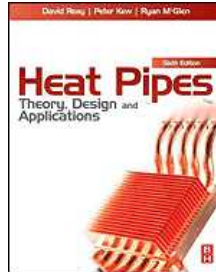# Chapters to Go

Heat Pipes: Theory, Design and Applications, Sixth Edition

by D.A. Reay, P.A. Kew and R.J. McGlen

Elsevier Science and Technology Books, Inc.. (c) 2014. Copying Prohibited.

Skillsoft

Chapter 3: Heat Pipe Components and Materials

OVERVIEW

In this chapter, we will discuss the main components of the heat pipe and the materials used. Since the fifth edition of *Heat Pipes* was written, the materials and components of heat pipes have remained essentially the same, perhaps with the exception of the addition of nanoparticles to working fluids and interest in magnesium as a wall/wick material. Nevertheless, life tests have had an opportunity to extend over a further 10-year period, and some working fluids have lost their attractiveness, as mentioned in Chapter 1. This may be dictated by health and safety considerations (see also Chapter 5) or by environmental pressures – for example the use of CFCs is now banned, and in some countries in Europe the application of HFCs is being phased out in favour of fluids that contribute less to global warming.

The temperature range affected by these trends is principally between −50°C and +100°C. This affects products in the electronics thermal control, domestic and heat recovery areas, as well as (although less important in the context of global warming) spacecraft – see Chapters 7 and 8 on applications.

The issue of compatibility and the results of life tests on heat pipes and thermosyphons remain critical aspects of heat pipe design and manufacture. In particular, the generation of non-condensable gases that adversely affect the performance of heat pipes in either short term or long term must be taken particularly seriously in the emerging technology of microheat pipes and arrays of such units (see also Chapter 6, where microheat pipes are discussed). It is encouraging to note that the reporting of extended life tests on heat pipes (including loop thermosyphons) has not abated, and data given later from the 16th International Heat Pipe Conference for sodium, naphthalene and a selection of high-temperature organic fluids are given later. Even CO_2 has been examined in its supercritical form as a working fluid.

An aspect of heat pipes that has always been of interest to researchers is the compatibility of water with steel (mild or stainless variants). The superior properties of water and the low cost of some steels, together with their strength, make the combination of water–steel attractive, if sometimes elusive. Later in this chapter, substantial discussion of the combination is given.

A considerable quantity of data on heat pipe life tests was accumulated in the 1960s–1980s. To many, this was the most active period of heat pipe research and development, and in many applications heat pipes are now routine components in many terrestrial and space applications. It is therefore important to retain much of the early life test data (often now discarded in paper copies of reports from company libraries, etc.). Thus, apart from examples where the fluids have been discarded due to environmental or other considerations (for example refrigerants such as R11 and R113), the historical data are again retained in this sixth edition of *Heat Pipes*. The majority of the fluids, materials and operating conditions remain the same, so the life test data remain valid and should be of not just archival value to those entering the heat pipe field. These data, and some additional results, are given in Section 3.5.1.

However, the importance of life tests at each laboratory, once new designs are made, remains great, as explained in Chapter 5.

The three basic components of a heat pipe are as follows:

i. The working fluid

ii. The wick or capillary structure

iii. The container.

In the selection of a suitable combination of the above, inevitably a number of conflicting factors may arise, and the principal bases for selection are discussed below.

3.1 THE WORKING FLUID

A first consideration in the identification of a suitable working fluid is the operating vapour temperature range and a selection of fluids is shown in Table 3.1. Within the approximate temperature band several possible working fluids may exist, and a variety of characteristics must be examined in order to determine the most acceptable of these fluids for the application being considered. The prime requirements are as follows:

i. Compatibility with wick and wall materials

ii. Good thermal stability

Elsevier Science and Technology Books, Inc., David Reay, Peter Kew, Ryan McGlen (c) 2014, Copying Prohibited

iii. Wettability of wick and wall materials

iv. Vapour pressures not too high or low over the operating temperature range

v. High latent heat

vi. High thermal conductivity

vii. Low liquid and vapour viscosities

viii. High surface tension

ix. Acceptable freezing or pour point.

Table 3.1: Heat Pipe Working Fluids

Medium	Melting Point (°C)	Boiling Point at Atmospheric Pressure (°C)	Useful Range (°C)
Helium	−271	−261	−271 to −269
Nitrogen	−210	−196	−203 to −160
Ammonia	−78	−33	−60 to 100
Pentane	−130	28	−20 to 120
Acetone	−95	57	0 to 120
Methanol	−98	64	10 to 130
Flutec PP2[1]	−50	76	10 to 160
Ethanol	−112	78	0 to 130
Heptane	−90	98	0 to 150
Water	0	100	30 to 200
Toluene	−95	110	50 to 200
Flutec PP9[1]	−70	160	0 to 225
Thermex[2]	12	257	150 to 350
Mercury	−39	361	250 to 650
Caesium	29	670	450 to 900
Potassium	62	774	500 to 1000
Sodium	98	892	600 to 1200
Lithium	179	1340	1000 to 1800
Silver	960	2212	1800 to 2300

[1]Included for cases where electrical insulation is a requirement.

[2]Also known as Dowtherm A, a eutectic mixture of diphenyl ether and diphenyl.

Note The useful operating temperature range is indicative only. Full properties of most of the above are given in Appendix 1.

The selection of the working fluid must also be based on thermodynamic considerations which are concerned with the various limitations to heat flow occurring within the heat pipe. These were also discussed in Chapter 2 and are the viscous, sonic, capillary, entrainment and nucleate boiling limitations.

Many of the problems associated with long-life heat pipe operation are a direct consequence of material incompatibility. This involves all three components of the heat pipe and is discussed fully later. One aspect peculiar to the working fluid, however, is the possibility of thermal degradation. With certain organic fluids, it is necessary to keep the film temperature below a specific value to prevent the fluid breaking down into different compounds. A good thermal stability is therefore a necessary feature of the working fluid over its likely operating temperature range.

The surface of a liquid behaves like a stretched skin except that the tension in the liquid surface is independent of surface area. All over the surface area of a liquid there is a pull due to the attraction of the molecules tending to prevent their escape. This surface tension varies with temperature and pressure, but the variation with pressure is frequently small.

The effective value of surface tension may be considerably altered by the accumulation of foreign matter at the liquid/vapour liquid/liquid or solid surfaces. Prediction of surface tension is discussed in Chapter 2.

In heat pipe design, a high value of surface tension is desirable in order to enable the heat pipe to operate against gravity and to generate a high capillary driving force.

In addition to high surface tension, it is necessary for the working fluid to wet the wick and container material. That is the contact angle must be zero, or at least very small. In spite of suggestions that additives can improve the performance of heat pipes – for example by the addition of small amounts of a long-chain alcohol to water heat pipes [1] – such a practice is not generally recommended. Those designing and assembling heat pipes for testing should not be tempted to consider additives which may be claimed to improve the 'wettability' of surfaces. In two-phase systems, additives tend to get left behind when phase change occurs! (However, the addition of a fluid such as ethylene glycol to a water thermosyphon can be shown to have some benefits, not least as an 'anti-freeze solution' – see later.)

The vapour pressure over the operating temperature range must be sufficiently great to avoid high vapour velocities which tend to set up a large temperature gradient, entrain the refluxing condensate in the counter-current flow, or cause flow instabilities associated with compressibility. However, the pressure must not be too high because this will necessitate a thick-walled container.

A high latent heat of vaporisation is desirable in order to transfer large amounts of heat with a minimum fluid flow, and hence to maintain low pressure drops within the heat pipe. The thermal conductivity of the working fluid should also preferably be high in order to minimise the radial temperature gradient and to reduce the possibility of nucleate boiling at the wick–wall interface.

The resistance to fluid flow will be minimised by choosing fluids with low values of vapour and liquid viscosity.

A convenient means for quickly comparing working fluids is provided by the merit number, introduced in Chapter 2, defined as $\sigma_1 L \rho_1 / \mu_1$, where σ_1 is the surface tension, L the latent heat of vaporisation, ρ_1 the liquid density and μ_1 the liquid viscosity. Figure 3.1 gives the merit number at the boiling point for working fluids, covering temperature ranges between 200 and 1750 K. One obvious feature is the marked superiority of water with its high latent heat and surface tension, compared with all organic fluids, such as acetone and the alcohols. The final fluid selected is, of course, also based on cost, availability, compatibility and the other factors listed above. Graphical and tabulated data on merit numbers of a range of common working fluids are present in Ref. [2]. (Note that this reference also presents thermosyphon figures of merit.)
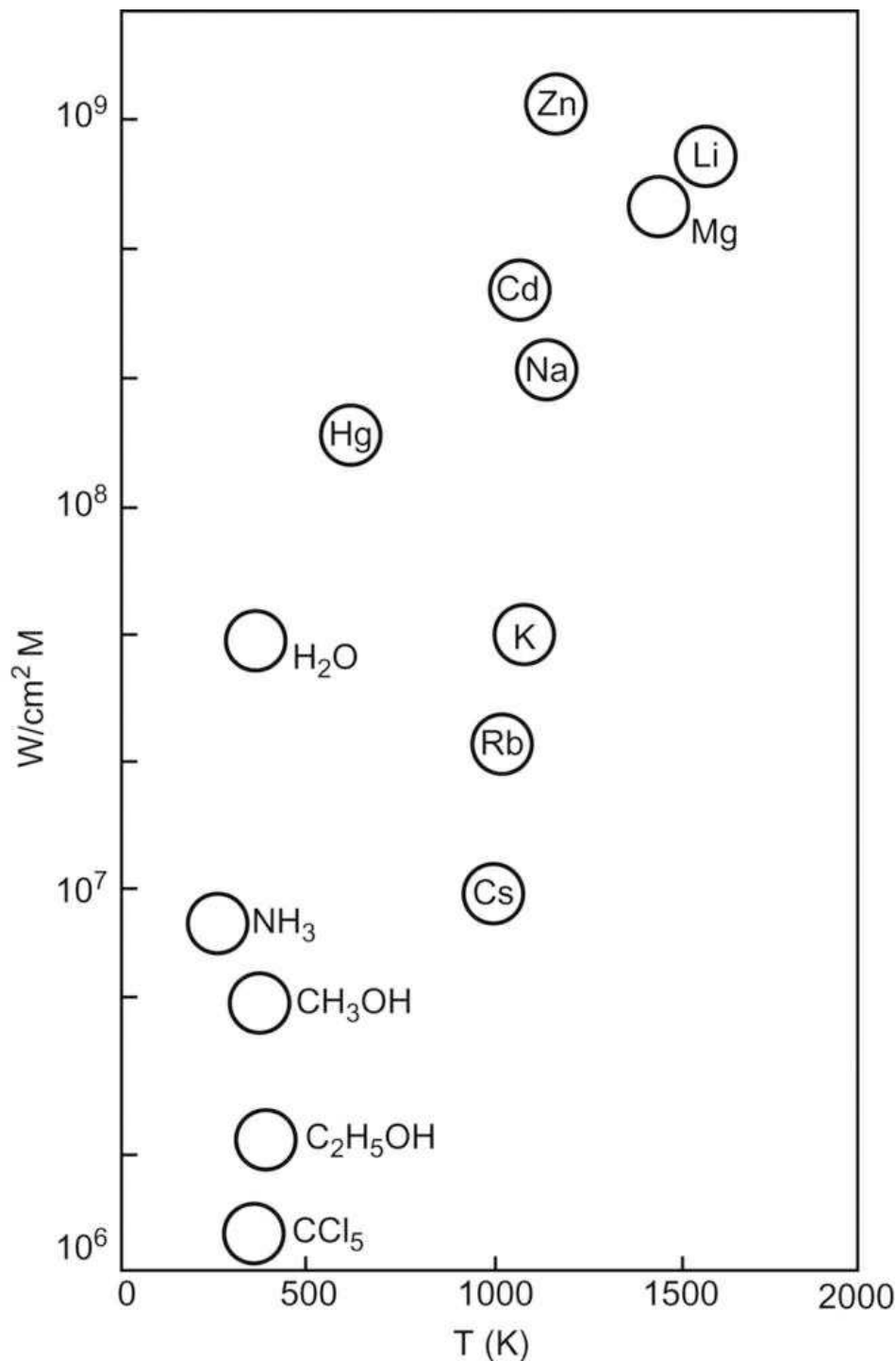
(Courtesy Philips Technical Review).

