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Tutorial on Single- and Two-Component Two-Phase Flow and Heat Transfer: Commonality and Difference

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Contents

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A.A.M. Delil

National Aerospace Laboratory NLR
P.O. Box 153, 8300 AD Emmeloord, The Netherlands
Phone +31 527 248229, Fax +31 527 248210, adelil@nlr.nl

Abstract. It is assessed to what extent the results of two-phase two-component flow and heat transfer research can be usefully applied to support research on the flow and heat transfer in two-phase single-component systems. The latter single-component two-phase systems, envisaged for spacecraft thermal control applications, are Mechanically Pumped and Vapour Pressure Driven Loops, Capillary Pumped Loops, and Loop Heat Pipes. In these single-component systems the working fluid is a mixture of a liquid (for example ammonia, carbon dioxide, ethanol, or other refrigerants, etc.) and its saturated vapour. The two-component systems considered consist of liquid-gas mixtures, e.g. water-air. Various aspects are discussed qualitatively and quantitatively to determine commonality and difference between two physically looking similar and close, but essentially different systems. It is focused on the different pressure gradient constituents and total pressure gradients, on flow regime mapping (including evaporating and condensing flow trajectories in the flow pattern maps), on adiabatic flow and the impact of flashing, and on thermal-gravitational scaling issues. It is elucidated that, though there is a certain degree of commonality, the differences are appreciable. The conclusion is that one shall be very careful in interpreting two-component outcomes to develop single-component two-phase thermal control systems.

INTRODUCTION

Multiphase flow, the simultaneous flow of the different phases (states of matter) gas, liquid and solid, strongly depends on the level and direction of gravitation, since these influence the spatial distribution of the phases, having different densities. Of major interest for aerospace applications are the more complicated liquid-vapour or liquid-gas flows, that are characteristic for aerospace thermal control systems, life sciences systems and propellant systems. Especially for liquid-vapour flow in aerospace two-phase thermal control systems, the phenomena are extremely complicated, because of heat and mass exchange between the two phases by evaporation, condensation or flashing. Though a huge amount of publications discuss two-phase flow and heat transfer, publications on the impact of reduced gravity and supergravity are very scarce. This is the main driver to do research on the impact of various gravity levels.

The various heat and mass transfer research issues of two-phase heat transport technology for space applications are discussed in the next chapters. It is focused on the most complicated case of liquid-vapour flow with heat and mass exchange. Simpler cases, like adiabatic or isothermal liquid-vapour flow or liquid-gas flow, can straightforwardly be derived from this liquid-vapour case, as various terms in the constitutive equations can be set zero.

The discussions start with the background of the research, followed by a short general description of two-phase flow and heat transfer phenomena. The impact of the gravity level will be assessed. The discussions focus on development supporting theoretical work (thermal/gravitational scaling of two-phase flow and heat transport in two-phase thermal control loops, including aspects of gravity level dependent two-phase flow pattern mapping and condensation), in-orbit technology demonstration experiments, and some current R&D. They are concluded by the subject of this tutorial, being commonality and difference in single- and two-component two-phase flow and heat transfer.

BACKGROUND

A thermal utility or thermal bus is a pumped fluid, high-capacity heat transport system, serving as a common temperature controlled heat sink or source to more than one payload, usually to many payloads. Such thermal management systems for future large spacecraft have to transport large amounts of dissipated power (gathered at many dissipating stations) over large distances to the heat sinks, the radiator(s), where the heat is radiated to the cold space environment. Pumping pressures can be achieved by mechanical (powered) pumps, capillary action or other means, like osmotic pumps or compressors (Almgren, 1981; Stalmach, 1982; Delil, 1984, 1995). Conventional single-phase thermal busses are mechanically pumped. They are based on the heat capacity of the working fluid, they are simple, well understood, easy to test, inexpensive and low risk. A very serious disadvantage is the required precise ordering of the modules in the thermal circuit. Changes in location or heat load of any individual module (station) will interfere with all other downstream stations. A prescribed, desired width of the isothermality band of the system (and its components) and the heat load determine the size of the pumping system (Delil, 1984). Consequently, for proper thermal control with small end-to-end temperature differences to limit radiator size and mass, they require heavy thick walled, large diameter lines and noisy, heavy, high power pumps, hence leading to enlargement of solar arrays and radiators. Alternatives for mechanically pumped single-phase systems are mechanically pumped two-phase systems, pumped loops accepting heat by working fluid evaporation at heat dissipating stations and releasing heat by condensation at heat demanding stations and at radiators, for the heat rejection into space. Such systems, relying on the heat of vaporisation, have small end-to-end temperature differences (operate nearly isothermally) for large variations in direction and magnitude of the heat exchange with the individual payloads. The pumping power is reduced by orders of magnitude (as compared to single-phase systems), thus minimising radiator and solar array sizes. The basic difference between mechanically pumped single-phase (caloric heat transport by the liquid) and two-phase systems (transport by latent heat of evaporation/condensation). This implies for dissipating stations in series in a single-phase system a temperature increase in the downstream direction of the loop. For two-phase systems, with evaporators in series, it means an increase of the vapour quality in the downstream direction, accompanied by a (usually small) decrease of the saturation temperature. A two-phase thermal bus can serve several modules by, depending on operating conditions of any particular module, extracting heat from or dumping heat into it. Components can be coupled to it to transfer heat from hot to cold regions. The ordering of modules in the circuit is hardly important and certainly not crucial. The stations can be arranged in a pure series (Fig. 1), a pure parallel (Fig. 2), or in a hybrid configuration, being a combination of parallel and series. As compared to the parallel concept, the series concept (originally an ammonia, serial thermal bus was planned to be the central thermal management system of the Space Station) has the advantage of simplicity and shorter total piping length. But it has the disadvantage of a larger pressure drop (unless a larger piping diameter is chosen), some (minor) restrictions with respect to the sequence of the stations in the loop, and somewhat more complexity with respect to modularity. The advantage of the parallel concept is the modular approach, in which branches with dissipating stations (evaporators/cold plates) or heat demanding stations (condensers/ radiators) simply can be added or deleted. But it also has the drawbacks of the tubing length, and of the complex feedback control system to adjust the vapour quality of the two-phase mixture in the exiting line of each cold plate. The latter control system is necessary to keep these mixture qualities close to a certain, chosen value in order to guarantee the proper performance of the thermal bus, by preventing system instabilities/oscillations.

