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Challenges in operating and testing loop heat pipes in 500–700 K temperature ranges

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Abstract The potential applications of loop heat pipes (LHPs) are the nuclear power space systems, fuel cell thermal management systems, waste heat recovery systems, medium temperature electronic systems, medium temperature military systems, among others. Such applications usually operate in temperature ranges between 500–700 K, hence it is necessary to develop an LHP system that will meet this requirement. Such a thermal management device require to meet various technical problems and challenges currently existing in the development of LHP working in medium temperatures, including: (1) selection of appropriate working fluid; (2) selection of appropriate LHP construction material; (3) construction of suitable test rig capable of testing at elevated temperatures; (4) development of new testing methods. Currently, there are no proven working fluids that can be used in LHPs in medium temperature ranges. Water can be applicable only at temperatures up to 570 K. Caesium can be applicable at temperatures above 670 K. Organic fluids usually tend to generate non-condensable gasses and/or decompose at elevated temperatures and their viscosity dramatically increases. For halides, most of them are very reactive or toxic and their full property data are not available or the majority of the physical properties are predicted, also live tests and their environmental impact data are not adequate. As for casing/LHP construction material, there are no full chemical compatibility tables with most of the medium temperature working fluids and the reactivity of fluids significantly limits the potential materials. Also, testing such an LHP is an endeavour as the reactivity of medium temperature fluids and the use of obscure metals create new chal-

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lenges. Altogether creates multiple challenges in the development, testing, handling and operating of LHP in the medium temperature range.

Keywords: Loop heat pipe; Working fluid; Material compatibility

Abbreviations

HP	–	heat pipe
LHP	–	loop heat pipe
NCG	–	non-condensable gasses
RELHP	–	reservoir embedded

1 Introduction

Loop heat pipes (LHP) are very efficient, passive, thermal management devices whose operating principle is based on the evaporation and condensation of working fluid circulating inside the loop. Their major advantages are the ability to operate against gravity or under high gravitation and acceleration forces (g-loads), the capability to transport heat over long distances via flexible bendable and routable flow paths, where multiple heat sources or sinks can also be incorporated into one thermal management system. LHPs require no external power or moving parts for operation and are therefore extremely reliable and stable with a long operational life span. These advantages have made the LHP an attractive thermal management element, among a variety of other options available. LHPs utilise latent heat of vaporisation of working fluid inside a loop to transport heat from a source to a sink and to achieve this they take advantage of surface tension generated in a porous structure (wick) to create the capillary forces needed for the circulation of the fluid [1,2,20].

Loop heat pipes are used for thermal management for a large number of aerospace and terrestrial applications and their application is limited to the properties of working fluid and components material of which LHP is constructed. The scientific literature widely describes the theory and principles of the selection of working fluids and components, to cite a few [1,2]. The current trend in LHP research concerns primarily applications operating at near room temperature. However, when it comes to potential applications of LHP working in temperatures between 500–700 K such as space bimodal systems, space nuclear power system radiators for the exploration of deep space, fuel cell thermal management, geothermal power applications, waste heat recovery systems, medium-temperature electronic cooling (e.g.

electronics based on silicon-carbide semiconductors), medium-temperature military fire control systems, radio-electronic weaponry, railguns and lasers installed on military systems, a research gap is created. A literature search did not reveal many comparative data for medium temperature LHPs and is limited to some outdated papers by Anderson *et al.* [3–6] and Faghri *et al.* [7, 8] and hence recently no working fluids and their chemical compatibility with LHP components and materials have been validated in this temperature range and no live test results are present.

2 Loop heat pipe working fluids

The first consideration in the selection of proper working fluid is the vapour temperature range, however, for most of the working fluids, the more important factor is the so-called 'operating range' as not all the working fluids are useful in the whole range of vapour temperature due to e.g. high vapour pressure. The LHP operating temperature should be lower than the critical point of the working fluid and the triple point temperature should be lower than the lowest temperature reached by the system. Below in Fig. 1 presented a list of the most important and hitherto tested working fluids in LHP applications and their useful range. As shown in the table, there are no working fluids suitable for applications operating in temperatures between 500–700 K. Notwithstanding, in multiple different heat transfer and refrigeration applications operating in these temperatures rages might exists suitable working fluids (e.g. organic working fluids) but in LHP systems the working fluid must be specific and satisfy the following requirements:

- The high latent heat of vaporization.
- The high thermal conductivity.
- The good thermal stability.
- The high surface tension (to provide high capillary pressure and enable LHP to operate against gravity). In addition, the working fluid must wet the wick and the container material, hence the contact angle should be zero or very small.
- The high vapour density (to limit the vapour velocity and consequently generate a pressure loss).
- Low dynamic viscosity (for liquid and vapour phase – to reduce the pressure drops).

