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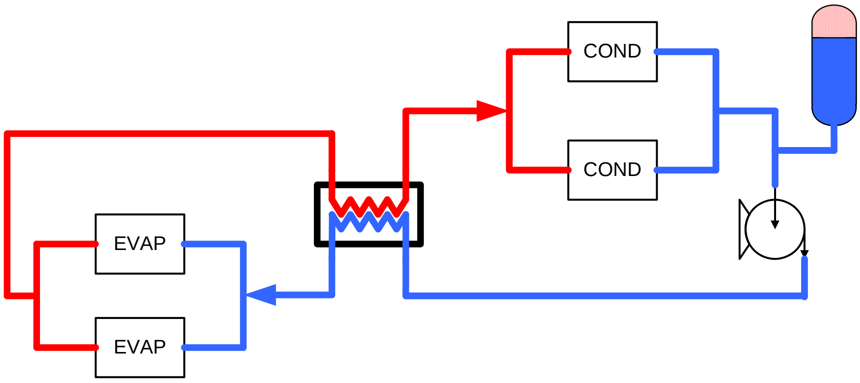
Executive summary

Benefits and Drawbacks of Using Two-Phase Cooling Technologies in Military Platforms



Problem area

The next generation military platforms will be equipped with more and more powerful sensors and avionics. The increasing power densities in electronic subsystems ask for more cooling power while survivability requirements limit the possibilities to extend or add cooling systems. This trend inevitably leads to thermal challenges which need to be solved. Two-phase heat transport systems make use of the fluid's latent heat as means of heat transportation. Implementation such systems in high-power applications can lead to improved thermal performance and mass reductions.

Description of work

In this article first an overview of the state-of-the-art two-phase heat transport systems is given. Then the advantages and disadvantages of two-phase heat transport systems are elucidated by recent examples in space and aerospace projects. Subsequently design guidelines are presented to define the applicability of two-phase technologies for land-air- space- and marine-based systems.

Results and conclusions

The article shows that rough design guidelines can be given for the applicability of the several two-phase systems for airborne, land-based and navy platforms. For future platforms development needs are defined needed for a more common implementation.

Applicability

The article is specifically useful for platform system engineers to select the right two-phase system for their specific platform and application.

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This paper is presented at the NATO AVT- Specialists' Meeting on System Level Thermal Management for Enhanced Platform Efficiency (NATO Unclassified) AVT-178/RSM-026 organized by the Applied Vehicle Technology Panel, Bucharest, Romania, 4-7 October 2010.

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Benefits and Drawbacks of Using Two-Phase Cooling Technologies in Military Platforms

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Increasing power densities in platform electronic subsystems lead to more common use of latent heat as means of heat transportation to make use of the large evaporation heat per mass unit working fluid. In this article first an overview of the state-of-the-art two-phase heat transport systems is given. Then the advantages and disadvantages of two-phase heat transport systems are elucidated by recent examples in space and aerospace projects. Subsequently design guidelines are presented to define the applicability of two-phase technologies for land- air- space- and marine-based systems. The article concludes with development needs for successful introduction of two-phase technologies in near future platforms.

SYMBOLS AND ABBREVIATIONS

CERN	*European Organisation for Nuclear Research*
CPL	*Capillary Pumped Loop*
FSHP	*Flat Swinging Heat Pipe*
HP	*Heat Pipe*
LHC	*Large Hadron Collider*
LHP	*Loop Heat Pipe*
MECLHP	*Multi Evaporator Condenser Loop Heat Pipe*
OHP	*Oscillating Heat Pipe*
SAR	*Synthetic Aperture Radar*
VELO	*Vertex Locator detector*
D	*Diameter [mm]*
M	*Heat Pipe figure of merit*
λ	*Latent heat of vaporization [J/kg]*
ρ_l	*Liquid density [kg/m^3]*
σ	*Surface tension [N/m]*
μ_l	*Dynamic viscosity liquid [N/m^{2}s]*
ΔT	*Temperature difference [K]*

INTRODUCTION

The next generation military platforms will be equipped with more and more powerful sensors and avionics. The increasing power densities in electronic subsystems ask for more cooling power while survivability requirements limit the possibilities to extend or add cooling systems. This trend inevitably leads to thermal challenges which need to be solved. Roughly two types of measures can be distinguished. The first type of measures aims to increase the cooling capacity to the environment. This approach is most practical for new platforms. A second measure better applicable to upgrades of existing platforms is to optimize the existing systems and fully exploit the capabilities. One of the focal points will be the reduction of the temperature drop between the dissipating electronics and the heat sink. A typical temperature drop along a thermal path is schematically shown in Figure 11 and Figure 22.

