lv}$ = Boil (-)
Cp	specific heat at constant pressure (J/kg.K)
D	diameter (m)
Eu	Euler number = $\Delta p/\rho v^2$ (-)
Fr	Froude number = v^2/gD (-)
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)
k	thermal conductivity (W/m.K)
L	length (m)
Ma	Mach number = $v/(\partial p/\partial \rho)_s^{1/2}$ (-)
Mo	Morton number = $\rho_l \sigma^3/\mu_l^4\, g$ (-)
$\dot{m}$	mass flow rate (kg/s)
Nu	Nusselt number = hD/λ (-)
p	pressure (Pa = N/m^2)
Pr	Prandtl number = $\mu Cp/\lambda$ (-)
Q	power (W)
Re	Reynolds number = $\rho vD/\mu$ (-)
S	slip factor (-)
T	temperature (K = 273 + °C)
v	velocity (m/s)
We	Weber number = $\rho v^2 D/\sigma$ (-)

X	vapour quality = vapour mass fraction (-)
z	axial or vertical co-ordinate (m)
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
e	evaporator
f	friction
g	gravitation
l	liquid
m	momentum, model
o	reference condition, outer
p	pore, prototype
t	total
tp	two-phase
v	vapour

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PART II

CONVECTION AND INTERFACIAL MASS EXCHANGE (CIMEX)

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Abstract

The CIMEX research program aims to investigate processes involving mass transfer through interfaces, and their coupling with surface-tension-driven flows and instabilities. During the first two-year phase of this MAP (Microgravity Application Promotion) project, four experiments are being prepared for subsequent flight onboard the International Space Station (ISS), using the Fluid Science Laboratory (FSL). The main focus is on flows and instabilities with evaporation. Both single component and multi-component fluid systems are studied, in collaboration between several European teams, an industrial partner (SABCA), and with the advice of non-EU collaborators. On a fundamental point of view, progress is expected in the understanding of different regimes of interfacial mass transfer processes, in the presence of several effects (inert gas, Marangoni convection, micro-regions or triple lines, surfactants). On the applied point of view, both direct and prospective research is conducted, aiming to optimize heat pipes, thin-film evaporators, two-phase flow and boiling technologies.

I. Introduction : CIMEX Research Program

The general structure of the CIMEX-MAP project is represented in Fig. 1. As detailed hereafter, research on volatile pure liquids will be conducted not only on evaporating layers and thin-films, but also on heat pipes and two-phase flow technologies. In addition, the effect of surfactants on Marangoni convection and evaporation will also be studied, both for drops and bubbles. The various goals of the program are strongly inter-related, and will now be described separately in more details.

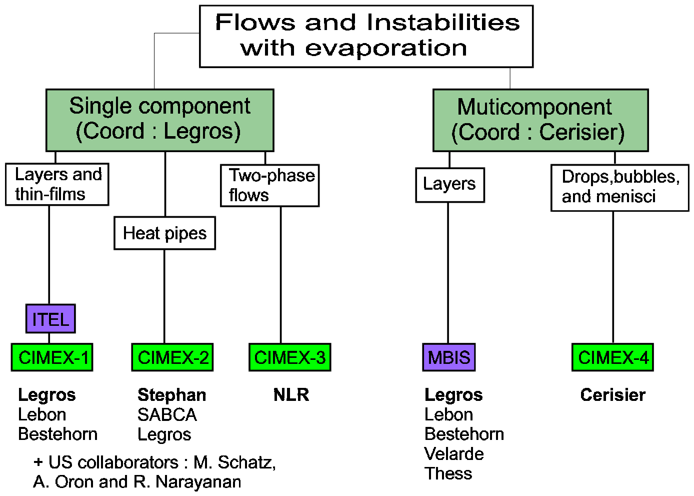

Figure 1: Structure of the CIMEX program. Microgravity experiments foreseen for the space station are denoted by CIMEX-1,2,3,4.

II. CIMEX-1 and ITEL: Evaporative convection in layers

Highly volatile liquids such as diethyl ether or ethyl alcohol are most often subject to surface-tension-driven instabilities, even under standard atmospheric conditions (see Fig. 2). For instance, a thin-film of diethyl ether, visualized using a Schlieren set-up (see Fig. 3), shows patterns reminiscent of the Marangoni-Bénard instability, occurring when a liquid layer is heated from below.