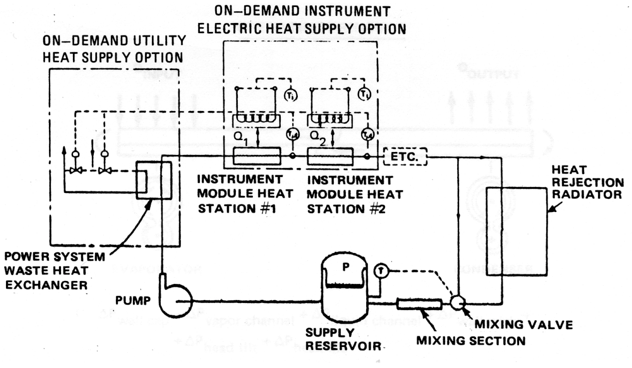

FIGURE 1. Schematic of a Mechanically Pumped Two-Phase Thermal Bus Series Configuration (Almgren, 1981).

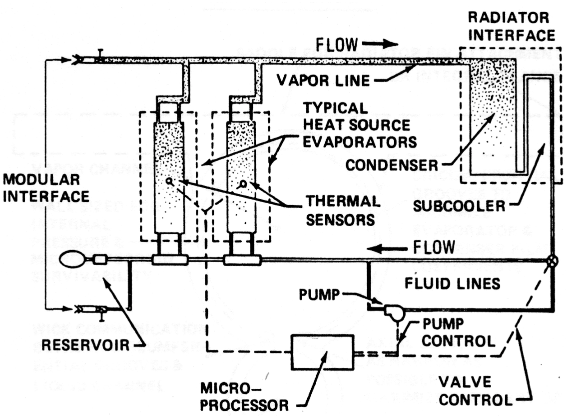

FIGURE 2. Schematic of Mechanically Pumped Two-Phase Thermal Bus Parallel Configuration (Haslett, 1983).

Most important issues in developing two-phase thermal busses were formulated in the early 80's (Oren, 1981; Stalmach, 1982; Haslett, 1983; Delil, 1984). Though they focused on developments for Space Station and other manned/ unmanned Space Platforms, their outcomes can be usefully applied to develop other dedicated thermal control systems. The important general and more detailed issues can be summarised by:

- Evaluation of candidate techniques and identification and generation of promising thermal utility/bus concepts.
- Comparison of promising concepts with respect to mass, sizing, complexity, reliability, required redundancy (to meet lifetime and maintenance specifications).
- Identification of critical items for the three principle elements of two-phase thermal management systems.

These three elements are:

- The transport system or thermal bus, which can be pure parallel, pure series, or hybrid.
- Radiators, which can be direct condensation radiators or indirect heat pipe radiators.
- Heat exchangers between the various instruments/modules and the thermal bus: Via a cold plate or a direct fluid coupling, via a temperature-controlled enclosure, via a self-contained instrument fluid loop/cold plate configuration.