- The working fluid should be chemically compatible with other LHP components, non-toxic, eco-friendly and non-flammable, and not generate non-condensable gasses (NCG) in the system (the presence of NCG blocks the pores inside the wick and vapour grooves and hence impede the LHP operation).

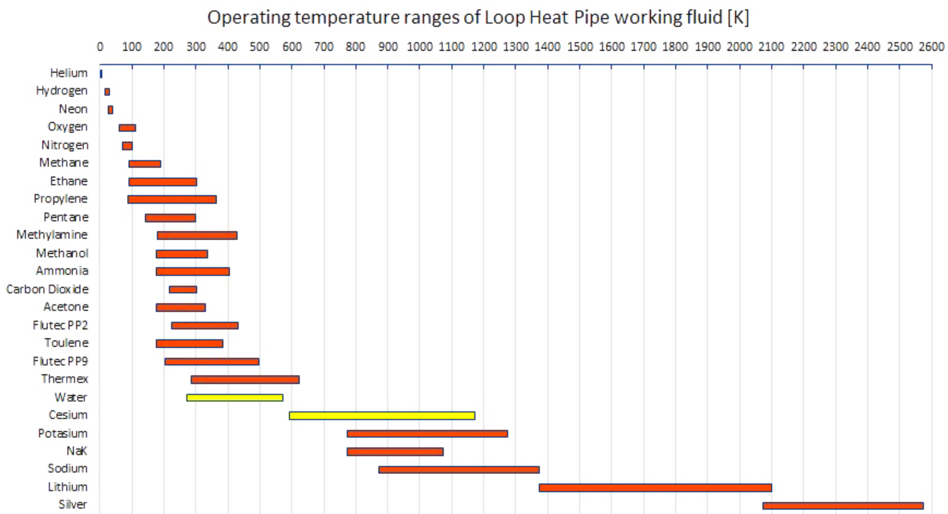

Figure 1: The list of LHP's most typical working fluids and their operating temperature ranges.

Apart from the above-mentioned requirements, the selection of the working fluid must also meet the LHP related thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the system such as viscous, sonic, capillary, entrainment, and nucleate boiling limits.

To assess and compare the performance of potential working fluid, some scholars introduced the so-called Merit number for a working fluid

$$M_l = \frac{\rho_l \sigma \lambda}{\mu_l}\,, \tag{1}$$

where: ρ_l – liquid density, σ – surface tension, λ – enthalpy of vaporisation, μ_l – liquid viscosity.

Working fluids with the highest Merit number are considered to have better performance characteristics. The Merit number as a function of temperature is shown in Fig. 2 for the most typical LHP working fluids. The desired working fluid must have high surface tension to increase capillary pumping capability, high liquid density, high enthalpy of vaporisation to reduce mass flow rates (and thus frictional losses) and low liquid viscosity to reduce the liquid pressure drop for a given power.