A reduced temperature drop allows to reject/transfer the dissipated heat at a higher temperature level to the overall cooling system or to the environment. This additional temperature margin can relax the overall cooling system requirements or add cooling margin for other systems.

To optimize a thermal design it is of importance to try to reduce each contribution. That is why lots of research is performed on thermal interfaces, more efficient heat exchangers and (new) high conductive materials. In parts of the thermal path a very effective way of temperature reduction can be two-phase heat transport. The possible benefit of two-phase heat transport systems in the thermal path is shown in Figure 22 (right), indicated in red. The overall temperature drop can be reduced considerably. This can reduce the size of the heat exchanger to the environment.

Two-phase heat transport systems make use of evaporation and condensation of fluids. As boiling and condensation occur both at the same saturation temperature the temperature drop between the hot and cold side is very small and only related to the pressure drop between hot and cold side (< 2 C).

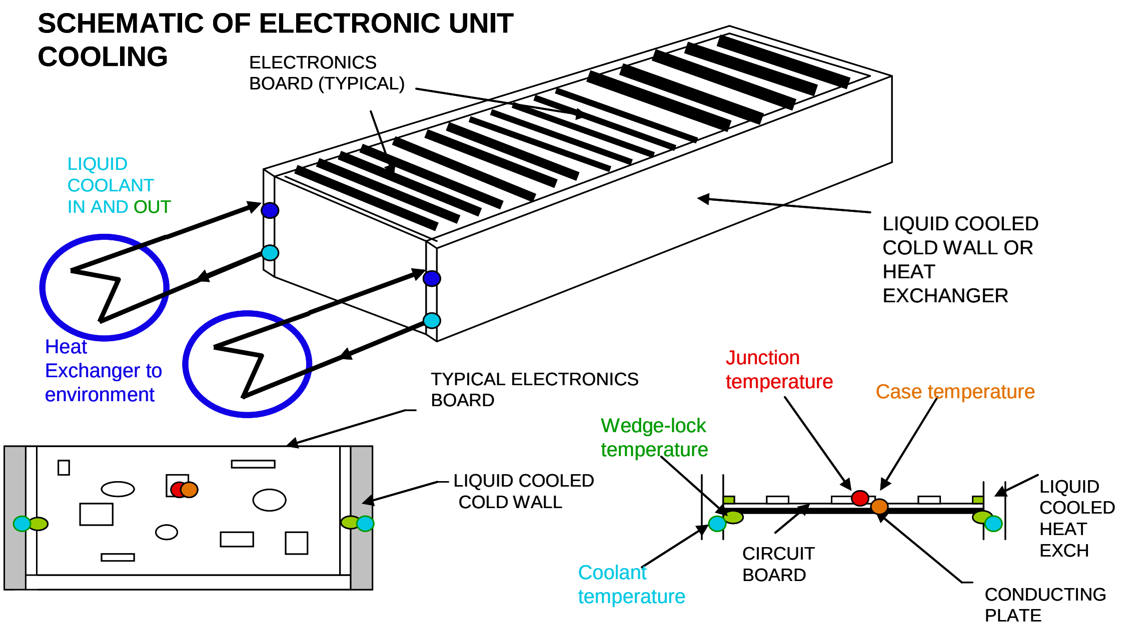


Figure 11: Typical Electronics Box with indicated thermal path.