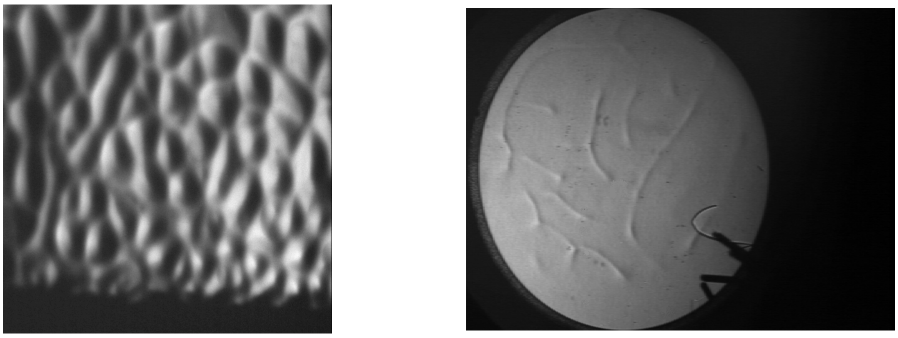

Figure 2: Surface patterns visualized using a Schlieren set-up (grayity level proportional to surface slope in one direction). Left: thin film of diethyl ether on a rigid plate under ambient air. Right: a 4 mm-thick layer in a closed circular vessel at atmospheric pressure and under a flow of air. For thin films, the Marangoni effect dominates, leading to polygonal patterns. For increasing film thickness, buoyancy becomes the major destabilizing mechanism, though the intensity of the Marangoni effect also increases, leading to sharper ripples or "streamers".

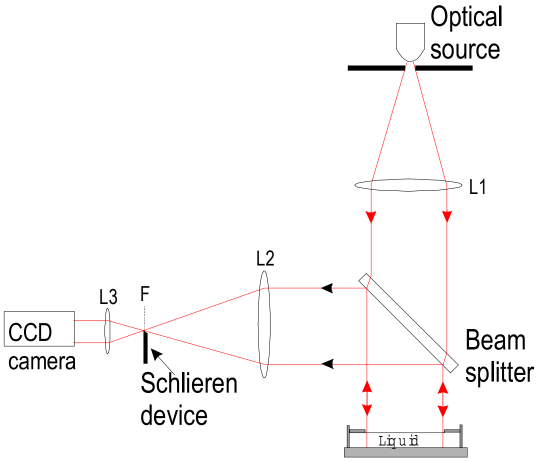

Figure 3: Typical Schlieren set-up used for visualizing deviations of an initially parallel light beam.

In some conditions, the surface patterns evolve chaotically [1] and lead to a strong increase of the evaporation rate. Although it is believed that the intensity of such "interfacial turbulence" is increased at higher fluid depths (increasing Marangoni number), research still needs to be conducted in order to assess about the influence of various effects. First of all, thicker layers are strongly influenced by buoyancy, and it is not possible to investigate about high Marangoni number regimes of evaporating liquids without conducting experiments in micro-gravity. Second, it appeared from theoretical modeling and preliminary experiments that the presence of an inert gas such as air in the gas phase, in addition to vapor, should allow larger fluctuations of temperature along the free surface, and hence stronger Marangoni effect [2]. To explain this, we may first consider an experiment in a closed vessel where all air is removed, and the liquid layer is in contact with its pure vapor. In most cases, the interface is near *local* thermodynamic equilibrium, and according to the phase rule, there is a direct relation (e.g. the Clausius-Clapeyron law) between the interfacial temperature T_i and the vapor pressure p_s. As pressure fluctuations in a gas are very small in usual conditions, the temperature is bound to remain constant all along the interface, and no surface-tension effect occurs. Clearly, introducing a second component in the vapor phase, such as air, yields a supplementary degree of freedom. Surface-tension-driven instabilities are then enhanced, as only the total pressure is bound to remain quasi-homogeneous in the gas mixture, while the partial pressure, or equivalently the local concentration in the gas, may undergo strong and slowly evolving fluctuations (see Figure 4).