Figure 3.1: Merit number for selected working fluids for their boiling point

A high merit number is not the only criterion for the selection of the working fluid, and other factors may, in a particular situation, be of greater importance. For example on grounds of cost, potassium might be chosen rather than caesium or rubidium which is one hundred times more expensive. Also, over the temperature range 1200–1800 K, lithium has a higher merit number than most metals, including sodium. However, its use requires a container made from an expensive lithium-resistant alloy, whereas sodium can be contained in stainless steel. It may, therefore, be cheaper and more convenient to accept a lower performance heat pipe made from sodium/stainless steel.

Working fluids used in heat pipes range from helium at 4 K up to lithium at 2300 K. Figure 3.1 shows the superiority of water over the range 350–500 K, where the alternative organic fluids tend to have considerably lower merit numbers. At slightly lower temperatures, 270–350 K, ammonia is a desirable fluid, although it requires careful handling to retain high purity, and acetone

and the alcohols are alternatives having lower vapour pressures. These fluids are commonly used in heat pipes for space applications. Water and methanol, both being compatible with copper, are often used for cooling electronic equipment.

Where HFCs are acceptable, R134A and R407C have been investigated as heat pipe/thermosyphon working fluids in the context of solar collectors [3]. In a comparison with a third fluid, R22 (now being phased out), it was found that R407C gave a superior performance to the other two fluids, but it is unclear why water was not selected. Some of these 'new' HFCs have boiling ranges, and care should be exercised in their use in heat pipes. (See also Chapter 7 where renewable energy uses of heat pipes are discussed.) Another alternative to CFCs are PFCs, perfluorocarbons, that generically have the formula F_nC_{2n+2} and are made by a number of companies (see Flutec PP fluids in Table 3.1 as examples). Their merit is that they are dielectric fluids and can be used for direct cooling of electronics systems (as well as other uses).

Although they have not received a great deal of attention as heat pipe working fluids – they were promoted as relatively benign alternatives to CFCs many years ago but do not suffer from having a high global warming potential (GWP) – recent work has looked at their performance in small thermosyphons, with the possibility of use in electronics cooling [4]. The 3M products Fluorinert FC-84, FC-77 and FC-328 were tested in 6 mm internal diameter thermosyphons but unless the dielectric properties were essential, water would be the fluid of choice, dictated principally by the abysmally low latent heats of evaporation of PFCs in general.

Work by Robert Dobson in South Africa [5] introduces us to the use of supercritical CO_2 as a working fluid, albeit in closed-loop thermosyphons. The particular paper discussing its use presents a methodology for evaluation of the transient performance of such systems, and does not contain experimental verification, but the analysis indicates that using CO_2 as the working fluid in a natural circulation heat transfer loop would result in 95% more heat transfer than in a similar water-based loop.

For temperatures over 500 K and up to 650 K, the high-temperature organic heat transfer fluids, normally offered for single-phase duties, may be used. These are available from companies such as The Dow Chemical Company and are eutectics of diphenyl and diphenyl oxide. The boiling point is around 260°C at atmospheric pressure.

Unfortunately, they have a low surface tension and poor latent heat of vaporisation. As with many other organic compounds, diphenyls are readily broken down when film temperatures exceed the critical value. However, unlike many other fluids having similar operating temperature ranges, these eutectic mixtures have a specific boiling point, rather than a boiling range. Other fluids such as silicons are being studied for use at above 600 K.

One of the most comprehensive sets of compatibility tests was that carried out at IKE, Stuttgart [6,7], on a number of organic working fluids. These concentrated on thermosyphons made using a range of boiler and austenitic steels, and the data obtained are summarised in Table 3.2. It can be seen from the test results that organic fluids operating at temperatures much in excess of 300°C tend to be unsuitable for long-term use in heat pipes.

Table 3.2: Compatibility Tests with Organic Working Fluids [7]

Test Duration (Year)	Working Fluids	Structural Materials (Operating Temperatures)		
		Compatible	Fairly Compatible	Incompatible
4.5–5	N-Octane	St35 (230°C)	X10CrNiT189 (200°C, 250°C)	
	Diphenyl		St35 (270°C)	St35 (300°C)
			X10CrNiTi189 (300°C)	X10CrNiTi189 (350°C)
	Diphenyl Oxide	St35 (220°C)		
3	Toluene	St35 (250°C)		
		13CrMo44 (250°C)		
		X2CrNiMo1812 (280°C)		
	Naphthalene	St35 (270°C)	13CrMo44 (270°C)	
1	Diphenyl	Ti99.4 (270°C)		CuNi10Fe (250°C)
	Diphenyl	13CrMo44 (250°C)		13CrMo44 (400°C)
		X2CrNiMo1812 (250°C)		X2CrNiMo1812 (400°C)
	QM			13CrMo44 (320°C, 400°C)
				X2CrNiMo1812 (350°C, 400°C)
	OMD			13CrMo44 (350°C,400°C)
				X2CrNiMo1812 (350°C, 400°C)
	Toluene	Ti99.4 (250°C)		
		CuNi10Fe (280°C)		
	Naphthalene	X2CrNiMo1812 (320°C)	CuNi10Fe (320°C)	

Table 3.2: Compatibility Tests with Organic Working Fluids [7]

Test Duration (Year)	Working Fluids	Structural Materials (Operating Temperatures)		
		Compatible	Fairly Compatible	Incompatible
		Ti99.4 (300°C)		

It was pointed out by the research workers [8] that diphenyl and naphthalene, the two working fluids most suitable for operation in this temperature regime, can both suffer from decomposition created by overheating at the evaporator section. This leads to the generation of non-condensable gas that can be vented via, for example, a valve.

The use of naphthalene is also reported in thermosyphons by Chinese researchers [9]. Vapour temperatures in excess of 250°C were achieved in the experiments but no degradation/compatibility data were given. Although not covering compatibility, the use of naphthalene in a stainless steel loop thermosyphon was reported by academics in Brazil. The overall system performance had limitations that were not influenced by incompatibilities [10].

More recently [11] the temperature range of 400–700 K has received attention from workers at NASA Glenn Research Centre. The suggestion is that metallic halides might be used as working fluids within this temperature range. The halides are typically compounds of lithium, sodium, potassium, rubidium and copper, with fluorine, iodine, bromine and iodine [12]. The suggestion in much of the literature is that these will be reactive, and it should be pointed out that mixtures of iodine and sulphur were investigated as heat pipe fluids by the UK Atomic Energy Authority, some 25–30 years ago.

The NASA Glenn Research Centre, together with a heat pipe manufacturer – Advanced Cooling Technologies, Inc. (see Appendix 3), has updated its life test report in 2011 [13] in the context of both conventional and loop heat pipes (LHPs), calling in this case the intermediate temperature range as 450–750 K. Water was shown to be compatible with titanium and Monel for temperatures up to 550 K (277°C), based upon life tests over 54 000 hours. The work on halides mentioned above has been continued, and it was concluded that long-term tests that at the time of reporting had reached 50 000 hours and exhibited compatibility between titanium and TiBr at 653 K and $AlBr_3$ with Hastelloy C-22 was deemed 'viable' at 673 K, with the occurrence of some slight corrosion. As an alternative, titanium with $TiBr_4$ was proposed, based upon the same life test period. It should be noted that the interest in these latter non-organic fluids is prompted by the potential use of heat pipes in nuclear reactors, where radioactivity can adversely affect organic fluids.

At higher temperatures, one now enters the regime of liquid metals. Mercury has a useful operating temperature range of about 500–950 K and has attractive thermodynamic properties. It is also liquid at room temperature, which facilitates handling, filling and start-up of the heat pipe.

Apart from its toxicity, the main drawback to the use of mercury as a working fluid in heat pipes, as opposed to thermal syphons, is the difficulty encountered in wetting the wick and the wall of the container. There are few papers specifically devoted to this topic, but Deverall [14] at Los Alamos and Reay [15] have both reported work on mercury wetting.

Japanese work on mercury heat pipes using type 316L stainless steel as the container material showed that good thermal performance could be achieved once full start-up had been overcome, but the materials compatibility proved a problem, due to corrosion [16]. Such problems were not reported in the series of experiments, including a 1-month 'life test' by Macarino and colleagues at IMGC in Turin, Italy, using a unit supplied by the Joint Research Centre, Ispra. One of a series of gas-controlled heat pipes for accurate temperature measurements, the unit was also made in stainless steel and operated at a vapour temperature of around 350°C [17].