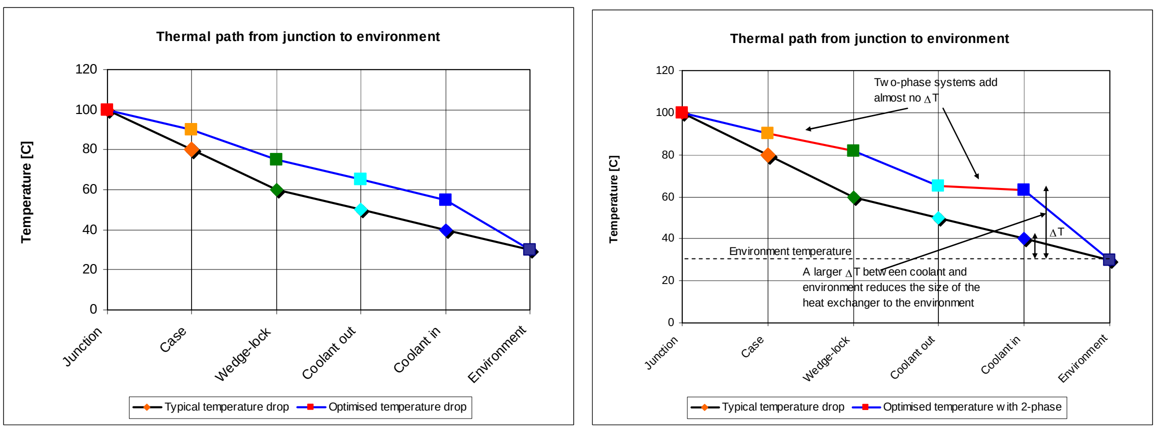


Figure 22: Typical temperature drop along thermal path (left): Typical temperature drop with implemented two-phase systems, (right).

Two-phase heat transport systems make use of the large evaporation heat per mass unit working fluid and therefore need only small mass flows. These benefits are of course at the cost of adding more complexity. In view of the upcoming thermal challenges, implementing two-phase systems will certainly be part of the solution strategy.

In this article the implications of implementation are further investigated. First an overview of the state-of-the-art two-phase heat transport systems is given. Then the advantages and disadvantages of two-phase heat transport systems are elucidated by recent examples in space and aerospace projects. Subsequently design guidelines are presented to define the applicability of two-phase technologies for land- air- space- and marine-base systems. The article concludes with development needs for successful introduction of two-phase technologies in near future platforms.

OVERVIEW OF TWO-PHASE HEAT TRANSPORT SYSTEMS

Heat Pipes

The most well-known two-phase heat transport system is a heat pipe. A heat pipe is a closed pipe filled with vapour and liquid of a dedicated working fluid. On the walls of the heat pipe a capillary structure is implemented (axial grooves and/or a capillary wick) and therefore contains the liquid in the pipe.

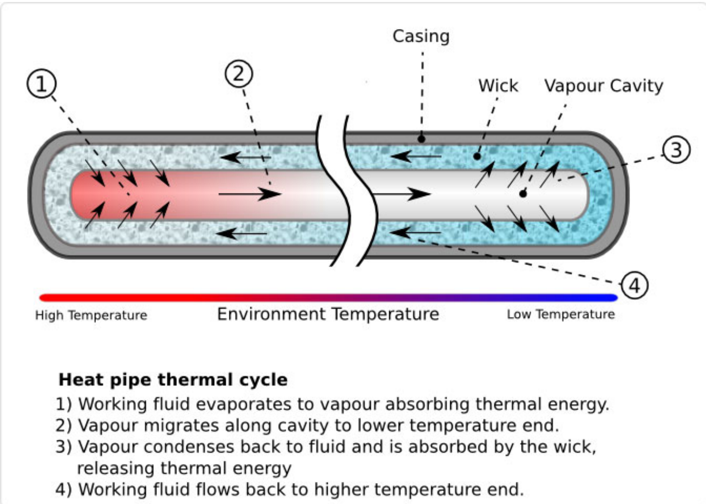
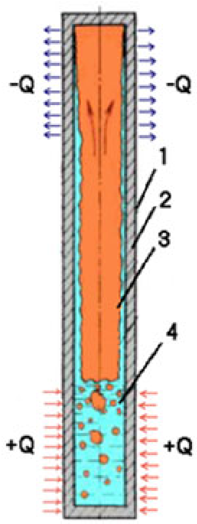


Figure 33: Heat pipe Principle (Source: internet).

On one end of the heat pipe the dissipating electronics are attached. The dissipated heat evaporates the liquid, and absorbs the heat. By the creation of the additional vapour the vapour flows to the other side of the heat pipe where it condenses and subsequently dumps its heat. The liquid is pumped back by capillary action closing the loop. Because the evaporation and condensation “occurs” at the same temperature the temperature drop over the pipe is only a few degrees induced by the vapour pressure drop over the pipe. Heat pipes are widely used in terrestrial design (laptops, CPU-cooling) and spacecraft thermal design (heat pipe radiators). The main drawback of heat pipes is their poor performance when used against gravity.