On the other hand, even for a pure vapor phase, fluctuations of temperature may in principle take place along the interface, provided the latter is maintained sufficiently far from local thermodynamic equilibrium. On a modeling point of view, this means that instead of an equilibrium condition $T_i=T_s(p_{vap})$, a kinetic relation should be used, and is generally taken as a Hertz-Knudsen law [3,4] for the net evaporation flux J. Note also that recent studies by Ward and co-workers have shown that the usual assumption of continuity of temperature across the interface may be violated, even for moderate evaporation fluxes [5]. In these conditions, kinetic relations should be generalized [6,7].

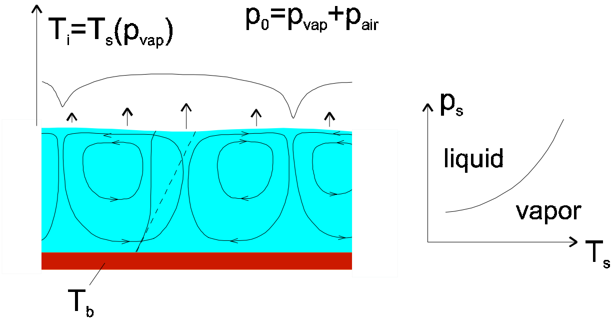

Figure 4: during evaporation of a liquid layer in contact with a gas mixture (vapor+air), even though an equilibrium relation $T_i=T_s(p_{vap})$ may hold all along the interface, surface-tension driven instabilities may occur provided surface temperature fluctuations are coupled to concentration (or partial pressure) fluctuations in the gas. The resulting flows homogenize the temperature within the layer and lead to a strong enhancement of the evaporation rate.

In practice, whether or not the interface is at local equilibrium depends on the evaporation regime considered. In usual situations, it turns out that the evaporation flux is limited by the conduction of heat towards the interface (*heat-diffusion-limited regime*), where it is turned into higher enthalpy of vapor molecules (latent heat). When a second component (inert gas) is present in the gas phase, the latter molecules have to diffuse though the inert gas, which is the more *classical mass-diffusion-limited regime* [8]. In both these cases, the interface may be assumed at equilibrium, and it is only in cases where both these diffusion mechanisms are very efficient that the limitation arises from the non-equilibrium kinetics of evaporation itself (*reaction-limited regime*).

In addition to the theoretical and experimental research performed by ULB-MRC, thermodynamic aspects of the evaporation process will be examined by Ulg, using tools of Extended Irreversible Thermodynamics [9]. Direct 3D numerical simulations and models of nonlinear dynamics (see, e.g. [10]) will also be developed by BTU. It is believed that the fundamental understanding gained during the CIMEX-1 project, via the study of planar geometries, will allow to determine which are the effects pertinent to the evaporation of liquids in more complicated geometries such as used in heat transfer technologies. For instance, in one-component systems, the distinction between heat-diffusion-limited and reaction-limited regimes appears to be essential in order to assess about the importance of Marangoni convection in heat pipe grooves (see next section) or for nucleate boiling [11].

A preliminary step in he preparation of the CIMEX-1 experiment is the ITEL (Interfacial Turbulence in Evaporating liquids) experiment, foreseen for the MASER-9 sounding rocket flight et the end of 2001. During the 6 min micro-gravity phase, ethyl alcohol will be evaporated in a closed cell, using both reflection-Schlieren and 3D temperature field reconstruction via optical tomography. The latter diagnostic will use interferometry in six directions parallel to the liquid/gas interface, to measure integrated optical paths along different directions. The six projections are then grabbed and treated numerically via some reconstruction algorithm, to determine the 3D temperature field within the liquid layer. More details about the set-up currently implemented in the ITEL breadboard, in collaboration with SSC

(Swedish Space Corporation) can be found in [12]. A sketch of the cell, including correction optics and reference cell for interferometry, and inert gas (nitrogen) circulation, is represented in Fig. 5.