Major critical items were called to be: The development of reliable mechanical and capillary pumps, and getting a better understanding of two-phase flow and heat transfer in micro-gravity. These aspects of two-phase technology development issues were investigated in the last 17 years, by NLR or with NLR involvement. An overview (Delil, 2001), containing more than 100 references to relevant NLR publications, summarises these NLR activities that include research on:

- The impact of gravity level and direction on two-phase flow and heat transfer.
- Thermal/gravitational modelling and scaling of two-phase heat transport systems and system components.
- Modelling of the two-phase pressure drop as a function of the vapour quality.
- The development of two-phase (R114, NH_3, ethanol, and CO_2) test rigs for experimentation and calibration of components developed (vapour quality sensors, a high-efficiency low pressure drop condenser, (in)direct radiators.
- Development and testing of two-phase heat transport systems for the in-orbit demonstration of two-phase technology, and the evaluation of flight results: ESA’s In-Orbit Technology Demonstration TPX (Delil, 1995) and the Loop Heat Pipe Flight eXperiment (Bienert, 1998), conducted by a team led by Dynatherm, consisting of the Naval Research Laboratory and two USAF Laboratories, BMDO, three NASA Institutes, Hughes Space & Communications, and NLR.

Two-phase thermal control systems have reached a certain level of maturity and they are becoming more and more accepted as reliable heat transport systems. However, the design of a two-phase flow loop is still rather difficult and cumbersome due to the character of two-phase single-component flow dynamics and heat transfer. In the two-phase lines of mechanically pumped loops and in the condenser of any two-phase loop, the flow pattern dependent heat transfer is of great importance for the definition of a particular thermal management system.

Two very important near-future mechanically pumped two-phase heat transport system applications are:

- The two-phase ammonia thermal control system of the Russian segment of the International Space Station, ISS (Grigoriev, 1999; Cykhotsky, 1999; Leontiev, 1997).
- The hybrid two-phase carbon dioxide thermal control loop of the AMS-2 Tracker Thermal Control System (Delil, 2001). AMS-2, the Alpha Magnetic Spectrometer experiment planned for a five years mission as attached payload on ISS, is an international experiment searching for anti-matter, dark and missing matter. AMS-2, an improved version of AMS-1 flown on STS 91, consists of different particle detector systems, one is the Tracker.

Concerning this Tracker Thermal Control System (TTCS) it is remarked that:

- In mechanically pumped two-phase loops, the flow pattern dependent heat transfer coefficient for convective flow boiling is reported to be between say 4 and 5 $kW/m^2.K$ (Carey, 1992). This is not true for refrigerants (to be used in the TTCS) at qualities below 0.15 for which the value can increase to say 20 $kW/m^2.K$ at qualities of less than 0.03 (Kandlikar, 1989). Data from experiments with CO_2 in small diameter tubes confirm this (Pettersen, 2000). The above implies that a mechanically pumped system has to be designed such that any evaporator exit quality is below 0.15 (preferably even much lower) for efficiency reasons.
- In the case of very lengthy lines in mechanically pumped two-phase loops the pressure (saturated temperature) gradient has to be kept small to guarantee a small end-to-end pressure (saturated temperature) difference to meet the requested isothermality, and to keep the evaporator exit vapour quality below 0.15, as in flowing refrigerants the vapour quality usually increases with pressure decay (Delil, 1992). Ethane is an exception: Quality increases below say 0.7, but decreases above 0.7. This issue (called flashing) will be discussed in a later chapter, since it is the one of the crucial differences between single- and two-component two-phase flow.
- A dedicated hybrid two-phase loop configuration will guarantee both the required isothermality and quality range.

Alternatives for mechanically pumped systems are capillary pumped systems, using surface tension driven pumping of capillary evaporators, to transport (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 working fluid for capillary-pumped two-phase loops also. Two systems can be distinguished: the western-heritage Capillary Pumped Loop CPL (Stenger, 1966) and the Russian-heritage Loop Heat Pipe LHP (Maidanik, 1995). Active control of the set point temperature of any two-phase loop can be realised by control of the temperature of the reservoir or the 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 (power to be transported) or in heat sink (radiator temperature).
Because of performance advantages and unique operational characteristics CPLs and LHPs are planned for several future spacecraft missions, not only low-orbit or geo-synchronous satellites, but also for missions to planets (Butler, 1999). Examples are the American Earth Observation Satellite EOS-AM, the European earth observation spacecraft ATLID, the French technology demonstration satellite STENTOR, the Russian spacecraft OBZOR, the Hubble Space Telescope retrofit mission, the US COMET spacecraft, the Hughes 702 satellites, and other commercial geo-synchronous communication satellites. However, since two-phase flow and heat transfer is essentially different in earth gravity, lunar gravity, Mars gravity and micro-gravity, the two-phase heat transport system technology has to be demonstrated in space. Therefore several in-orbit experiments were carried out. Examples are: ESA’s Two-Phase eXperiment TPX I & (Delil, 1995), NASA’s CApillary Pumped Loop experiments CAPL 1&2 (Butler, 1995), the Loop Heat Pipe Flight eXperiment LHPFX (Bienert, 1998), the all US Loop Heat Pipe with Ammonia ALPHA, the Cryogenic Capillary Pumped Loop CCLP (Hagood, 1998), and the Two-Phase Flow experiment TPF (Ottenstein, 1998). Other experiments are planned for future flights. Development supporting, scientific, experiments were also carried out in the last decade, within research programmes concentrating on the physics of microgravity two-phase flow and heat

transfer. Experiments were done in drop towers, during Microgravity Science Laboratory missions on STS, and during reduced-gravity aircraft flights. But the usefulness of the results of most of these experiments is unfortunately only of limited use for two-phase heat transport systems developments, since they suffer from the severe restriction of short experiment duration, or as they pertain to two-component not to single-component two-phase flow.