Thermosyphons



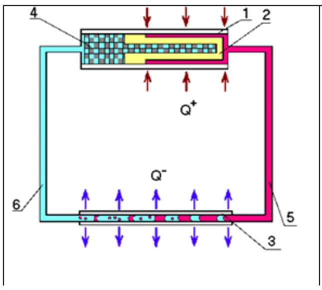
1. Container
2. Axial grooves (optional)
3. Vapour
4. Boiling liquid

A special type of heat pipe is the thermosyphon. A thermosyphon is a heat pipe which uses gravity to transport the liquid. The heat is therefore always collected and evaporated on the bottom side and condensed at the top side where the heat is removed by forced cooling or radiation. The liquid flows back to the bottom to close the loop. Thermosyphons are for example used in mountainous areas to keep roads or railways snow-free. In space it is proposed for cooling of lunar based equipment The design is straightforward and robust, however even more dependent on orientation than a normal heat pipe.

Figure 44: Thermosyphon principle (Courtesy: Kiev Research and technology centre).

Loop Heat Pipes (LHP) and Capillary Pumped Loops (CPL)

The Loop Heat Pipe (LHP) and Capillary Pumped Loop (CPL) are more advanced types of heat pipes. These loops separate, concentrate and optimize the capillary pumping action in the evaporator section (See Figure 55).



1. Evaporator (EV)
2. Wick
3. Condenser
4. Compensation chamber (CC)
5. Vapour transport line
6. Liquid transport line

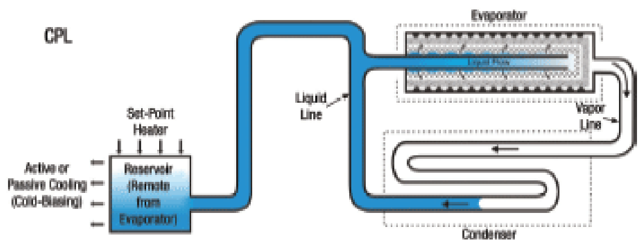


Figure 55: LHP (left) and CPL (right) principle (Courtesy: Swales).

LHP's and CPL's can therefore provide more pumping power and work to a certain extent (few meters) against gravity. Main difference between the LHP and CPL is that the CPL has a separate temperature controlled reservoir which can dictate the saturation temperature in the evaporator and therefore set the pay-load temperature. In a LHP the reservoir (or compensation chamber) and evaporator are combined. This gives an advantage in starting up over the CPL as the wick of the evaporator is wetted in all conditions. Drawback of the LHP is the variation in pay-load temperature with pay-load power. Because of their robustness LHP designs are used extensively in satellite design and ground-based applications and also in specific applications for fighter aircraft (F-16 and UAV's). The drawback of LHP's and CPL's is the difficulty to extend them to multi-evaporator systems. Lots of research has been performed [1,2] which resulted in improved designs but it did not lead yet to implementations. In Figure 66 an ammonia-filled MECLHP with two parallel evaporators and two parallel condensers is shown as tested at NLR.