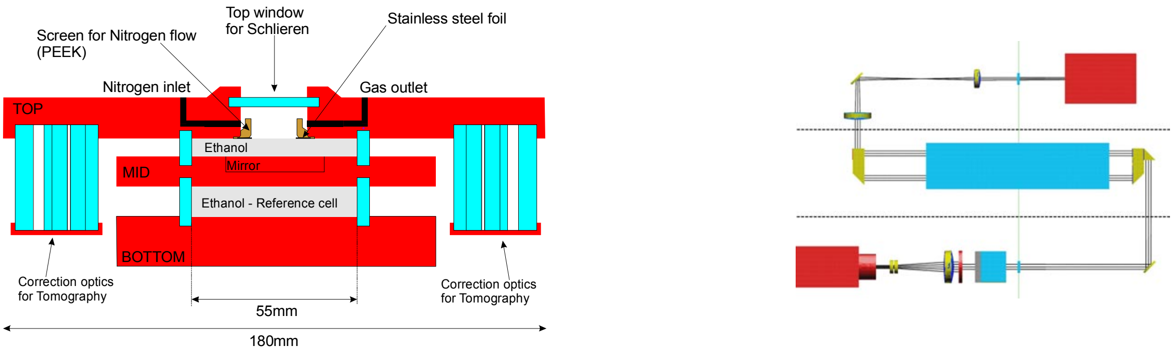

Figure 5: Sketch of the ITEL breadboard module. The cell, at the left, is at the middle level of a three-level module depicted on the right (only one tomographic arm is presented). Tomographic sources (laser diodes) are on the lower level, the CCD cameras are on the upper level. An optical system allows to recombine the six views on two CCD chips.

Due to the short micro-gravity time of MASER, only transient effects will be investigated (ripple formation). It indeed appeared that the development of thermal ripples occurs on a sufficiently fast time scale, while the overall organization of the pattern typically takes a much longer time. The CIMEX-1 experiment will also investigate other liquids, and allow to obtain maps of regimes as a function of the governing parameters (pressure, temperature, gas flow rate, liquid depth). In addition to Schlieren and holographic interferometry, it is also planned to make use of light-sheet capabilities of FSL in order to measure fluid velocities using tracers.

III. CIMEX-2: Heat pipes

The CIMEX-2 experiment is dedicated to the physical understanding of micro-region effects in heat pipe grooves (see Figs. 6-7), and optimization of heat pipe performances using advanced capillary structures (see Fig. 8).

Due to the high thermal conductivity of the solid metal grooved structure compared to that of the liquid, most of the evaporation flux takes place in the micro-regions, and it is therefore essential to understand the physics of evaporation in their vicinity [13]. To this end, the CIMEX-2a (M4) experiment is developed by TUD in Darmstadt, conjointly with ULB-MRC and SABCA in Brussels.

TUD has developed a ground set-up for the study of micro-region effects, which allows the visualization of the meniscus, hence the measurement of the contact angle, as well as the temperature field in the vicinity of the triple line. Using temperature sensitive liquid crystals on the backside of the transparent cell walls, it is possible from a numerical simulation of the temperature within the wall, to calculate the temperature distribution on the wall in contact with the liquid.

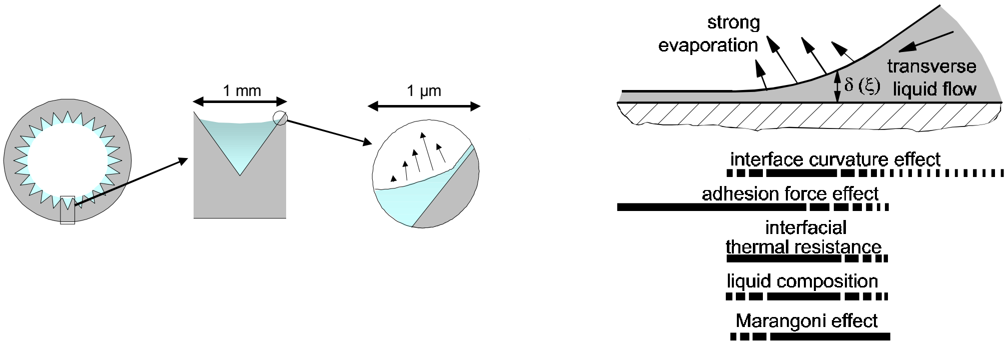

Figure 6: Left : in each of the grooves of a heat pipe evaporator, there are micro-regions in the neighborhood of the triple line (liquid-vapor-solid). In these regions, various effects are important (right), which may strongly affect the global evaporation rate, hence the heat pipe performance.