Bienert [18], in proposing mercury/stainless steel heat pipes for solar energy concentrators, used Deverall's technique for wetting the wick in the evaporator section of the heat pipe and achieved sufficient wetting for gravity-assisted operation. He argued that nonwetting in the condenser region of the heat pipe should enhance dropwise condensation which would result in higher film coefficients than those obtainable with film condensation. Work at Los Alamos has suggested that magnesium can be used to promote mercury wetting [19].

Moving yet higher up the vapour temperature range, caesium, potassium and sodium are acceptable working fluids and their properties relevant to heat pipes are well documented (see Appendix 1). Above 1400 K, lithium is generally a first choice as a working fluid but silver has also been used [20]. Working on applications of liquid–metal heat pipes for nuclear and space-related uses, Tournier and others at the University of New Mexico [21] suggest that lithium is the best choice of working fluid at temperatures above 1200 K. For those interested in the start-up of liquid metal, in particular lithium heat pipes, the research at the University of New Mexico is well worth studying.

3.1.1 Nanofluids

Introduced in Chapter 2, the literature on nanofluids – fluids to which nanoparticles have been added, is growing at a rapid

rate, but is not a new phenomenon as far as heat pipes are concerned – see for example Tsai et al. in 2004 [22]. Heat pipes and thermosyphons have not escaped the attention of this trend and one must consider a number of aspects when addressing the use of such particles, including, but not limited to, the following:

1. What is their role?

2. What size/shape of nanoparticle do I need and what is available?

3. How much do they cost (some have used gold particles)?

4. Will they adversely affect any aspect of heat pipe performance?

5. Are they compatible with the working fluid?

6. Can they be recovered safely at the end of the heat pipe life?

7. Do I have adequate data from earlier tests on nanoparticles in heat pipes?

The usual reason for including such particles in a liquid is to enhance heat transfer, most commonly by increasing the liquid thermal conductivity or reducing the size of nucleation bubbles/increasing their number.

This seemed to be the outcome of the work reported in Ref. [22]. Gold nanoparticles of different sizes were prepared by reduction of HAuCl4 with solutions of tetrachloroaurate, trisodium citrate and tannic acid. In the present study, the size of gold nanoparticle was adjusted by changing the amounts of tetrachloroaurate, trisodium citrate and tannic acid. The heat pipe using the nanofluid had a length of 170 mm and an outer diameter of 6 mm. The thermal resistance of the heat pipes ranged from 0.17°C/W to 0.215°C/W with different nanoparticle solutions. These values indicated that the thermal resistance of the heat pipes with nanoparticle solution was up to 37% lower than that with water alone. The authors concluded that 'as a result, the higher thermal performances of the new coolant (really the working fluid!) have proved its potential as a substitute for conventional water in vertical circular meshed heat pipe'.

While, as one would expect, most of the improvement in thermal resistance took place in the evaporator – and the authors attributed the improvement largely to reduced size of nucleation bubbles here – the authors claimed small reductions in the condenser. This latter improvement was attributed to improved liquid thermal conductivity, but of course one must query how solid particle reached the condenser by way of the vapour space, unless the entrainment limit was exceeded.

Nanofluids have been proposed for use in heat pipes cooling Pentium chips [23] where aluminium oxide – a very common nanoparticle – was investigated together with titanium dioxide. Several fluids were tested using nanoparticle concentrations of 1–5% by volume of the fluid. It was found that the screen mesh was coated by the particles and it was proposed that this promoted a good capillary structure for wicking.

This was born out by research by Brusly Solomon et al. [24] in a comprehensive assessment of the performance of wicked heat pipes using mesh already coated with nanoparticles. A 40% thermal resistance reduction at the evaporator was noted, and the results of wick coating are illustrated in Fig. 3.2.
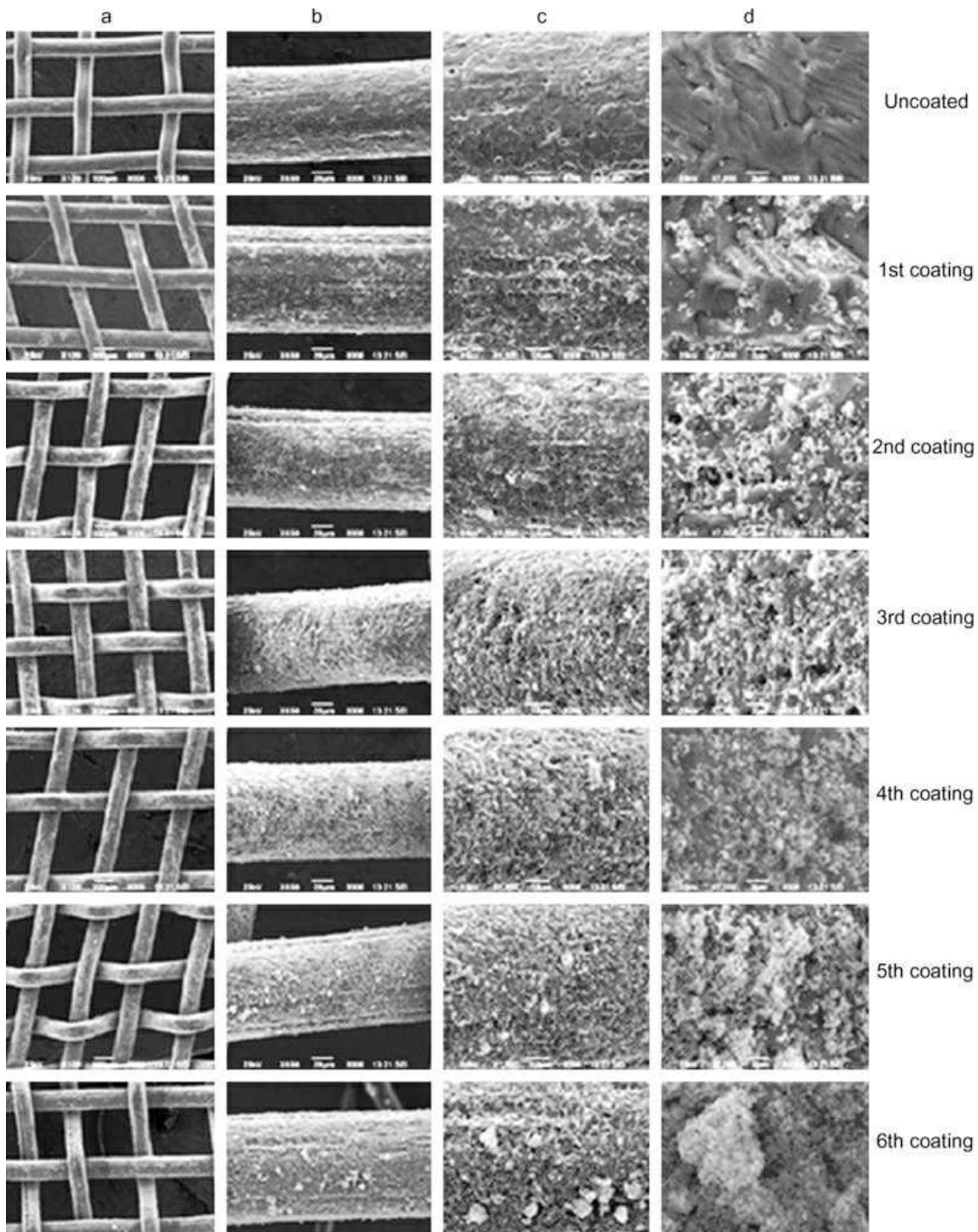
Figure 3.2: Depositions of nanoparticles on the wick surface at different magnifications (a) 120×, (b) 550×, (c) 1500× and (d) 7000× [24]

Leong and colleagues in Malaysia investigated nanofluids in a thermosyphon air preheater [25]. It was found, as shown in Fig. 3.3, that the impact on performance of the thermosyphon was influenced much more by the air velocity across the thermosyphons than the amount of nanoparticles included in the fluid. Results were similar in trend for both alumina and titanium dioxide nanoparticles. Leong et al. suggested therefore that the role of enhanced liquid thermal conductivity due to nanoparticles was minor.
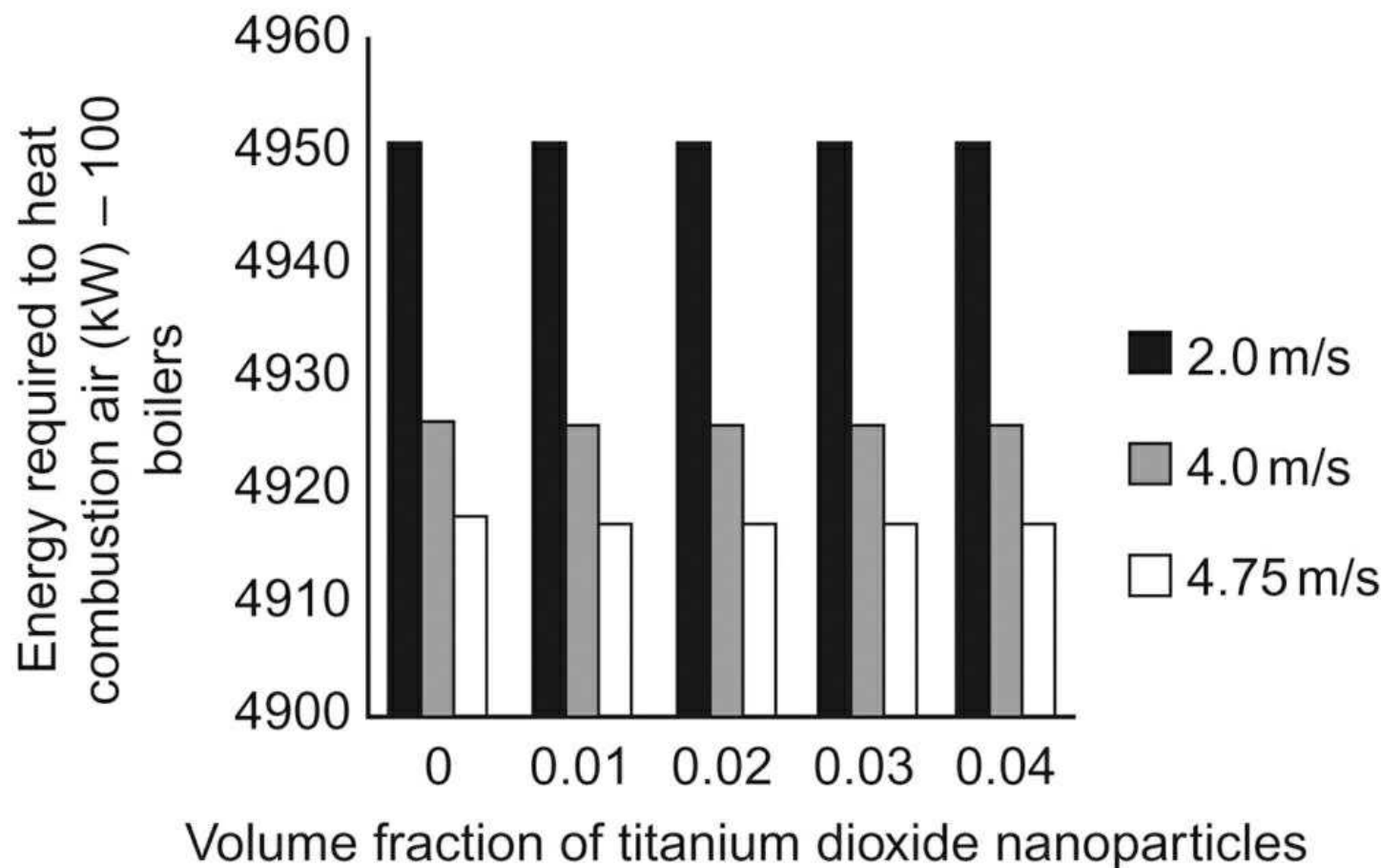
Figure 3.3: Effect of titanium dioxide nanoparticles' volume fraction and hot air velocity to energy performance of thermosyphon heat exchanger [25]