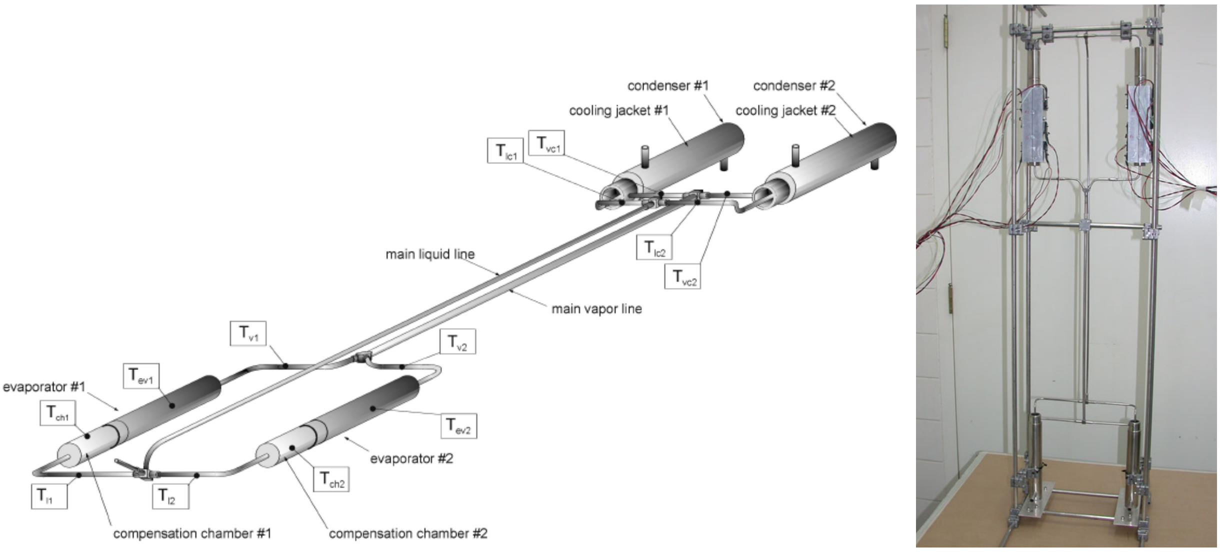


Figure 66: Multi-evaporator-condenser LHP (manufactured by Institute of Thermal Physics, Ural Branch Russian Academy of Sciences, Russia tested @ NLR [1]).

Two-Phase Mechanically Pumped Loop (2Φ-MPL)

Instead of capillary pumping forces also a mechanical pump can be implemented in a two-phase loop. The schematic is shown in Figure 77. Main components are an accumulator, an evaporator and a condenser section, a heat exchanger (optional) and of course a pump. The accumulator is temperature- or pressure controlled and sets the evaporation temperature. Although the pump adds complexity and a life-time issue this system has considerable advantages.

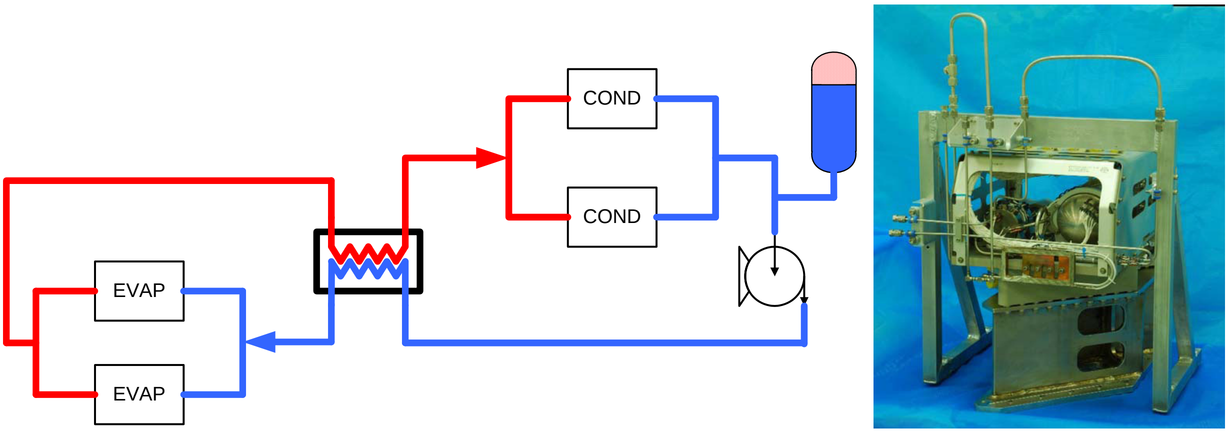


Figure 77: Principle of 2Φ-MPL's (left) TTCS Two-phase pumped loop box (right).

The system is more flexible in evaporator and condenser design and has the possibility to locate the temperature control at a distant location (up to 100 meters) far away from the to be cooled item or instrument. Further it has the possibility to provide thermal control for distributed dissipative elements and it has a reliable straightforward operation and start-up. Because of these advantages a two-phase pumped loop was selected as the only feasible concept for the Tracker Thermal Control System (TTCS) of the AMS02 [4] experiment, a development lead by NLR [5,6,7]. The system will fly aboard the STS-134 and will be installed on ISS for a 15 year mission. The CO_2 system provides <0.2 ˚C temperature stability for the Tracker pay-load. The same concept is now also implemented in the Large Hadron Collider VELO detector [7] at CERN in Geneva and is planned for updates of the CERN ATLAS and CMS detectors. In view of the pump electronics mass 2Φ-MPL's are most suitable for navy and land-based military applications requiring accurate temperature control (e.g. active antennas). When smaller pumps with less bulky electronics are developed 2Φ-MPL's will also become attractive for air-based and satellite platforms. The first developments have already been started at ThalesAlenia Space [8].

Vapour Chambers

A less common type of heat pipe is the vapour chamber. In fact it is a flat heat pipe with a very small length over diameter ratio.