TWO-PHASE FLOW & HEAT TRANSFER ISSUES

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. Flow-related (hydraulic) two-phase, single-component and two-component flows are described by the same mathematical model equations. Therefore results of calculations and experiments in one system can be used in the other, as long as they pertain to flow phenomena only, hence there is no heat transfer.

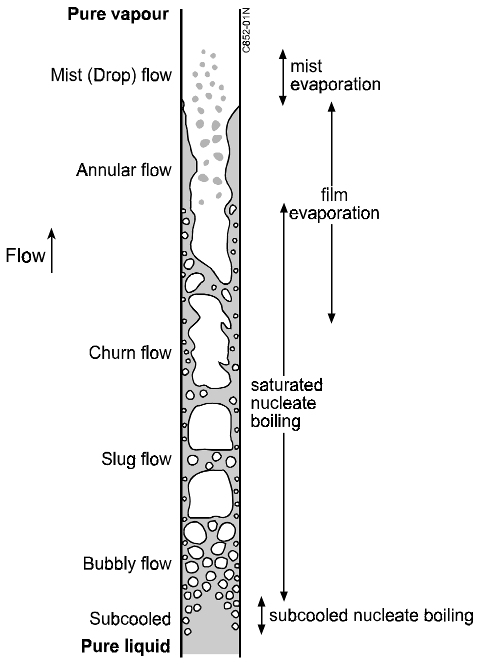

FIGURE 3: Flow Patterns/Boiling Mechanisms, for Up-Flow in a Vertical Line on Earth.

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 can not 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 dedicated two-phase single-component experiments. Though liquid-vapour flows obey all basic fluid mechanics laws, their constitutive equations are more numerous and more complicated than the equations for single-phase flows. The complications are due to the fact that inertia, viscosity and buoyancy effects can be attributed both to the liquid phase and to the vapour phase, and also due to the impact of surface tension effects.

Flow Pattern Issues

An extra, major, complication is the spatial distribution of liquid and vapour, the so-called flow pattern. Figure 3 schematically shows the various flow patterns and boiling mechanisms for up-flow in a, radially heated, vertical tube evaporator: The entering pure liquid gradually changes to the exiting pure vapour flow, via the main (morphological) patterns for bubbly, slug, annular and mist (or drop) flow. The hybrid flow patterns, bubbly-slug, slug-annular (churn), and annular-wavy-mist, can be considered as transitions between main patterns. Figures 4a,b show the various flow patterns for horizontal evaporating and condensing flow in a gravity field. It is obvious that each flow pattern (regime) requires its own mathematical modelling. In addition, transitions from one pattern to another are to be modelled. Within a regime, further modelling refinement can be based on extra criteria: The relative magnitudes of the various forces or the difference between laminar and turbulent flow. Various textbooks on two-phase flow and heat transfer (Wallis, 1969; Carey, 1992), derive and discuss in the constitutive equations for the various (main) flow patterns, focusing on one-dimensional liquid-vapour (or gas) flow. Such one-dimensional models, especially for homogeneous (bubbly and mist) flow, and 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 levels in various space environments also are circular symmetric. Writing the 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 for the creation of flow pattern maps, like the maps in the figures 5 to 7. Alternatively one can derive dimensionless numbers by dimension analysis or similitude in