3.2 THE WICK OR CAPILLARY STRUCTURE

The selection of the wick for a heat pipe depends on many factors, several of which are closely linked to the properties of the working fluid. Obviously the prime purpose of the wick is to generate capillary pressure to transport the working fluid from the condenser to the evaporator. It must also be able to distribute the liquid around the evaporator section to any areas where heat is likely to be received by the heat pipe. Often these two functions require wicks of different form, particularly where the condensate has to be returned over a distance of, say, 1 m, in 0 gravity. Where a wick is retained in a 'gravity-assisted' heat pipe, the role may be to enhance heat transfer and to circumferentially distribute liquid.

It can be seen from Chapter 2 that the maximum capillary head generated by a wick increases with decreasing pore size. The wick permeability, another desirable feature, increases with increasing pore size, however. For homogeneous wicks, there is an optimum pore size, which is a compromise. There are three main types in this context. Low-performance wicks in horizontal and gravity-assisted heat pipes should permit maximum liquid flow rate by having a comparatively large pore size, as with 100 or 150 mesh. Where pumping capability is required against gravity, small pores are needed. In space the constraints on size and the general high-power capability needed necessitates the use of non-homogeneous or arterial wicks aided by small pore structures for axial liquid flow.

Another feature of the wick, which must be optimised, is its thickness. The heat transport capability of the heat pipe is raised by increasing the wick thickness. However, the increased radial thermal resistance of the wick created by this would work against increased capability and would lower the allowable maximum evaporator heat flux. The overall thermal resistance at the evaporator also depends on the conductivity of the working fluid in the wick. (Table 3.3 gives measured values of evaporator heat fluxes for various wick/working fluid combinations.) Other necessary properties of the wick are compatibility with the working fluid and wettability. It should be easily formed to mould into the wall shape of the heat pipe and should preferably be of a form that enables repeatable performance to be obtained. It should be cheap.

Table 3.3: Measured Radial Evaporator Heat Fluxes in Heat Pipes

Working Fluid	Wick	Vapour Temperature (°C)	Radial Flux (W/cm^2)
Helium [26]	s/s Mesh	−269	0.09
These are not necessarily limiting values.			

Table 3.3: Measured Radial Evaporator Heat Fluxes in Heat Pipes

Working Fluid	Wick	Vapour Temperature (°C)	Radial Flux (W/cm^2)
Nitrogen [26]	s/s Mesh	−163	1.0
Ammonia [27]	Various	20–40	5–15
Ethanol [28]	4×100 Mesh s/s	90	1.1
Methanol [29]	Nickel foam	25–30	0.03–0.4
Methanol [29]	Nickel foam	30	0.24–2.6
Methanol [29]	1×200 Mesh (horizontal)	25	0.09
Methanol [29]	1×200 Mesh (−2.5 cm head)	25	0.03
Water [27]	Various	140–180	25–100
Water [28]	Mesh	90	6.3
Water [28]	100 Mesh s/s	90	4.5
Water [29]	Nickel felt	90	6.5
Water [30]	Sintered copper	60	8.2
Mercury [26]	s/s Mesh	360	180
Potassium [26]	s/s Mesh	750	180
Potassium [27]	Various	700–750	150–250
Sodium [26]	s/s Mesh	760	230
Sodium [27]	Various	850–950	200–400
Sodium [31]	3×65 Mesh s/s	925	214
Sodium [32]	508×3600 Mesh s/s twill	775	1250
Lithium [26]	Niobium 1% zirconium	1250	205
Lithium [33]	Niobium 1% zirconium	1500	115
Lithium [33]	SGS-tantalum	1600	120
Lithium [34]	W-26 Re grooves	1600	120
Lithium [34]	W-26 Re grooves	1700	120
Silver [26]	Tantalum 5% tungsten	–	410
Silver [34]	W-26 Re grooves	2000	155
These are not necessarily limiting values.			

A guide to the relative cost of wicks may be given by noting that the mass-produced heat pipes for electronics applications use sintered copper powder or woven wire mesh, while where aluminium gravity-assisted units can be used (as in some solar collectors), extruded grooves are employed. Microheat pipes may not need a separate 'wick'. The corners of the pipe (where non-circular) may generate capillary action (see Chapter 6).

3.2.1 Homogeneous Structures

Of the wick forms available, meshes and twills are the most common. These are manufactured in a range of pore sizes and materials, the latter including stainless steel, nickel, copper and aluminium. Table 3.4 shows measured values of pore size and permeabilities for a variety of meshes and twills. Homogeneous wicks fabricated using metal foams, and more particularly felts, are becoming increasingly useful, and by varying the pressure on the felt during assembly, varying pore sizes can be produced. By incorporating removable metal mandrels, an arterial structure can also be moulded in the felt.

Table 3.4: Wick Pore Size and Permeability Data

Material and Mesh Size	Capillary Height[1] (cm)	Pore Radius (cm)	Permeability (m^2)	Porosity (%)
Glass fibre [35]	25.4	–	0.061×10^{-11}	–
Refrasil sleeving [35]	22.0	–	0.104×10^{-10}	–
Refrasil (bulk) [36]	–	–	0.18×10^{-10}	–
Refrasil (batt) [36]	–	–	1.00×10^{-10}	–
Monel beads [37]				
30–40	14.6	0.052[2]	4.15×10^{-10}	40
70–80	39.5	0.019[2]	0.78×10^{-10}	40

Table 3.4: Wick Pore Size and Permeability Data

Material and Mesh Size	Capillary Height[1] (cm)	Pore Radius (cm)	Permeability (m^2)	Porosity (%)
100–140	64.6	0.013[2]	0.33×10^{-10}	40
140–200	75.0	0.009	0.11×10^{-10}	40
Felt metal [38]				
FM1006	10.0	0.004	1.55×10^{-10}	–
FM1205	–	0.008	2.54×10^{-10}	–
Nickel powder [35]				
200 μm	24.6	0.038	0.027×10^{-10}	–
500 μm	>40.0	0.004	0.081×10^{-11}	–
Nickel fibre [35]				
0.01 mm diameter	>40.0	0.001	0.015×10^{-11}	68.9
Nickel felt [39]	–	0.017	6.0×10^{-10}	89
Nickel foam [39]				
Ampornik 220.5	–	0.023	3.8×10^{-9}	96
Copper foam [39]				
Amporcop 220.5	–	0.021	1.9×10^{-9}	91
Copper powder (sintered) [38]	156.8	0.0009	1.74×10^{-12}	52
Copper powder (sintered) [40]				
45−56 μm	–	0.0009	–	28.7
100−145 μm	–	0.0021	–	30.5
150−200 μm	–	0.0037	–	35
Nickel 50 [35]	4.8	–	–	62.5
50 [41]	–	0.0305	6.635×10^{-10}	–
Copper 60 [38]	3.0	–	8.4×10^{-10}	–
Nickel 60 [40]	–	0.009	–	–
100 [41]	–	0.0131	1.523×10^{-10}	–
100 [42]	–	–	2.48×10^{-10}	–
120 [38]	5.4	–	6.00×10^{-10}	–
120[3] [38]	7.9	0.019	3.50×10^{-10}	–
2[4]×120 [43]	–	–	1.35×10^{-10}	–
120 [44]	–	–	1.35×10^{-10}	–
s/s 180 (22°C) [45]	8.0	–	0.5×10^{-10}	–
2×l80(22°C) [45]	9.0	–	0.65×10^{-10}	–
200 [40]	–	0.0061	0.771×10^{-10}	–
200 [38]	–	–	0.520×10^{-10}	–
Nickel 200 [35]	23.4	0.004	0.62×10^{-10}	68.9
2×200 [43]	–	–	0.81×10^{-10}	–
Phosp./bronze	–	0.003	0.46×10^{-10}	67
200 [46]				
Titanium 2×200 [40]	–	0.0015	–	67
4×200 [40]	–	0.0015	–	68.4
250 [42]	–	–	0.302×10^{-10}	–
Nickel[3] 2×250 [40]	–	0.002	–	66.4
4×250 [40]	–	0.002	–	66.5
325 [40]	–	0.0032	–	–
Phosp./bronze [44]	–	0.0021	0.296×10^{-10}	67
s/s (twill) 80[5] [47]	–	0.013	2.57×10^{-10}	–

Table 3.4: Wick Pore Size and Permeability Data

Material and Mesh Size	Capillary Height[1] (cm)	Pore Radius (cm)	Permeability (m^2)	Porosity (%)
90[5][47]	–	0.011	1.28×10^{-10}	–
120[5][47]	–	0.008	0.79×10^{-10}	–
250 [43]	–	0.0051	–	–
270 [43]	–	0.0041	–	–
400 [43]	–	0.0029	–	–
450 [47]	–	0.0029		

[1]Obtained with water unless stated otherwise.

[2]Particle diameter.

[3]Oxidised.

[4]Denotes number of layers.

[5]Permeability measured in direction of warp.