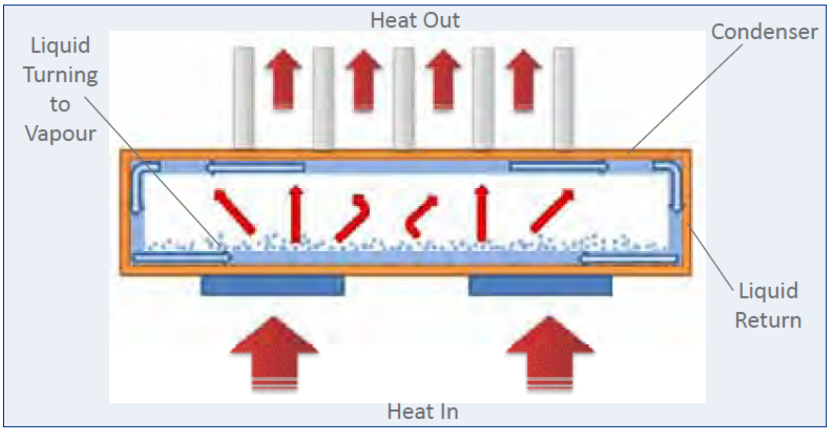
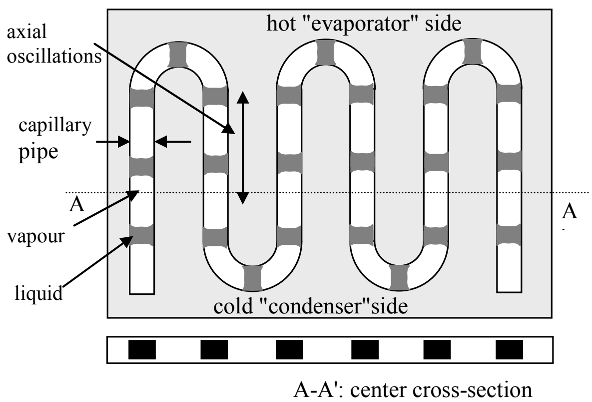


Figure 88: Schematic of a vapour chamber (Courtesy: Thermacore).

Vapour chambers are used to increase heat transfer of heat sinks, for example to enhance CPU- or power electronics cooling. Vapour chambers are gravity dependent but flat versions or types with the right wick design can be ruggedized to withstand acceleration forces. This type of heat pipes are mainly used as heat spreader but can also be used for accurate (mK-level) temperature control.

Oscillating Heat Pipes (OHP)

A special two-phase system is the Oscillating Heat Pipe (OHP) [9,10] shown in Figure 99.



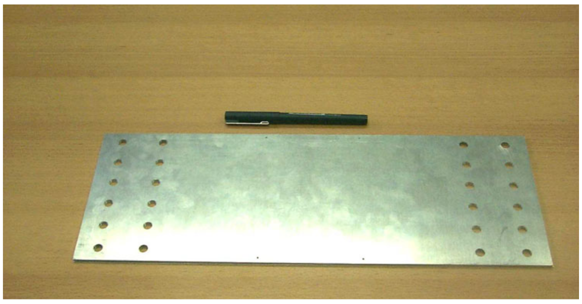


Figure 99: OHP Principle (left) and a Flat Swinging Heat Pipe (FSHP) prototype (right).

Despite its name the OHP-principle is completely different from a heat pipe. The OHP is in fact an undulating capillary pipe (D = 0.5-2 mm) filled with liquid plugs and vapour slugs from the same working fluid. The OHP-operation relies on the oscillating of the slugs and plugs. The oscillating movement is induced by evaporation of liquid [11]. The evaporation expansion causes the adjacent liquid slugs to accelerate. The resulting oscillatory motion dynamics is governed by inertia forced by sudden expansions at the multiple heat sources on the hot side of the OHP. Heat is transported from the hot to the cold side mainly by the sensible heat of the liquid, therefore the temperature drop along an OHP is approximately 10-15 K and much larger than for a classical heat pipe. An interesting feature of the OHP is however that it can operate under high g-loads [12]. In Figure 99 (right) the NLR developed Flat Swinging Heat Pipe (FSHP) is shown which has been tested upto 8.4g without decrease in performance. Until now OHP's are only implemented in laptops and for space applications further developed as heat switch [13].