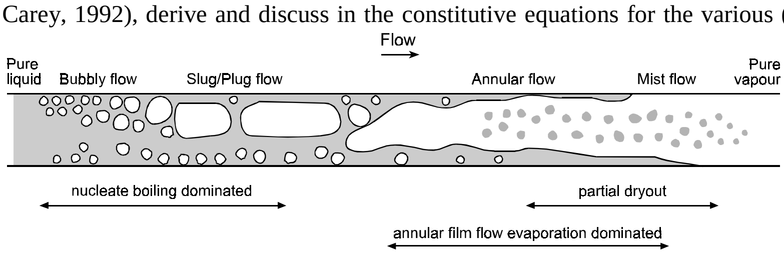

FIGURE. 4a. Flow Patterns for Horizontal Evaporation in a Gravity

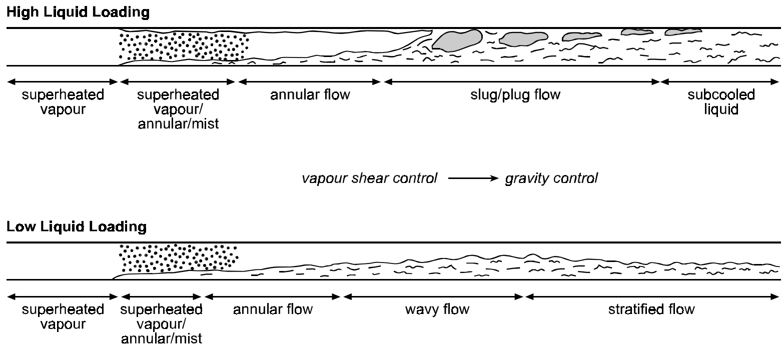

FIGURE. 4b. Flow Patterns for Horizontal Condensation in a Gravity Field.

engineering, discussed in specialised textbooks (e.g. Murphy, 1950). Figure 5 (Oshimowo, 1974) shows a map in a normalised form. Figure 6 (Carey, 1992) shows how a boiling trajectory crosses different flow regimes. By combining cross-sections of figures like 7a,b (Hamme,1997) one can create flow pattern maps for a chosen g-level. A comparison of the latter two maps and maps produced during the Cyrene experiment ((Lebaigue, 1998) and TPX I (Delil, 1995) indicates that they partly contradict each other. A comparison between the figures 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 due to either by different working fluids used (R12/ammonia/ammonia) or the different inner line diameter (10.5 mm/4.7 mm/4.93 mm). More data are to be gathered to draw final conclusions on this.

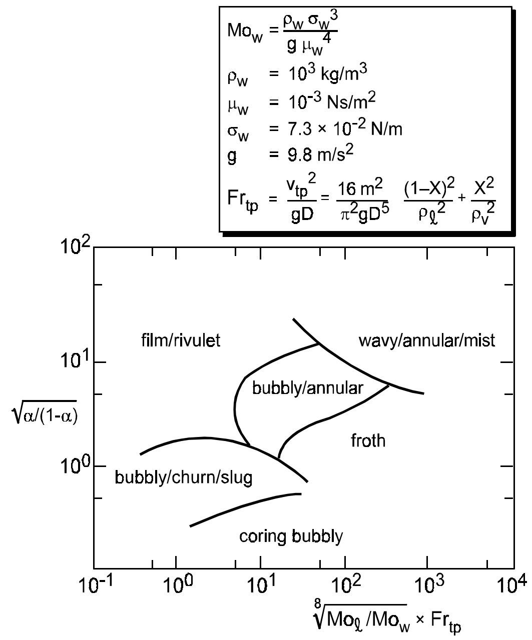

FIGURE 5. Flow Pattern Map for Vertical Co-Current Flow.

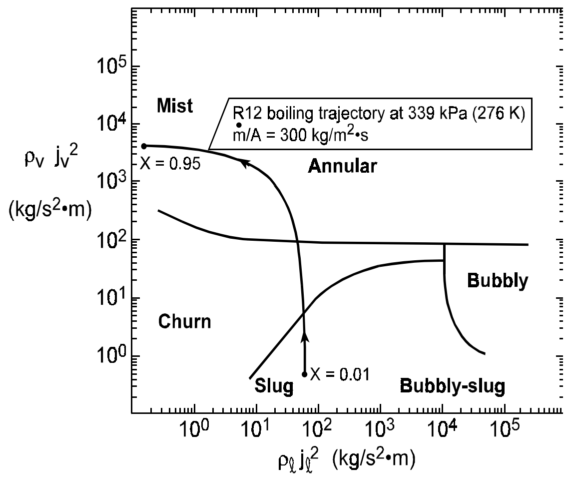

FIGURE 6. Flow Pattern Map for Vertical Flow.

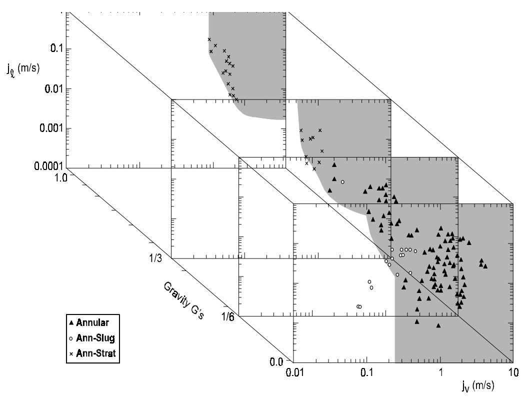

FIGURE 7a. Annular Flow: Gravity Dependent 3-D Map.