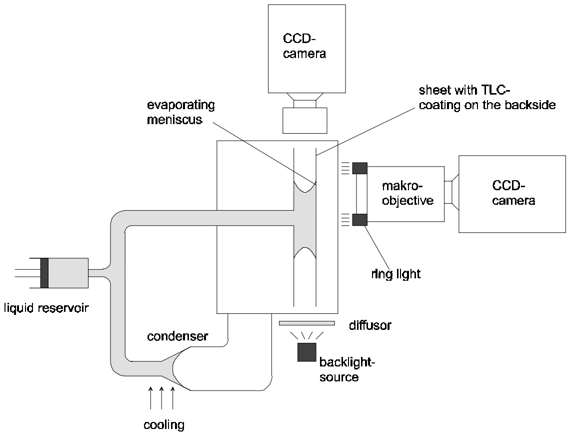

Figure 7: Sketch of the set-up planned for CIMEX-2a, to measure the wetting angle and the meniscus shape (top CCD camera) and the temperature distribution (right CCD camera) using temperature-sensitive liquid crystals (TLC) on the backside of the transparent cell walls.

The CIMEX-2b (M5) experiment aims to measure the performance of an advanced capillary structure, designed and built by SABCA, and based on two different sizes of grooves (macro and micro-grooves). The set-up foreseen for the ISS experiment is depicted in Fig. 8, and will also be tested onboard the next flight of the Russian FOTON satellite.

Note that in both CIMEX-2 experiments, the behavior of the liquid will be investigated at the level of the flat-plate evaporator ("unwrapped" circular evaporator), while the re-condensed vapor will flow back to the evaporator by capillarity, like in heat pipes. The possibility of using such kind of closed-loop system for other experiments is currently investigated.

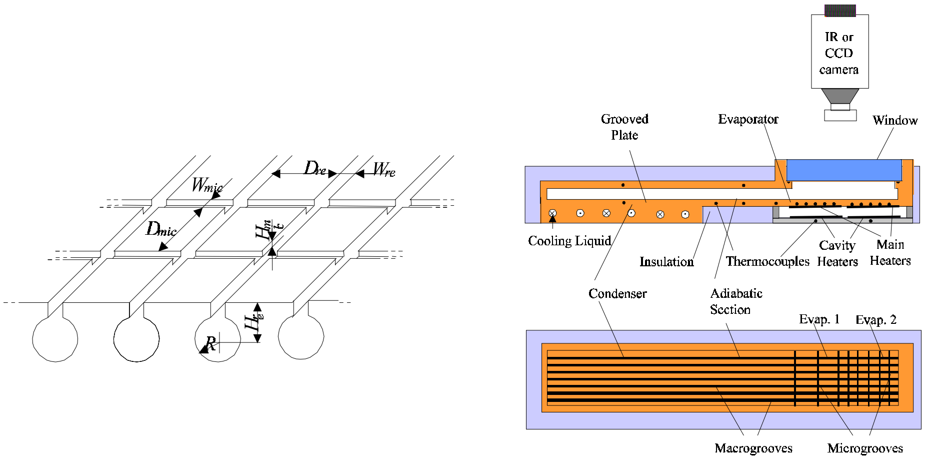

Figure 8: Sketch of the set-up planned for CIMEX-2b, allowing to measure the efficiency of SABCA advanced capillary structures for heat pipes.

IV. CIMEX-3: Two-phase flows

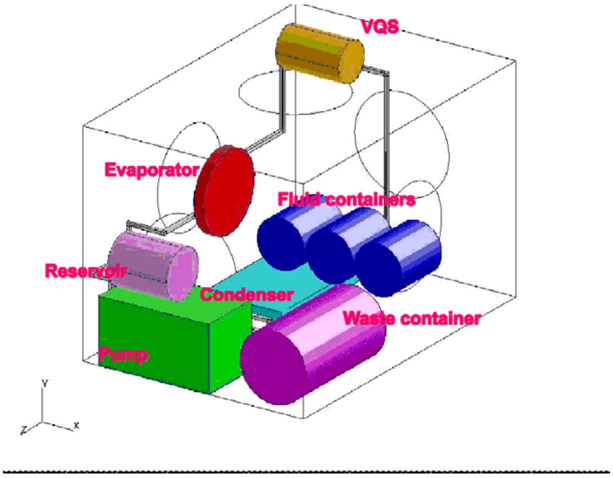

Figure 9: CIMEX-3 two-phase loop baseline, allowing visualization of evaporator and condenser sections, vapor quality measurement (VQS), and fluid circulation by mechanical pumping.