ADVANTAGES AND DRAWBACKS OF TWO-PHASE HEAT TRANSPORT SYSTEMS

To elucidate where the above listed two-phase systems are best suited, first the disadvantages are discussed. Main general disadvantages of two-phase systems for use in military platforms are:

- Gravity dependence
- Inflexibility of the interface to the pay-load (evaporator)
- Use of toxic working fluids (ammonia, ethanol, methanol)

The gravity dependence makes the use of general heat pipes and thermosyphons only possible in gravity assisted and zero-gravity environments and therefore unsuitable for air-based platforms. Some special heat pipe designs are available but the transport length is limited or in case of OHP's the performance is much lower. Normal heat pipes are however perfectly suited for satellite applications and are extensively used in satellite thermal radiator design. LHP's and CPL's can withstand high-g forces and are therefore also suitable for aircraft applications. Drawback is the rather bulky evaporator section which has impact on the pay-load interface.

This inflexibility of pay-load interface is the second general drawback of two-phase heat transport systems. Evaporation sections of heat pipes themselves are flexible enough and are implemented in an extensive amount of satellite, marine and ground-based designs. The concentrated LHP and CPL evaporator sections are however bulky and limited in length. Therefore sensors or other payloads with distributed elements are not easy to cover by one or two LHP evaporators. In satellite applications combined HP-LHP networks are successfully used to cope with this problem at the cost of extensive test campaigns. In aircraft design heat pipe networks are not feasible in view of the gravity problems, therefore only single LHP evaporators are used for concentrated payload sensors. For pay-load sensors with more distributed electronics the 2Φ-MPL's are a feasible option as the evaporator can facilitate multiple widespread sensors with only small diameter (3-8 mm) tubing. The 2Φ-MPL's bulky accumulator and pump section can be located far away from the pay-load. This makes 2Φ-MPL specifically suitable for implementation in existing pay-loads for platform upgrades.

In that case the two-phase systems also have to compete with ram air-cooling or single phase mechanically pumped systems. Among many advantages the toxic properties of the most common two-phase working fluids are a point of concern. Water and ammonia are by far the two best two-phase working fluids. Problem of water is freezing and water was therefore rejected for most military applications because of the operational requirements at low temperature. Recently however a first ruggedized two-phase water system is implemented in a satellite design. This ruggedization implies additional control heaters to prevent the water from freezing. Ammonia is however more commonly used in satellite HP and LHP systems. Ammonia is however not preferred in large quantities in terrestrial, navy or aircraft applications. Alternative working fluids are available but at the cost of performance.

Advantages

Two-phase systems would not be so popular if there were no clear benefits. The most well-known advantage is the mass effectiveness. As the latent heat of most fluids is at least one or two orders larger than the sensible heat, a two-phase heat transport system can transport considerably more heat per fluid mass resulting in a lower system mass and smaller cooling tubes. This led to the extensive application of heat pipes and loop heat pipes in spacecraft and aircraft design as in these platforms mass is a driving requirement.

The second clear but less well-known advantage is the high temperature stability of two-phase heat transport systems. As two-phase systems make use of evaporation (boiling) of a liquid and boiling always happens at one temperature two-phase systems can perfectly control delicate pay-loads on a stable temperature (e.g. active antennas and radar application). This same advantage can be used to reduce the temperature drop from junction to the environment and provide the required cooling margin for upgrades of existing platforms.

DESIGN GUIDELINES AND DEVELOPMENT NEEDS FOR TWO-PHASE SYSTEMS

Rough Two-Phase Design Guideline

In the two tables below the above advantages and disadvantages are condensed. The tables give a rough guideline for system engineers which type of two-phase heat transport system would fit best for their type of platform and pay-load. In Table 11 the applicability of the types of two-phase systems for the different platforms is summarised. The main selection driver in this table is the gravity dependence.

Table 11: Two-phase system platform design guideline.

	Land and Marine-based	Airborne platforms	Spacecraft
Heat pipes	gravity assisted only	limited length	excellent
Thermosyphons	gravity assisted only	not possible	not possible
LHP's and CPL's	specific benifits are not used	good	excellent
OHP's	relative low performance	good in confined locations	in specific cases
2Ξ-MPL’s	accurate T-control	accurate T-control	accurate T-control
Vapour chambers	as heat spreader	as heat spreader	as heat spreader

= excellent | = in specific conditions | = not preferred | = not possible

Table 22: Two-phase system payload design guideline.