Foams (see www.Porvair.com for data on a variety of foams) and felts are growing in importance for a variety of heat transfer duties. As well as incorporating arteries in felts, like foams, their structure can be 'graded' to allow the structure to be designed for 'local' conditions that may differ from those in other parts of a heat pipe wick (e.g. radially or axially). The research at Auburn University in the United States [48] was directed at examining whether the heat transfer limits of heat pipes could be increased by gradation of the pore structure. In particular, variables could include the porosity, fibre diameter, pore diameter and pore diameter distribution. The particular layouts selected by the Auburn research team – which resemble composite mesh wicks in concept – were unsuccessful due to vapour being unable to escape into the vapour space, but the concept, with different variants, has merit.

Fibrous materials have been widely used in heat pipes, and generally have small pore sizes. The main disadvantage is that ceramic fibres have little stiffness and usually require a continuous support for example by a metal mesh. Thus, while the fibre itself may be chemically compatible with the working fluids, the supporting materials may cause problems. Semena and Nishchik [49] discuss metallic fibre (and sinter) wick properties and recently Kostornov et al. [50] studied the performance of wicks made from copper and stainless steel fibres, concentrating upon the evaporator behaviour. Capillary structure porosities were examined over a wide range (40–90%), with wick thicknesses from 0.2 to 10 mm; water and acetone were among the fluids tested.

Interest has also been shown in carbon fibre as a wick material. Carbon fibre filaments have many fine longitudinal grooves on their surface, have high capillary pressures and are, of course, chemically stable. A number of heat pipes have been successfully constructed using carbon fibre wicks, including one having a length of 100 m. This demonstrated a heat transport capability three times that of one having a metal mesh wick [51]. The use of carbon-fibre-reinforced structures as wall material cannot be ruled out in future aerospace applications. Other designs incorporating this wick material have been reported [52,53].

Sintered powers are available in spherical form in a number of materials, and fine pore structures may be made, possibly incorporating larger arteries for added liquid flow capability. Leaching has been used to produce fine longitudinal channels, and grooved walls in copper and aluminium heat pipes have been applied for heat pipes in zero-gravity environments (Fig. 3.4). (In general grooves are unable to support significant capillary heads alone in earth gravity applications. Also entrainment may limit the axial heat flow. Covering grooves with a mesh prevents this.)
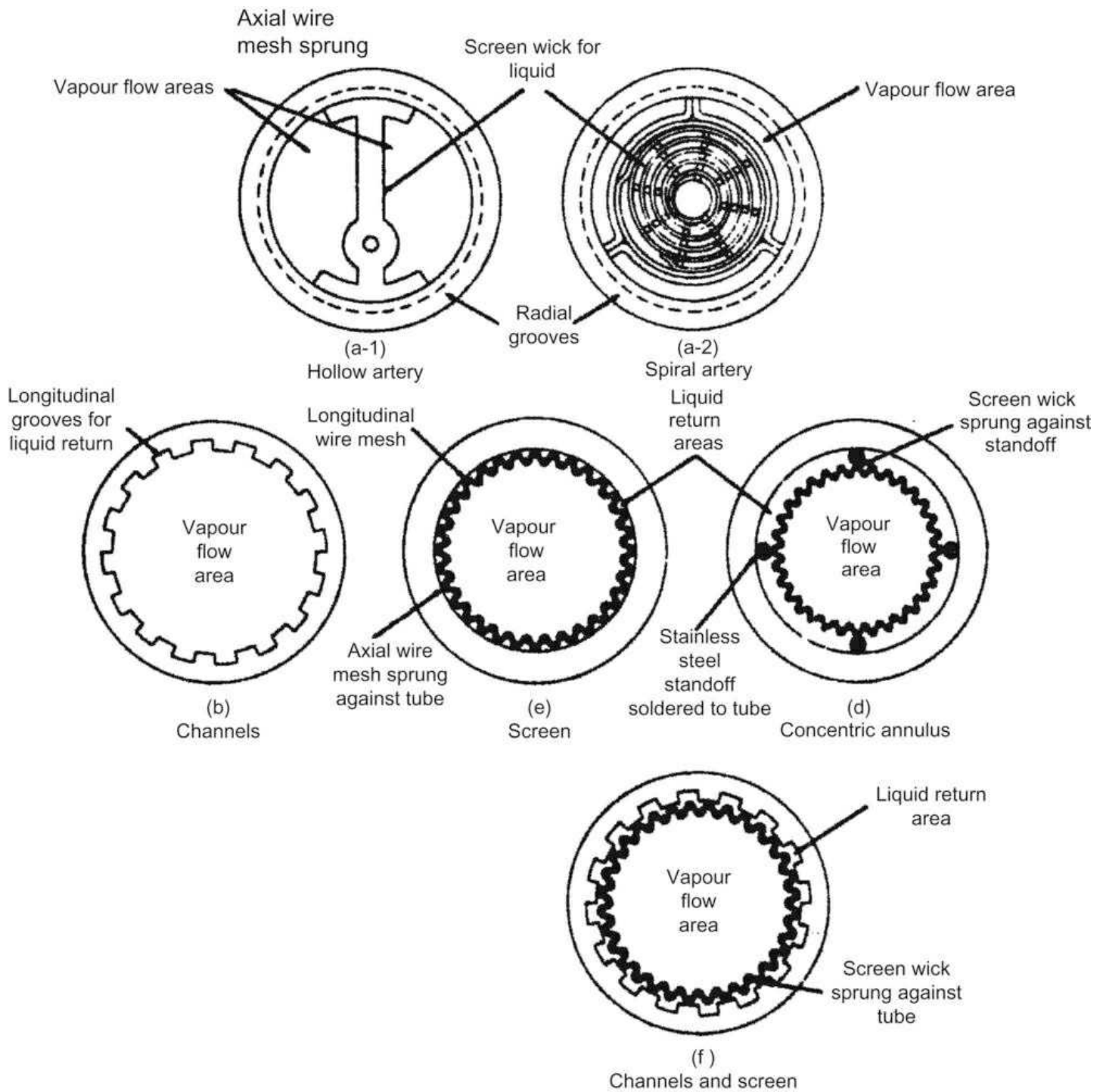
(Courtesy NASA).

Figure 3.4: Forms of wick used in heat pipes

A relatively new term is being used to describe heat pipe wicks in which sintered structures of differing porosity might be used – 'bi-porous'. Similar to composite wicks and sintered structures where a low pressure drop flow path may parallel a high capillary driving force one, mono- and bi-porous wicks are shown in Fig. 3.5 [54].
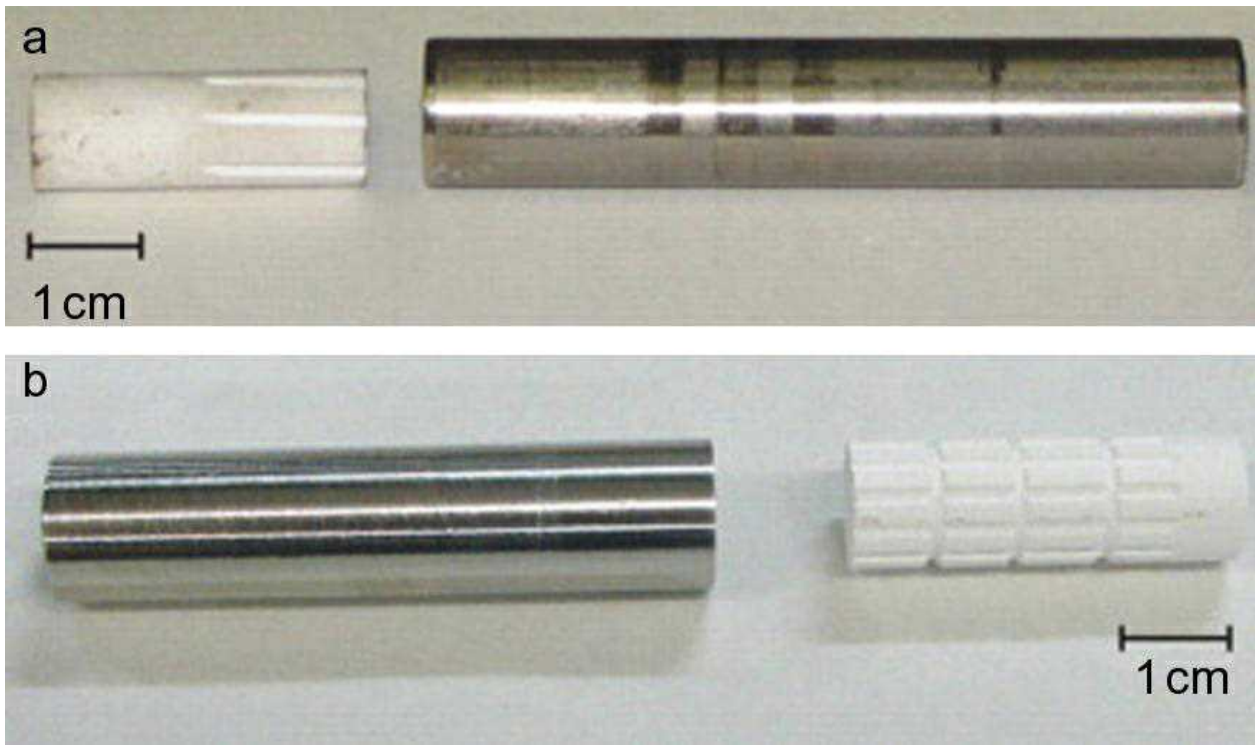
Figure 3.5: Sintered glass wick samples showing (a) a mono-porous wick and (b) the bi-porous unit [54]

Polymers have been proposed for use as heat pipe wall and wick materials in the past, and for example early flexible heat pipes illustrated in earlier editions of *Heat Pipes* included a polymer section to give this flexibility. The specific porosity/pore size requirements used in the wicks of some modern LHPs have encouraged users to examine a variety of porous structures, including ceramics and polyethylene, as well as porous nickel. As stated by Figus and colleagues at Astrium SAS in France [55], high-performance porous media are needed to achieve high evaporator heat fluxes (greater than 10 000 W/m^2 K). Early polymer wicks had very small pore sizes but low permeabilities (10^{-4} m^2), orders of magnitude lower than those of the wicks listed in Table 3.4, for example. Polytetrafluoroethylene has also been used by Astrium in LHP evaporators. (Note the wicks in Table 3.4 are principally for 'conventional' heat pipes, not LHPs.)

In December 2001 [56,57], the capillary pumped loop (CPL) successfully demonstrated, during a flight on the Shuttle spacecraft (STS-108), that a CPL with two parallel evaporators using polyethylene wicks could start-up and operate for substantial periods in high-power (1.5 kW) and low-power (100 W) modes. Over the preceding 2-year fully charged storage period, no gas generation had been observed (see Fig. 1.10).