The principal objective of the CIMEX-3 versatile loop system, developed by NLR, concerns the study of micro-gravity two-phase flow and heat transfer issues, by :

- Developing transparent Swirl Evaporators & HELPD-Condensers
- Measuring void/mass fraction in adiabatic line for VQS calibration
- Flow pattern characterization and creation of flow pattern maps
- Viability demonstration of Mechanically and Capillary Pumped two-phase Loop
- Using different working fluids or mixtures

Making use of crew/experimenter interaction and of the optical capabilities of FSL, the general baseline of the CIMEX-3 modular two-phase loop is represented in Fig. 9.

One of the goals of the CIMEX-3 experiment is to test High-Efficiency Low Pressure Drop (HELPD) Condensers (two-phase flow in an annular tube with central cooling) using IR thermography (see Fig. 10). It is also planned to test these condensers using a series configuration.

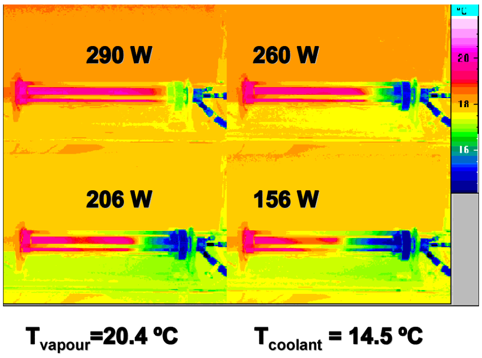

Figure 10: Infrared images of a transparent condenser, allowing mapping of its different regimes as a function of working power, vapor and coolant temperatures.

Moreover, NLR has developed a capacitance-based Vapor Quality Sensor (VQS), which measures the void fraction of the two-phase flow, a crucial parameter for the functioning of two-phase loops (see Fig. 11). During CIMEX-3, it is further planned to calibrate this sensor using an optical sensor, currently developed by NLR. The two-phase flow behavior will be investigated using optical observation, within the swirl evaporators, the condenser and the adiabatic section. FSL capabilities will be particularly useful for this purpose : IR cameras for observing the condenser and the evaporator, CCD cameras to observe the vapor line, holographic interferometry, …