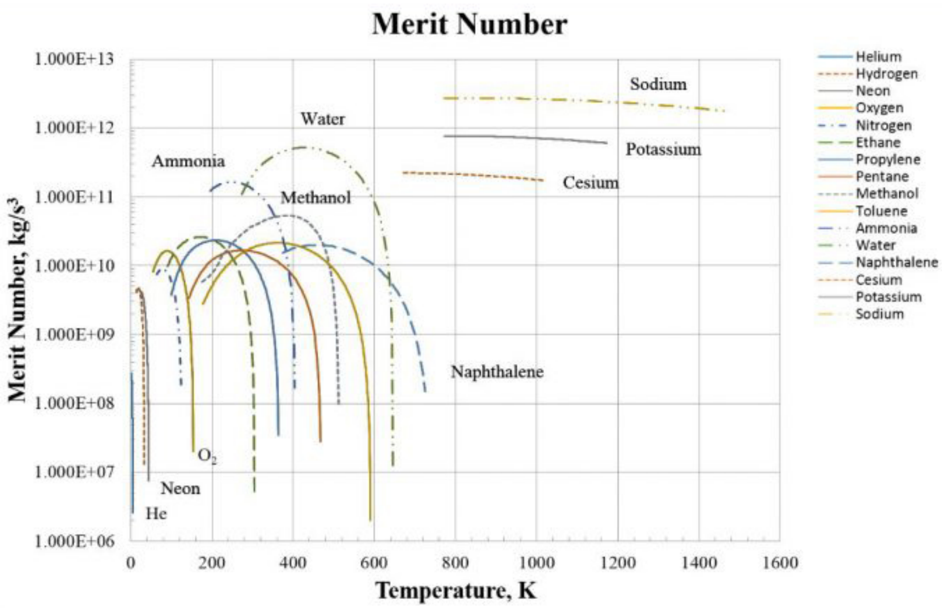

Figure 2: The relation of Merit numbers and the temperature of the commonly used LHP's working fluids [9].

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According to the working fluid properties data listed the potential working fluids that can operate in the intermediate temperature range (500–700 K) include organic fluids, elements and halides. Below presented a table (Table 1) with physical parameters of potential working fluids hitherto tested in LHP installations and a short description of the advantages and disadvantages of those fluids in application LHP systems.

It should be noted here, that not all the working fluids that are presented in the literature as applicable in heat pipes (HPs) can also be applicable in the LHP installations. Loop heat pipes wicks have much smaller pore sizes in comparison to HP wicks, hence the working fluid in LHPs must have much higher wetting parameters than those in heat pipes (especially with screen wick) are more easily wetted than the small fine pores wicks of the LHPs.

Table 1: A list of potential working fluids tested in LHP installations [2–6, 10].

Working fluid	Symbol	Melting point	Boiling point at ambient temp.	Critical temp.	Critical pressure	Density	Surface tension	Viscosity
		(K)	(K)	(K)	(MPa)	(kg/m^3)	(N/m)	(Pa s)
Water	H_2O	273	373	647	22.12	831 (500 K)	0.031 (500 K)	0.0001 (500 K)
Caesium	Cs	302	941	2045	9.4	–	–	–
Halides								
Tin tetrachloride	$SnCl_4$	240	388	592	3.75	1944 (400 K)	0.0155 (400 K)	0.360 (400 K)
Titanium par tetrachloride	$TlCl_4$	243	409.6	638	4.7	1543 (400 K)	0.0211 (400 K)	0.391 (400 K)
Gallium trichloride	$GaCl_3$	351	474	694	–	1743 (500 K)	0.0124 (500 K)	0.449 (500 K)
Titanium tetrabromide	$TiBr_4$	312	506	795.7	–	2758 (400 K)	–	–
Aluminium tribromide	$AlBr_3$	370	528	763	86.6	2331 (500 K)	–	0.809 (500 K)
Antimony tribromide	$SbBr_3$	370	553	1178	55.7	3193 (500 K)	–	0.957 (500 K)
Antimony trichloride	$SbCl_3$	346	556	794	–	2329 (500 K)	–	0.337 (500 K)
Organic Fluids								
Toluene	$C_6H_5CH_3$	178	384	592	41	638 (500 K)	0.0062 (500 K)	0.111 (500 K)
Aniline	C_6H_7N	267	457	699	53.1			
Naphthalene	$C_{10}H_8$	353	490	748	41	855 (500 K)	0.017 (500 K)	0.2 (500 K)
Dowtherm A	$C_{12}H_{10}$ $C_{12}H_{10}O$	285	530	770	31.4	672.5 (500 K)	–	0.12 (500 K)
Diphyl	$C_{12}H_{10}$	343	572	780	35	–	–	–
Diphenyl oxide	$C_{12}H_{10}O$	300	532	767	35	–	–	–
Phenol	C_6H_6OH	314	455	694	59.8	–	–	–
Hydrazine	N_2H_4	274	387	628	145	–	–	–

Incompatibility between the working fluid and LHP materials is directly linked to NCG generation and consequently oscillatory behaviour or termination of LHP operation. An extensive need exists to perform a full thermodynamic analysis of the behaviour of this capillary two-phase system to understand its thermal and hydraulic processes occurring in the LHPs operating at elevated temperature ranges. NGCs have been reported as one of the most common causes of the failure of two-phase heat transport devices [3–6, 11]. One of the main consequences of incompatibility among the materials and working fluid of a heat transport device is the generation of NCG, which is linked to the fact that elevated temperatures accelerate the NCG generation process, making it essential to dedicate special attention to the NCG impact in the LHP for elevated temperature, which would potentially include novel combinations of fluids and materials.