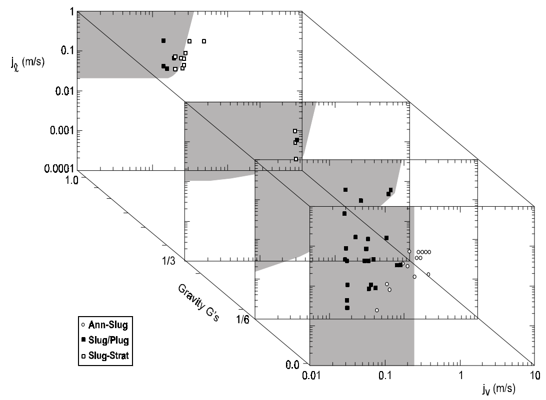

FIGURE 7b. Slug/Plug Flow: Gravity Dependent 3-D Map.

Thermal-Gravitational Modelling & Scaling Issues

Development supporting theoretical work, like thermal-gravitational modelling and scaling of two-phase heat transport systems (Delil, 1991, 1998), is being done to better understand the impact of gravitation level on two-phase flow and heat transfer phenomena, provide means for comparison and generalisation of data, and to develop tools to design spaceoriented two-phase loops (components), based on terrestrial tests, to reduce costs. The main goal of the scaling 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 proved to 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), and to define in-orbit experiments 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, to reduced g (0.16 g for Moon base, 0.4 g for Mars base systems), and to super-g values, pertaining to larger planets or rotating spacecraft.

Similarity considerations (Delil, 1991) led to the identification of 18 dimensionless numbers (so-called π-numbers) relevant for thermal gravitational scaling of mechanically and capillary pumped two-phase loops. These 18 π-numbers are listed in the first column of the table below. There is perfect similitude between model and prototype if all dimensionless numbers are identical in prototype and model. Only then scaling is perfect. It is evident that perfect scaling is not possible for two-phase flow and heat transfer: the phenomena are too complex, the number of important parameters or π-numbers is too large. Fortunately also imperfect (distorted) scaling can give useful results (Murphy, 1950). Therefore a careful estimation of the relative magnitudes of the different effects is required. Effects that can be identified to be unimportant for the identity requirement of some π-numbers superfluous for the problem considered.

A first step in a practical approach to scale two-phase heat transport systems is identification of important phenomena, to obtain π-numbers for which identity in prototype and model must be required to realise perfect scaling according to the so-called Buckingham pi theorem (crucial in similarity considerations). Distortion will be permitted for π-numbers pertaining to less important phenomena. Important phenomena and the relevant π-numbers will be different in different parts of a system. The relevance of the π-numbers in the various loop sections is indicated by • in the table (π-numbers for thermal gravitational scaling of two-phase loops), given earlier in this section. The best scaling approach is to choose combinations of π-numbers that optimally suit the problem under investigation.

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	•	•	•	•	•
$\pi_2 = Re_l = (\rho vD/\mu)_l$ = 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 = ρ_v/ρ_l			•	•	•
π_8 = viscosity ratio = μ_v/μ_l			•	•	•
$\pi_9 = We_l = (\rho v^2 D/\sigma)_l$ = inertia/surface tension			•	/•	•
$\pi_{10} = Pr_l = (\mu Cp/k)_l$		•	•		•
$\pi_{11} = Nu_l = (hD/k)_l$ = 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			•	/•	•
$\pi_{16} = Ma = v/(\partial p/\partial \rho)_s^{1/2}$			•	•	•
$\pi_{17} = (h/k_l)(\mu_l^2 g)^{1/3}$			•		•
$\pi_{18} = L^3 \rho_l^2\ g\ h_{lv}/k_l \mu_l (T-T_o)$			•		•

With reference to detailed discussions (Delil, 1991, 1992, 1998) it is remarked that, considering only the identity of Morton number and the identity of We/Fr for prototype and scale model, the following conclusions can be drawn from figures 8 and 9, showing the temperature dependence of $g.Mo_l = \rho_l.\sigma^3/\mu_l^4$ and $(\sigma/\rho_l)^{½} = D.g^{½}/(We/Fr)^{½}$:

- 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 scale ratios follow from reading the with these temperatures corresponding (σ/ρ_l)-values in figure 9, 2.5 : 4.5 : 8.4 : 4.2 : 3.0 : 5.0 : 3.6.
- Second, figure 8 also shows that scaling a high-pressure (say 110 °C) ammonia system can be done by a low-pressure (say -50 °C) ammonia system, which might be attractive for safety reasons or will to reduce the impact of earth gravity in vertical two-phase sections. It follows from figure 9 that the geometric scaling ratio between high-pressure prototype and low-pressure model (both characterised by $\rho_l\,\sigma^3/\mu^4_l = 2.10^{12}$ 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.
- Fourth, the figures 8 and 9 illustrate also that “fluid to fluid” scaling 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 g) of non-horizontal lines in the terrestrial model may lead to almost perfect scaling.