3.2.2 Arterial Wicks

Arterial wicks are necessary in high-performance heat pipes for spacecraft, where temperature gradients in the heat pipe have to be minimised to counter the adverse effect of what are generally low thermal conductivity working fluids. An arterial wick developed by one of the authors at IRD is shown in Fig. 3.6. The bore of the heat pipe in this case was only 5.25 mm. This heat pipe, developed for the ESA, was designed to transport 15 W over a distance of 1 m with an overall temperature drop not exceeding 6°C. The wall material was aluminium alloy and the working fluid acetone.

Machined stainless steel former
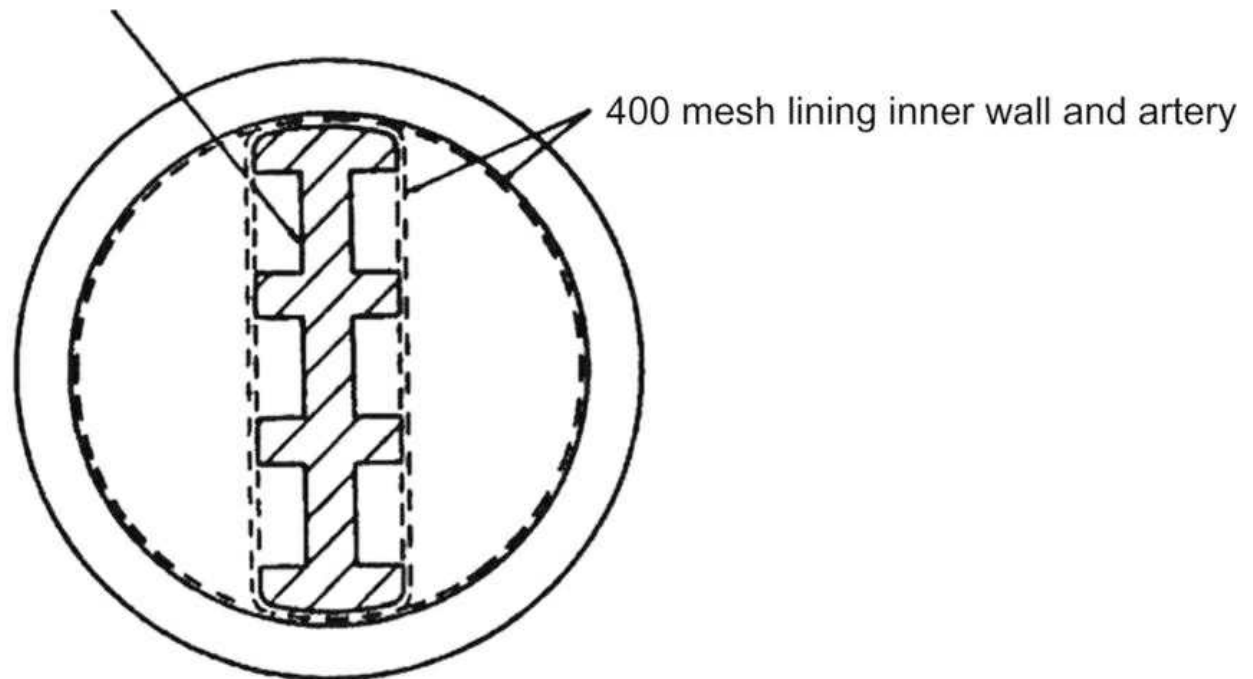
400 mesh lining inner wall and artery

Figure 3.6: Arterial wick developed at NEI-IRD

The aim of this wick system was to obtain liquid transport along the pipe with the minimum pressure drop. A high driving force was achieved by covering the six arteries with a fine screen.

In order to achieve the full heat transport potential of the arterial wick, the artery must be completely shut off from the vapour space. The maximum capillary driving force is thus determined by the pore size of the screen. Thus a high degree of quality control was required during the manufacturing process to ensure that the artery was successfully closed and the screen undamaged.

A further consideration in the design of arterial heat pipes is that of vapour or gas blockage of the arteries. If a vapour or gas bubble forms within or is vented into the artery, then the transport capability is seriously reduced. Indeed, if the bubble completely blocks the artery then the heat transport capability is dependent on the effective capillary radius of the artery, i.e. there is an effective state of open artery. In order that the artery will reprime following this condition, the heat load must be reduced to a value below the maximum capability associated with the open artery.

The implications of wick design and working fluid properties in arterial heat pipes are as follows:

i. The working fluid must be thoroughly degassed prior to filling to minimise the risk of non-condensable gases blocking the artery.

ii. The artery must not be in contact with the wall to prevent nucleation within it.

iii. A number of redundant arteries should be provided to allow for some degree of failure.

iv. Successful priming (i.e. refilling) of the artery, if applied to spacecraft, must be demonstrated in a one 'g' environment, it being expected that priming in a zero 'g' environment will be easier.

As mentioned above, arterial heat pipes have been developed principally to meet the demands of spacecraft thermal control. These demands have increased rapidly over the last decade, and while mechanical pumps can be used in two-phase 'pumped loops', the passive attraction of the heat pipe has spurred the development of several derivatives of 'conventional' arterial heat pipes.

One such derivative is the monogroove heat pipe, shown in Fig. 3.7. This heat pipe comprises two axial channels, one for the vapour and one for the liquid flow. A narrow axial slot between these two channels creates a high capillary pressure difference, while in this particular design circumferential grooves are used for liquid distribution and to maximise the evaporation and condensation heat transfer coefficient [58,59]. The principal advantage of this design is the separation of the liquid and vapour flows, eliminating the entrainment, or counter-current flow and limitation.
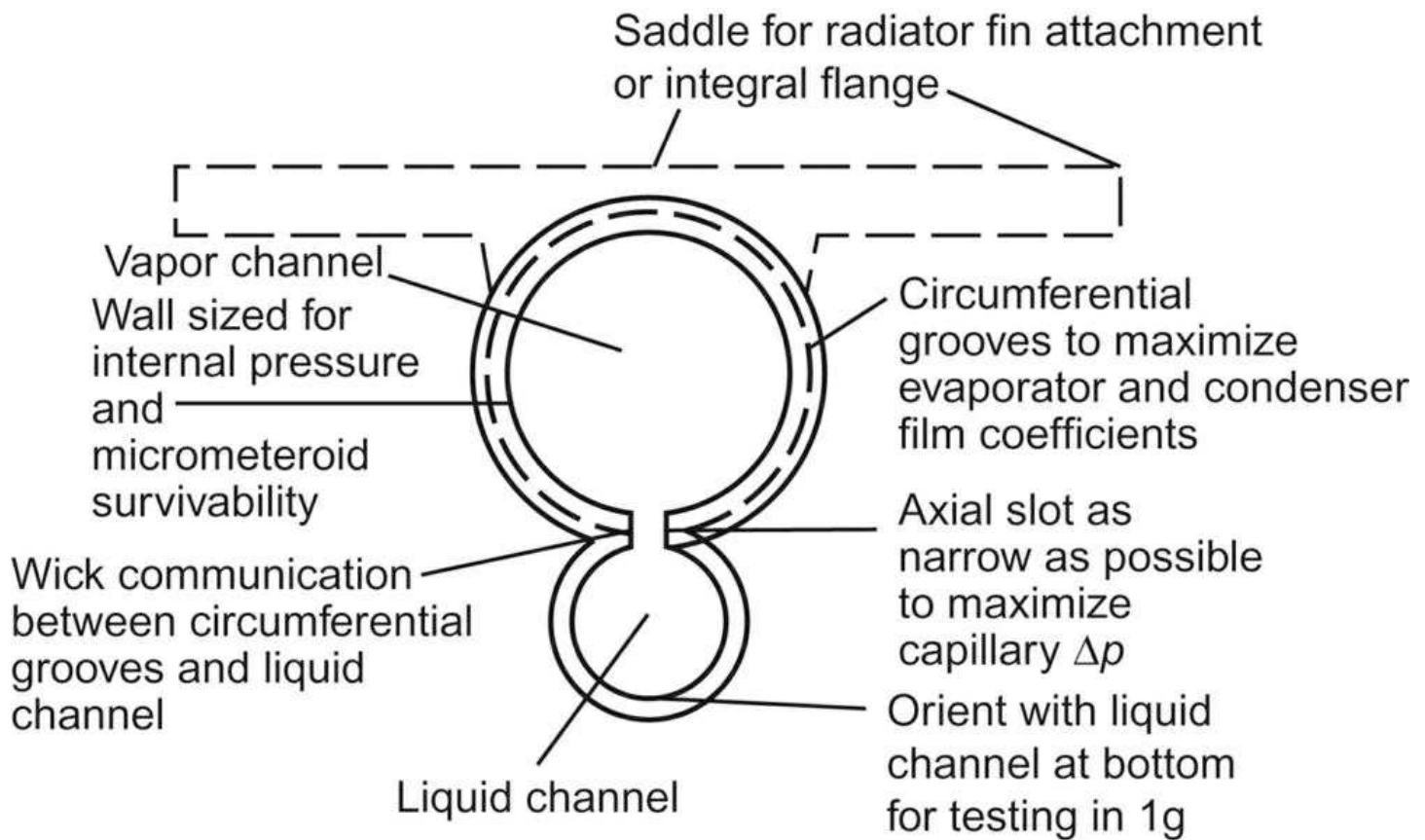
Figure 3.7: Monogroove heat pipe configuration

Not all wicks are associated solely with heat pipes. Research at GE Global Research Centre in the United States [60] is done to examine the wicking capability of a number of cryogenic fluids that are used in spacecraft for thermal management and as propellants. These include liquid nitrogen, helium, hydrogen and oxygen. The authors point out that the next generation of cryogen propellants (liquid oxygen and hydrogen) is currently planned by NASA for future space missions. In some applications the capillary structure is used to supply liquid propellant.

Using a commercially available stainless steel mesh with a pore size of about 5 μm, the research team indicated that a wicking height of approximately 60 mm was achieved using liquid nitrogen. The next challenge they are addressing is the construction of wicking structures with nanosized pores in order to demonstrate helium wicking.

3.3 THERMAL RESISTANCE OF SATURATED WICKS

One feature mentioned in discussions of the desirable properties of both the wick and the working fluid is the thermal conductivity. Expressions are available for predicting the thermal conductivities of saturated wicks of several types, and these are discussed below. The conductivity is an important factor in determining the allowable wick thickness.