Pernicious effects of NCG have been mainly reported for HP operation. A few studies have been performed for LHPs working in a near room temperature (up to ~360 K), but the limited information makes a deeper analysis of NCG impact on LHPs performance needed. Effects of NCG in LHPs have been studied by several authors. Thermal conductance degradation related to NCG in ammonia LHPs has been found by Nikitkin *et al.* [12]. Investigations compiled in this paper included both modelling and experimental analysis. The main conclusions obtained indicated that the performance of the LHP was almost insensitive to NCG in the experiments, unless for large quantities of gas when the LHP start-up time was increased and thermal conductance of the LHP was degraded. Moreover, it was concluded that the measured effects of NCG were less significant than those predicted by modelling. This fact was reported due to conservatism in the analysis since the Compensation Chamber is assumed isothermal and NCG solubility is neglected. The experimental results were believed influenced by gas absorbed by the working fluid and/or adsorbed by the wick or envelope. In addition, an unexpected increase in the evaporator conductance at the early stages of the NCG injections was observed. Furthermore, Wrenn *et al.* [13] reported the same effect in LHPs operation due to NCG accumulation inside the device. They performed a test campaign to evaluate the potential issues associated with the operation of LHPs with NCG and large thermal masses attached to the evaporator. An ammonia LHP was subjected to the testing. The main conclusions obtained as far as NCG effects on the LHP performance were concerned, indicated an increase of the LHP saturation temperature to accommodate the partial pressure of the gas (decrease of the LHP thermal conductance) and that the presence of the NCG did not affect the evaporator conductance. Effects of NCG in LHP operation were also studied by Ishikawa *et al.* in [14]. The operation of an LHP with NCG was analysed in the context of a reservoir embedded LHP (RELHP) integrated into a deployable radiator. The RELHP had an evaporator core used as a liquid reservoir to enhance operational reliability. In the paper, it is pointed out that for use on satellites, the RELHP would be required to have a lifetime greater than 10 years. In this line, the heat transport characteristics of the RELHP for different NCG volumes were analysed by experiment and calculations. The main findings were that NCG increases temperature rise at the evaporator. NCG volume in a RELHP has a huge influence on heat transport characteristics due to the reservoir pressure increase caused by NCG. Thermal conductance degradation in a water-copper LHP was reported by Singh *et al.* [15]. The performed investigation included experiments with a miniature water-copper LHP in which NCG was injected to study its impact on the device operation. The LHP had a flat disk-shaped evaporator, 30 mm in diameter and 10 mm thick, and a fin-and-tube type condenser, 50 mm in length and 10 mm in height, located at a distance of 150 mm from the evaporator. It was designed for the thermal control of computer microprocessors, with a maximum heat transport capability of 70 W while maintaining evaporator temperature below 373.15 K (100°C) limits for electronic equipment. For NCG detection, a digital vacuum transducer was used. The temperatures were measured along LHP by T-type thermocouples. Experiments revealed that the biggest part of the gas was generated in the first few thermal runs and was accumulated in the compensation chamber. Sensitivity tests showed that the overall effect of the NCG was an elevation of the steady-state operating temperature of the loop (a decrease of the LHP thermal conductance) and an increase in the start-up time.

He *et al.* [16] summarized some investigations related to the effects of NCG in a stainless steel envelope–Ni wick–ammonia LHP. The performance of the LHP was analyzed at two sink temperatures, 278.15 K and 288.15 K (+5°C and –15°C). The main findings consisted of the conductance degradation dependent on the heat load and sink temperature. The conclusions of this paper are in line with the investigations presented in a paper presented by Prado-Montes [17].

2.1 Water as a working fluid

Water is one of the most superior working fluids in LHP application in the ambient temperature range of about 300–400 K. It has a high latent heat and surface tension, compared to all organic fluids. It is very available and environmental friendly. Water is chemical compatible with lots of the most popular LHPs construction materials (e.g. copper, titanium, nickel, titanium) however, in some cases using water requires considerable attention. Cooper/water LHPs can function only at temperatures up to 523 K, after which the cooper structure becomes too weak to sustain high water vapour pressure (3.97 MPa). Water can also be applicable in LHP with titanium, monel and cooper/nikel for temperatures up to 570 K, test data have not been available at higher temperatures. The big disadvantage of water as a working fluid is its chemical non-compatibility with steel and aluminium (due to the creation of NCG). It should be noted that the critical temperature of the water is 647 K, which eliminates it from using in LHP application at temperatures close to 700 K [18, 19].