	Centralised pay-load	Distributed pay-load	Pay-load with confined access
Heat pipes	limited heat flux	in case of enough access	not preferred
Thermosyphons	good	not preferred	not preferred
LHP's and CPL's	good	not preferred	not possible
OHP's	not preferred	not preferred	good but limited in length
2Ξ-MPL’s	not preferred	excellent but adds mass	excellent
Vapour chambers	as heat spreader	not preferred	not possible

= excellent | = in specific conditions | = not preferred | = not possible

In Table 22 a rough division in pay-loads is made based on their lay-out of heat sources. A centralised pay-load is a pay-load with a concentrated heat source like linear motors. A distributed pay-load has a large number of widespread heat sources like active antennas or SAR radar applications. Finally a third type of pay-load is defined with confined access. By checking the application in the two tables a system engineer can judge whether a two-phase system is available and he can already make a pre-selection.

Working Fluid Selection

To illustrate the superiority of water and ammonia as best heat pipe liquids the well-known heat pipe figure of Merit [14] is shown as function of temperature.

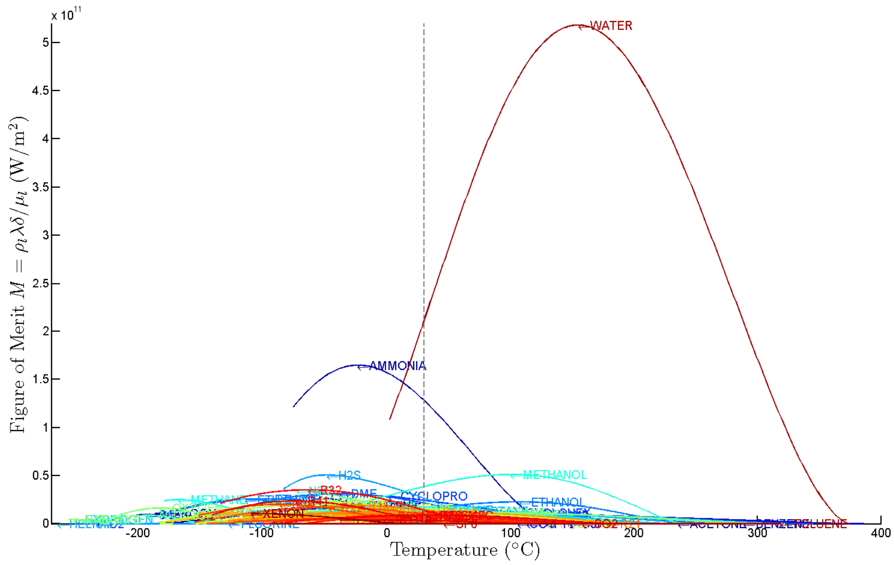


Figure 1010: Figure of Merit of 80 possible heat pipe working fluids as a function of the temperature.

The definition of the figure of Merit [14] shows that that the density, the heat of evaporation, and the surface tension must be as high as possible, while the liquid viscosity be as low as possible.

$$M = \frac{\rho_l \lambda \sigma}{\mu_l} \qquad \textbf{(1)}$$

Figure 1010 shows clearly that water has the highest figure of merit followed by ammonia. Similar graphs can be made for 2Φ-MPL's, thermosyphons and vapour chambers. In all cases water and ammonia show superior performance with alternating best alternatives.

Development Needs

Although two-phase systems are already used in many military platforms there are still improvements needed to increase the application range. To overcome the issue of toxic working fluids the use of water as two-phase working fluid should be considered. This requires implementation of freezing preventive measures in LHP and 2Φ-MPL's. An alternative is the development of advanced two-phase working fluids with large temperature windows. Although it is not likely that ammonia will be outperformed soon, developments in synthetic chemistry and/or nano-particles may lead to an acceptable alternative.

To advance the introduction of 2Φ-MPL's in platforms and platform upgrades it is needed to reduce the pump (electronics) mass and increase the pump reliability. Ruggedizing and improving commercial micro- and mini-pumps can lead to short-term results. Further the 2Φ-MPL accumulator needs to be adapted for high-g applications. This would be specifically beneficial for the introduction of 2Φ-MPL's in airborne platforms.

Conclusions

In this article an overview is given of two-phase heat transport systems with benefits and drawbacks of the systems. Rough design guidelines are given for the applicability of the several systems for airborne, land-based and navy platforms. Finally development needs are defined needed for a more common implementation of two-phase heat transport systems in future platforms.

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