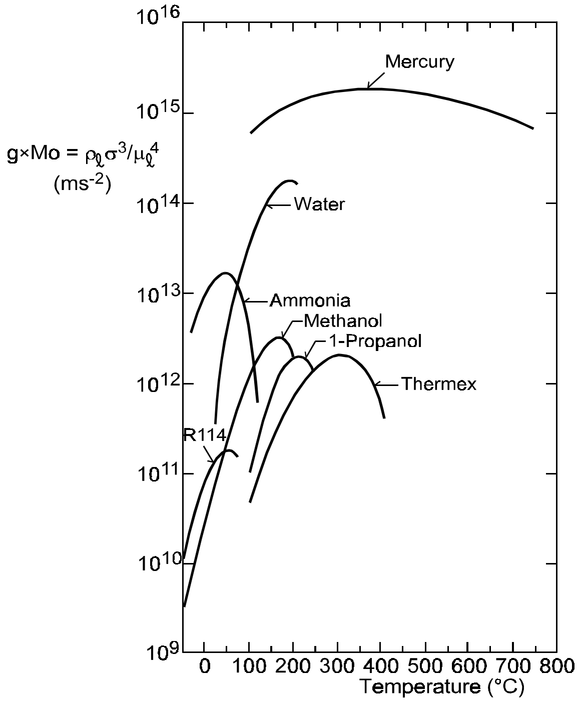

FIGURE 8.. $\jmath_l.\sigma^3/\mu_l^4$ Versus Temperature for Various Fluids.

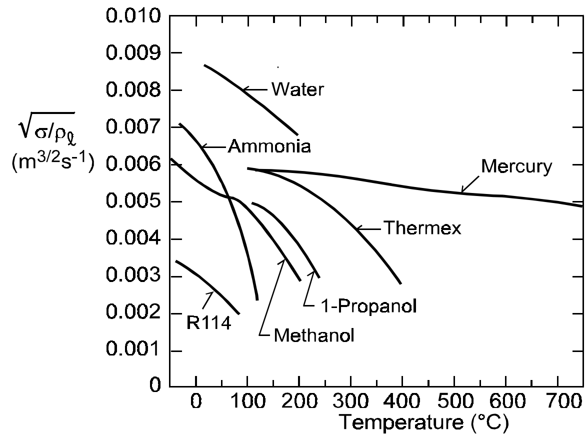

FIGURE 9. $(\mathring{u}/\jmath_l)^{½} = D.g^{½}/(We/Fr)^{½}$ Versus Temperature for Various fluids.

Pressure Drop

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, extensively discussed in literature (Delil, 1991, 1992, 1998) are based on an elaborate journal article (Soliman, 1968). The total local (local position z-dependent) pressure gradient for annular flow is the sum of friction, momentum and gravity gradients. Calculations show that for ammonia at 25 °C the gravity constituent overrules the sum of the two other constituents at vapour qualities below 0.8. At -25 °C this overruling holds for vapour qualities below say 0.4. This confirms the statement, that room temperature low-gravity behaviour can be simulated by terrestrial tests at far lower temperatures. 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 (Delil, 1992 a,b). 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 (Delil, 1994). 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. To assess the impact of saturation temperature on condensation, similar curves were calculated for two other temperatures, 243 K and 333 K and the parameter values given above (Delil, 1992). The 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. It confirms 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 (Delil, 1992) that: A factor 50 in power, 25 kW down to 500 W, corresponds in a zero gravity environment to a relatively minor reduction in full condensation length, i.e. from 600 D to 400 D (9.5 to 6.5 m); Under earth gravity conditions, power and full condensation length are strongly interrelated: from L_c = 554 D at 25 kW to only 19 D at 500 W; The gravity dependence of the full condensation length decreases with increasing power, until differences vanish at 1 MW condenser choking.

As the model developed is for annular flow, it is worthwhile to investigate the impact of other flow patterns inside the condenser duct (mist flow at high quality, slug and bubbly flow at low quality and wavy-annular-mist in between).

Flashing

The effect of flashing (mixture quality change) by other mechanisms than heat addition or withdrawal, can be illustrated as follows:

- In case of steady state, adiabatic two-component flow through a tube, the gas flow rate remains constant in each cross-section hence the entering and exiting gas flow rates are equal. The same is valid for the liquid flow rate. Consequently the quality remains constant. The effect of the pressure gradient along the tube (needed to overcome frictional losses) is only an increase of the void fraction (the relative volume of the gas) in the down-flow direction.
- In case of steady state, adiabatic single-component flow through a tube, only the total mass flow rate remains constant in each cross-section, the quality changes along the flow path. For most fluids this means quality increase. Ethane is an exception, as illustrated by its Mollier chart (Fig. 10). The isentropic (reversible) flow path indicated at the left side shows a quality increase from 0.1 to 0.2, caused by the pressure (temperature) decay. But the flow path at the right side shows a quality decrease from 0.9 to 0.8. Around 0.7 the quality remains constant. This effect, called flashing, is more pronounced in the more realistic case of non-reversible flow conditions.