2.2 Caesium as a working fluid

Caesium is a working fluid with suitable fluid properties and can be applicable in LHPs at temperatures above 670 K. At temperatures below 670 K, the heat flux that can be carried by Caesium is limited by the sonic limit as at this temperature range the vapour density is so low that the vapour sonic velocity limits the heat transfer. Also, the other disadvantage of this fluid is that it has a melting point of 302 K, hence LHP is frozen at the ambient temperatures (e.g prior to start-up) [2–6].

2.3 Organic fluids as working fluids

So far, among organic fluids in LHP and HP applications tested toluene, aniline, naphthalene, eutectic diphenyl/diphenyl oxides (know as Dowtherm A, Therminol or Diphyl), hydrazine and phenol. The disadvantage of these working fluids is the high generation of NCG in elevated temperatures in a relatively short time and the increase of their viscosity, hence the organic working fluids cannot be considered in long live space or industrial applications. The other disadvantage of the organic working fluid is the possibility of thermal degradation where fluids break down into different compounds at specific temperature levels. Also, according to the literature [2–5], their vapour pressures and Merit number at given temperatures are much smaller than water. The organic working fluids (e.g toluene and naphthalene) might be useful in LHP systems at lower temperatures (e.g. below 600 K).

2.4 Halides as working fluids

Halides are the working fluids that are might be attractive in LHP applications as they are more thermodynamically stable at medium temperatures than organic working fluids and their Merit numer is higher in this temperature range. Among halides, hitherto tested only gallium trichloride ($GaCl_3$), aluminium tribromide ($AlBr_3$), tin tetrachloride ($SnCl_4$), titanium tetrachloride ($TiCl_4$), titanium tetrabromide ($TiBr_4$) and antimony trichloride ($SbCl_3$) and antimony tribromide ($SbBr_3$) in HP application. Unfortunately, all the HP leaked after a short time of testing. So far, the full thermodynamical property data, chemical compatibility data environmental impact and live tests for those halides are not available (most of the data are predicted e.g. viscosities or surface tensions), as it is required before LHPs use these fluids can be reliably developed.

3 Metal case structure

Loop heat pipess are designed to operate without maintenance for long periods of time, e.g., deep space missions take about fifteen years. The most important requirement is that the LHP construction elements and working fluid must be chemically compatible. The major results of incompatibility are the generation of NCG and corrosion and material transport. Corrosion products (substances that are formed as a result of corrosion) can block the wick pores reducing the LHP performance. In more extreme and long live cases they can develop system leakage and consequently terminate LHP operation. Before using a working fluid and/or construction material lit is necessary to perform a life test that verifies that the LHP sustain a long operating time. The potential problems with non-compatible construction material are corrosion, blocking a wick by the corrosion products (as they block the wick pores and reduce LHP performance), leakage, material transport (dissolving components of the envelope/wick material in the condenser and carrying and re-deposing the particles in the evaporator) [2–5].

4 Other challenges in operating LHP in elevated temperatures

Apart from the aforementioned challenges in the development of LHP working in elevated temperatures, it is necessary to build a suitable test rig, capable of testing LHP at desired temperatures. Therefore specialist equipment capable of handling temperatures is necessary and new testing methods should be developed. The test rig must be properly insulated and before performing an LHP thermal testing, the system must be tested for NCG existence.

5 Conclusion

Development, testing and handling and operating of loop heat pipes in temperature ranges between 500–700 K causes many challenges and problems. The first challenge is to find a proper working fluid that can meet a dozen of LHP related criteria necessary when choosing the working medium. However, according to the literature, there are no proven working fluids that can meet these criteria. Most medium temperature working fluids are toxic, tend to decompose at elevated temperatures, tend to be reactive, generate non-condensable gasses, or are not chemically compatible with LHP construction material (casing, wick etc.) or have too low vapour density. Consequently, finding suitable metal case and wicks structures is also problematic as the reactivity of fluid limits materials. The casing material is supposed to be strong enough to resist high pressure and suppose to be chemically compatible with working fluid and be corrosion resistant.

Also, testing of loop heat pipe working in elevated temperatures cause multiple challenges, as some of the working fluids whose operating temperature is between 500–700 K tend to freeze at ambient temperature (LHP is frozen prior to startup) or are reactive or toxic which makes additional problems during testing and handling.

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