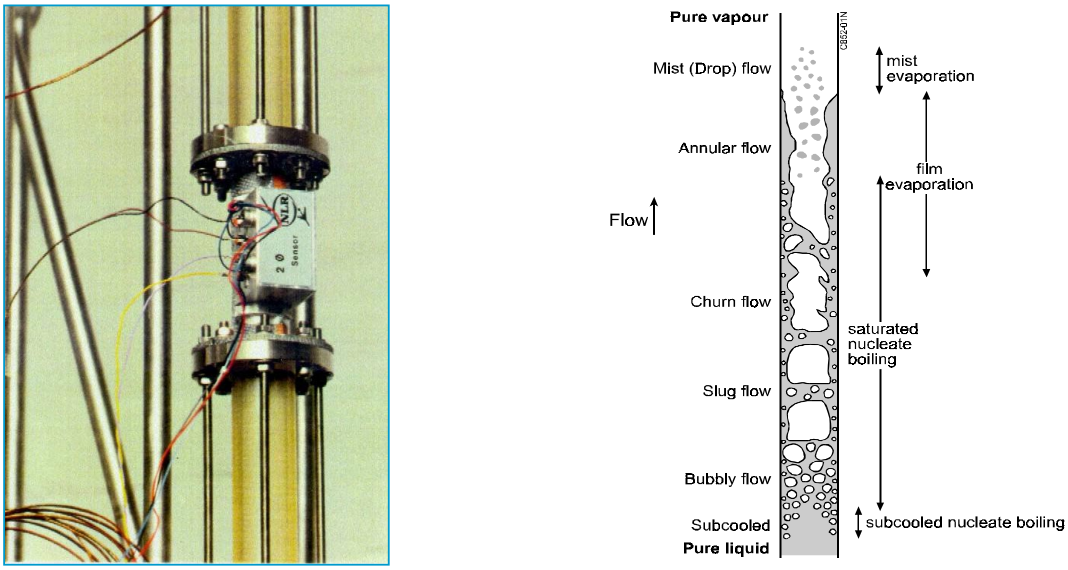

Figure 11: Left: NLR capacitance-based Vapor Quality Sensor. Right sketch of different regimes and transitions of two-phase flows in a tube.

Finally, the CIMEX-3 experiment will allow flow pattern maps to be created for a number of different working fluids, for both mechanically-pumped and capillary-pumped loops. This will also be useful for thermal-gravitational scaling [14], allowing ground-based two phase flow systems to be designed.

V. CIMEX-4: Bubbles, drops and surfactants

The CIMEX-4a experiment, realized by IUSTI, is dedicated to the investigation of thermocapillary flows generated around vapor bubbles in a liquid [15]. Using optical and thermal diagnostics, the axisymmetric steady flows around vapor bubbles attached on a heater (using a single artificial nucleation site), and their transitions to three-dimensional oscillating structures, will be investigated in order to study the bubble history from its appearance to detachment. As a preliminary step, parabolic flights have been realized in April 2000 (see Fig. 12).

Figure 12: Left : the cell used to investigate thermocapillary flows around bubbles. Right : parabolic flight hardware (CNES zero-g Airbus A-300) used for the preparation of CIMEX-4a.

Moreover, the dynamics of drops in a vapor phase will also be investigated by IUSTI during the CIMEX-4b experiment. The focus will be on the influence of the Marangoni effect and the vapor recoil force on the contact angle dynamics (see Fig. 13). Indeed, both these effects may influence the stability of the thermal boundary layer. The vapor recoil effect is due to the interfacial jump of momentum between arriving liquid molecules and departing vapor molecules, and acts as a back-pressure on the interface, which may lead to specific instabilities at very low pressure [4]. This effect has also recently been shown to be crucial for boiling, for which models of the boiling crisis (critical heat flux) have been proposed [16,17].

In addition, the influence of surfactants will also be investigated in this configuration. Surfactant molecules lower the surface tension, hence will make the contact angle smaller and the surface more flexible. Moreover, they also introduce a barrier to evaporation. Still, these qualitative arguments need to be quantified during the CIMEX-4b experiment.

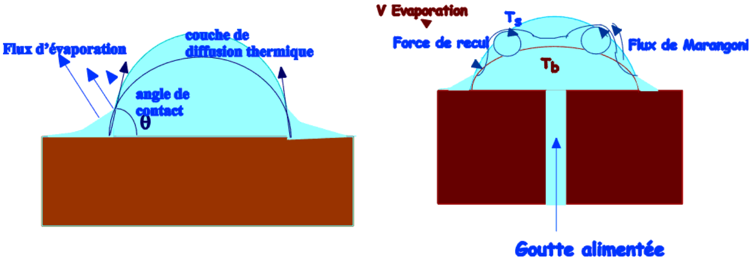

Figure 13: some effects relevant to the dynamics of evaporating drops on a rigid heater.

VI. Conclusions

The dynamics of evaporating liquids is a poorly-understood phenomenon, despite its importance both on the fundamental (non-equilibrium thermodynamics, nonlinear dynamics, contact line physics) and applied (heat pipes, two-phase flows, boiling, thin-film evaporators) point of views. Several objectives of the CIMEX project are related to improvement of knowledge and techniques in these fields. In addition, it should be stressed that many aspects of the coupling between evaporation and convection are shared by other processes of industrial interest, like liquid/liquid extraction, absorption/desorption, surface chemical reactions, dissolution, … These processes are also studied by some of the authors, in the framework of the European Union Network ICOPAC (Interfacial Convection and Phase Change).

VII. Acknowledgements

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