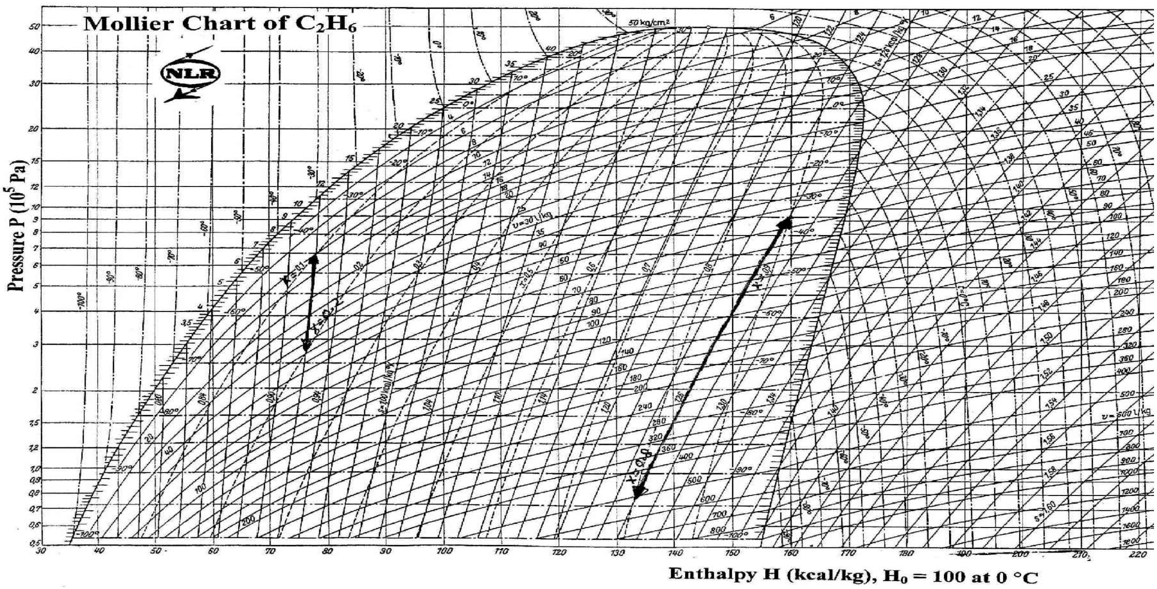

FIGURE 10. Mollier Chart of Ethane (1 kcal = 4.17 kJ).

CONCLUSIONS

The background of the developments is described. Critical issues are discussed. The main differences between single-component (liquid and its saturated vapour) and two-component (liquid and gas) flow and heat transfer were already mentioned in the preceding text. They can be summarised by:

- The heat transfer process in two-component systems is based on caloric heat only, the mechanisms are restricted to conduction and convection. Heat transfer in single-component systems is far more efficient, as the transport is not only by caloric heat but also by the larger contribution of latent heat (evaporation or condensation).
- If heat is added to liquid-gas flow the mixture temperature will increase in the down-flow direction. In case of heat withdrawal the mixture temperature will decrease. In case of single-component flow the temperature will always (in most cases only slightly) decrease in the down-flow direction, since the pressure drop needed for the flowing corresponds to a temperature drop of the saturated mixture.
- The effect of flashing, often not negligible in single-component systems, is completely absent in gas-liquid systems.

Flow pattern maps, created from two-component experiments, may be used for single-component system design. But in most cases these maps are created for properties of the two phases, which considerably differ from the actual single-component case. In other words, one shall be careful to use such maps.

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NOMENCLATURE

Bo	boiling number (-)
Cp	specific heat at constant pressure (J/kg.K)
D	diameter (m)
Eu	Euler number (-)
Fr	Froude number (-)
g	gravitational acceleration (m/s^2)
H	enthalpy (J/kg)
h	heat transfer coefficient (W/m^2.K)
h_{lv}	latent heat of vaporisation (J/kg)
j	superficial velocity (m/s)
L	length (m)
Ma	Mach number (-)
Mo	Morton number (-)
Nu	Nusselt number (-)
p	pressure (Pa = N/m^2)
Pr	Prandtl number (-)
Q	power (W)
Re	Reynolds number (-)
S	slip factor (-)
T	temperature (K) or (°C = K – 273.15)
v	velocity (m/s)
We	Weber number (-)
X	vapour quality (-)
z	axial or vertical co-ordinate (m)
α	vapour fraction (volumetric) (-)
Δ	difference, drop (-)
μ	viscosity (N.s/m^2)
σ	surface tension (N/m)
ϑ	thermal conductivity (W/m.K)
$\pi_{1, etc}$	dimensionless number (-)
ρ	density (kg/m^3)
ν	angle (with respect to gravity) (rad)

Subscripts: c = condenser l = liquid g = gravitation s = entropy v = vapour tp = two-phase w = water