3.3.1 Meshes

Gorring and Churchill [61] present solutions for the determination of the thermal conductivity of heterogeneous materials that are divided into three categories: dispersions, packed beds and continuous pairs. No satisfactory solution for a mesh is given because a mesh is a limiting case of dispersion, i.e. the particles are in contact but not tightly packed. However, since the conductivity of dispersions is less than that of packed beds, an estimate of mesh conductivity can be made using Rayleigh's expression for the effective conductivity of a dispersion consisting of a square array of uniform cylinders:

(3.1) $$k_w = \left(\frac{\beta - \varepsilon}{\beta + \varepsilon}\right) k_l$$

where

- $\beta = \left(1 + \frac{k_s}{k_l}\right) / \left(1 - \frac{k_s}{k_l}\right),$

- k_s is the thermal conductivity of solid phase,

- k_l is the thermal conductivity of liquid phase,

- ε is the volume fraction of solid phase.

A recent study of the effect of the number of layers of mesh in the wick on the overall heat pipe performance has thrown some doubt on the validity of conduction heat transfer models for wicks [62]. Most of the comparisons were made with the model of Kar and Dybbs [63], and no reference is made to the work of Gorring and Churchill [61] and the conductivity calculations derived above as a basis of their work. The experiments were limited to copper–water heat pipes, with copper mesh as the wick. The mesh was made of 0.109 mm diameter wire, with 3.94 strands per millimetre. The effect of fluid inventory (too little or too much fluid to saturate the wick) was investigated, and the effect of mesh layers was investigated using heat pipes with one, two and six layers of wick. In the latter three units, the amount of fluid to fully saturate the wick, no more and no less, was added.

It was found that with fully saturated wicks, the number of layers of wick had little influence on the effective thermal resistance. The difference in thermal resistance between a single mesh layer unit and one with six layers was only 40%, much less than would be predicted with conduction models. However, no alternatives to conduction models were proposed.

3.3.2 Sintered Wicks

The exact geometric configuration of a sintered wick is unknown because of the random dispersion of the particles and the varying degree of deformation and fusion, which occurs during the sintering process (see Chapter 4). For this reason, it is suggested that the sintered wick be represented by a continuous solid phase containing a random dispersion of randomly sized spheres of liquid.

Maxwell [64] has derived an expression that gives the thermal conductivity of such a heterogeneous material:

$$(3.2) \quad k_w = k_s \left[\frac{2 + k_l/k_s - 2\varepsilon(1 - k_l/k_s)}{2 + k_l/k_s + \varepsilon(1 - k_l/k_s)} \right]$$

Gorring and Churchill show that this expression agrees reasonably well with experimental results.

Work in Japan [65] has confirmed the applicability of Maxwell's equation above for screen wicks also. However, it is stressed that when the effective thermal conductivity is predicted from Eq. 3.2, it is necessary to accurately estimate the porosity. In order to do so, the intermeshing between the screen layers should be taken into account. This can be done by accurately measuring the overall thickness of the wick.

Xu et al. [66] more recently have reported on the thermal conductivity of sintered wicks used in LHPs. As with conventional heat pipes, the wick thermal conductivity in the evaporator is critical to optimum performance, and the work by these researchers concentrated on sintered nickel wicks with controlled porosity and pore characteristics. The porosities were between 70% and 75% with the mean pore size within a range of 10–80 μm. Thermal conductivities varied from 2 to 4 W/m K, and the thermal conductivity was influenced not only by the porosity but also by the pore size distribution. The conclusion was that for the same porosity, wicks with a smaller pore size and more uniform pore size distribution showed much lower thermal conductivity.

3.3.3 Grooved Wicks

The radial thermal resistance of grooves will be radically different in the evaporator and condenser sections. This occurs because of the differences in the mechanisms of heat transfer. In the evaporator the land or fin tip plays no active part in the heat transfer process. The probable heat flow path is conduction via the fin, conduction, across a liquid film at the meniscus and evaporation at the liquid–vapour interface.

In the condenser section, grooves will be flooded and the fin tip plays an active role in the heat transfer process. The build up of a liquid film at the fin tip will provide the major resistance to heat flow.

The thickness of the liquid film is a function of the condensation rate and the wetting characteristics of the working fluid.

Since the mechanism in the evaporator section is less complex and should provide the greatest resistance, we will concentrate on the analysis of that region.

Joy [67] and Eggers and Serkiz [68] propose identical models that assume one-dimensional heat conduction along the fin and one-dimensional conduction near the fin tip across the liquid to the liquid–vapour interface where evaporation occurs. In the liquid, the average heat flow length is taken to be a quarter of the channel width and the heat flow area, the channel half width

times the input length.

Thus,

$$(3.3) \quad \frac{\Delta T}{Q} = \frac{a}{k_s N f l_e} + \frac{1}{4 k_l l_e N} + \frac{1}{h_e \pi b N l_e}$$

where N is the number of channels, a the channel depth, b the channel half width and f the fin thickness.

Kosowski and Kosson [69] have made measurements of the maximum heat transport capability and radial thermal resistance of an aluminium grooved heat pipe using Freon 21 and Freon 113[1] and ammonia as the working fluids. The relevant dimensions of their heat pipes were as follows:

```
N                      = 30
a                      = 0.89 mm
2b                     = 0.76 mm
Pipe outside diameter  = 12.7 mm
Heat pipe no. 1 l_e    = 304.8 mm,  l_c = 477.6 mm
Heat pipe no. 2 l_e    = 317.5 mm,  l_c = 503 mm
```

The following heat transfer coefficients (based upon the outside area) were measured:

Fluid	h_c W/m^2 °C	h_c W/m^2 °C
Freon 21 (heat pipe no. 1)	1134	1700
Freon 113 (heat pipe no. 2)	652	1134
Ammonia (heat pipe no. 3)	2268	2840

Converting the heat transfer coefficients into a thermal resistance, we get:

Fluid	R °C/W(evap.)	R °C/W(cond.)
Freon 21	0.0735	0.031
Freon 113	0.122	0.044
Ammonia	0.035	0.0175

The contribution due to fin conduction is 0.0018°C/W (f=0.25 mm, k_w=200 W/m °C) and is negligible. This bears out Kosowski and Kosson's observation that the percentage fill has little effect upon the thermal resistance.

The evaporation term is also small, and the most significant contribution to the resistance is the liquid conduction term. Comparing the theory and experiment results suggest that the theory overpredicts the conduction resistance by a considerable amount (50–300%). It would therefore be more accurate to use the integration mean heat flow length

$$\left(1 - \frac{\pi}{4}\right) b$$

rather than $b/2$ such that

$$(3.4) \quad \frac{\Delta T}{Q} = \frac{\left(1 - \frac{\pi}{4}\right)}{2 k_l l_e N}$$

knowing the duty and allowable temperature drop into the vapour space, the number of grooves can be calculated for various geometries and working fluids.

In the heat pipe condenser section, or when the channels are mesh covered, the fin tip plays an active part in the heat transfer process, and the channels are completely filled. In this case, the parallel conduction equation is used:

$$(3.5) \quad k_w = k_s \left\{ 1 - \varepsilon \left(1 - \frac{k_l}{k_s} \right) \right\}$$

where ε, the liquid void fraction, is given by:

$$\varepsilon = \frac{2b}{2b + f}$$

where f is the fin thickness.

3.3.4 Concentric Annulus

In this case, the capillary action is derived from a thin annulus containing the working fluid. Thus:

(3.6) $k_w = k_l$

This case may also be used to analyse the effects of loose fitting mesh and sintered wicks.

3.3.5 Sintered Metal Fibres

Data tabulated by the Engineering Sciences Data Unit [70] on a variety of the more common wicks used in heat pipes include expressions for thermal conductivity. (Also included are expressions for porosity, minimum capillary radius, permeability and equivalent diameter.)

The following equation is given for the thermal conductivity of sintered metal fibre wicks:

(3.7) $k_w = \varepsilon^2 k_l + (1-\varepsilon)^2 k_s + \dfrac{4\varepsilon(1-\varepsilon)k_l\,k_s}{k_l + k_s}$

Values obtained using this equation may be compared with data obtained experimentally by Semena and his co-workers [49,71]. A more detailed discussion of metal felt wicks, with a presentation of data on other wick properties, is given by Acton [72].

3.3.6 Ceramic Wick Structures

Like the nickel-sintered wick mentioned above, the type of geometry of a wick in an LHP or CPL necessitates slightly different approaches – a typical LHP evaporator is shown in Fig. 6.27 – and the emphasis on thermal conductivity is obvious in this illustration. Santos et al. [73] in Brazil studied the use of ceramic wicks in both LHPs and CPLs, and the ceramic wicks used were sintered from alumina and mullite powders, giving porosities of 50%, a 1–3 μm pore size distribution and a permeability of 35×10^{-15} m^2. Grooves that act as vapour channels are visible in Fig. 3.8, and it was found that with practice a larger number of grooves could be machined in the units, as long as the wick was cleaned at 800°C for 1 h, afterwards, to remove any oil contamination.
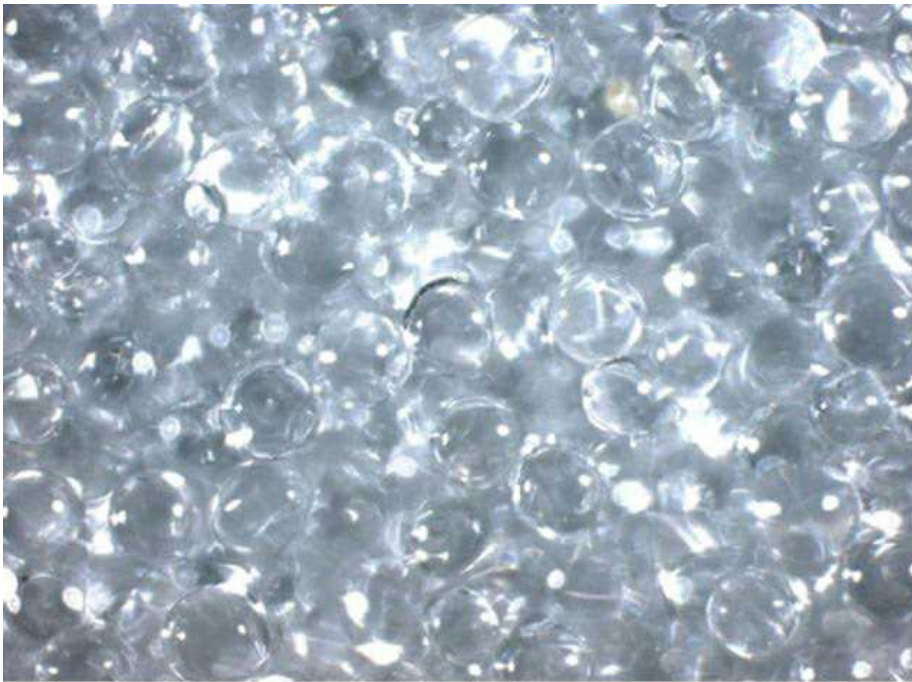
(a) Mono-porous wick (d: 275 μm)
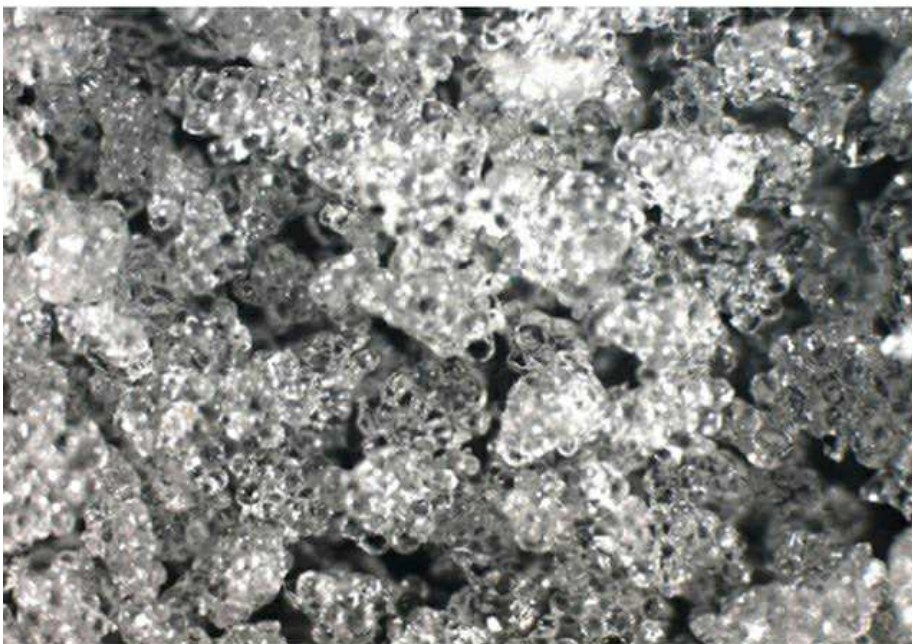
(b) Bi-porous wick (d: 125 μm, D: 675 μm)

Figure 3.8: (a) Ceramic wick with vapour channels (grooves) used in the LHP and (b) CPL [73]

[1]Note that R21 is not recommended for use now because of its toxicity. Other refrigerants, in particular those classed as CFCs and including R113, are banned or limited in their use because of their ozone layer depletion effects. 'New' refrigerants may be substituted as appropriate. R141b has been used in heat pipes, for example.

3.4 THE CONTAINER

The function of the container is to isolate the working fluid from the outside environment. It has, therefore, to be leak-proof, to maintain the pressure differential across its walls and to enable the transfer of heat to take place into and from the working fluid.

Selection of the container material depends on several factors. These are as follows:

i. Compatibility (both with working fluid and the external environment).

ii. Strength-to-weight ratio.

iii. Thermal conductivity.

iv. Ease of fabrication, including weldability, machineability and ductility.

v. Porosity.

vi. Wettability.

Most of these are self-explanatory. A high strength-to-weight ratio is more important in spacecraft applications, and the material should be non-porous to prevent the diffusion of gas into the heat pipe. A high thermal conductivity ensures minimum temperature drop between the heat source and the wick.

Recently work has been done on the potential of magnesium as a lightweight heat pipe structural material [74], where increasingly demanding electronics cooling applications both in space and in items such as graphics cards require increased heat pipe duties, more compact systems and lower weights. Compatibility data cited in Ref. [74] suggests that, subject to proper cleaning procedures, both pure ammonia and acetone were compatible with magnesium alloy.

The thermal conductivity of some wall materials is given in Appendix 2.

3.5 COMPATIBILITY

Compatibility has already been discussed in relation to the selection of the working fluid, wick and containment vessel of the heat pipe. However, this feature is of prime importance and warrants particular attention here.

The two major results of incompatibility are corrosion and the generation of non-condensable gas. If the wall or wick material is soluble in the working fluid, mass transfer is likely to occur between the condenser and the evaporator, with solid material being deposited in the latter. This will result either in local hot spots or blocking of the pores of the wick. Non-condensable gas generation is probably the most common indication of heat pipe failure and, as the non-condensables tend to accumulate in the heat pipe condenser section, which gradually becomes blocked, it is easy to identify because of the sharp temperature drop that exists at the gas–vapour interface.

Some compatibility data is of course available in the general scientific publications and from trade literature on chemicals and materials. However, it has become common practice to carry out life tests on representative heat pipes, the main aim of these tests being to estimate long-term materials compatibility under heat pipe operating conditions. At the termination of life tests, gas analyses and metallurgical examinations as well as chemical analysis of the working fluid may be carried out (see also Section 4.2).

Many laboratories have carried out life tests, and a vast quantity of data has been published. However, it is important to remember that while life test data obtained by one laboratory may indicate satisfactory compatibility, different assembly procedures at another laboratory, involving, for example a non-standard materials treatment process, may result in a different corrosion or gas generation characteristic. Thus, it is important to obtain compatibility data whenever procedural changes in cleaning or pipe assembly are made.

Stainless steel is a suitable container and wick material for use with working fluids such as acetone, ammonia and liquid metals from the point of view of compatibility. Its low thermal conductivity is a disadvantage, and copper and aluminium are used where this feature is important. The former is particularly attractive for mass-produced units using water as the working fluid. Plastic has been used as the container material, and at very high temperatures ceramics and refractory metals such as tantalum have been given serious consideration. In order to introduce a degree of flexibility in the heat pipe wall, stainless steel bellows have been used, and in cases where electrical insulation is important, a ceramic or glass-to-metal seal has been incorporated. This must of course be used in conjunction with electrically non-conducting wicks and working fluids.

3.5.1 Historical Compatibility Data

Long-term life tests on cryogenic heat pipes started a little later than those for higher temperature units. However, there are comprehensive data from ESA sources [75] on stainless steel (container was type 304L and wick type 316) heat pipes using as working fluids methane, ethane, nitrogen or oxygen, arising out of tests extending over a period of up to 13 years.

The test units were 1 m in length and either 3.2 or 6.35 mm outside diameter. Heat transport capability was up to 5 Wm (meaning that the pipe transport 5 W over 1 m, or, for example, 10 W over 0.5 m), and vapour temperatures 70–270 K. Tests were completed in the mid-1990s.

The main outcomes were as follows:

- All pipes retained maximum heat transport capability.

- All pipes maintained maximum tilt capability (capillary pumping demonstration).

- The evaporator heat transfer coefficient remained constant.

- No incompatibility or corrosion was evident in the oxygen and nitrogen pipes.

- Slight incompatibility, resulting in non-condensable gas extending over 1% of the heat pipe length and therefore affecting condenser efficiency, was noted in the ethane and methane units.

Unlike the oxygen and nitrogen TIG-welded pipes, the ethane and methane units were hard-brazed, and the implication is that the gas generation was attributed to this.

A comprehensive review of material combinations in the intermediate temperature range has been carried out by Basiulis and Filler [76] and is summarised below. Results are given in the paper over a wider range of organic fluids, most produced by Dow Chemicals, than given in Table 3.5.

Table 3.5: Compatibility Data – Low-Temperature Working Fluids

Wick Material	Working Fluids					
	Water	Acetone	Ammonia	Methanol	Dow-A	Dow-E
Copper	RU	RU	NU	RU	RU	RU
Aluminium	GNC	RL	RU	NR	UK	NR
Stainless steel	GNT	PC	RU	GNT	RU	RU
Nickel	PC	PC	RU	RL	RU	RL
Refrasil fibre	RU	RU	RU	RU	RU	RU
RU, recommended by past successful usage; RL, recommended by literature; PC, probably compatible; NR, not recommended; UK, unknown; GNC, generation of gas at all temperatures; GNT, generation of gas at elevated temperatures, when oxide is present.						

Tests in excess of 8000 h with ammonia/aluminium were reported, but only 1008 h had been achieved at the same time of data compilation with aluminium/acetone. No temperatures were specified by Basiulis for these tests: other workers have exceeded 16 000 h with the latter combination.

Later, the life test work at IKE, Stuttgart, was published [77], involving tests on about 40 heat pipes. The tests indicated that copper–water heat pipes could be operated without degradation over long periods (over 20 000 h), but severe gas generation was observed with stainless steel–water heat pipes. IKE had some reservations concerning acetone with copper and stainless steel. While compatible, it was stressed that proper care had to be given to the purity of both the acetone and the metal. The same reservation applied to the use of methanol.

Exhaustive tests on stainless steel–water heat pipes were also carried out at Ispra [78], where experiments were conducted with vapour temperatures as high as 250°C.

It was found that neither the variation of the fabrication parameters nor the addition of a large percentage of oxygen to the gas plug resulted in a drastic reduction of the hydrogen generation at 250°C. Hydrogen was generated within 2 h of start-up in some cases. The stainless steel used was type 316 and such procedures as passivation and outgassing were ineffective in arresting generation. However, it was found that the complimentary formation of an oxide layer on the steel did inhibit further hydrogen generation.

Gerrels and Larson [79], as part of a study of heat pipes for satellites, also carried out comprehensive life tests to determine the compatibility of a wide range of fluids with aluminium (6062 alloy) and stainless steel (type 321). The fluids used included ammonia, which was found to be acceptable. It is important, however, to ensure that the water content of the ammonia is very low, only a few parts per million concentration being acceptable with aluminium and stainless steel.

The main conclusions concerning compatibility made by Gerrels and Larson are given below, data being obtained for the following fluids.

n-Pentane	CP-32 (Monsanto experimentalfluid)

n-Heptane	CP-34 (Monsantoexperimental fluid)
Benzene	Ethyl alcohol
Toluene	Methyl alcohol
Water (with stainlesssteel)	Ammonia
	n-Butane

The stainless steel used with the water was type 321.

All life tests were carried out in gravity refluxing containers, with heat being removed by forced air convection, and being put in by immersion of the evaporator sections in a temperature-controlled oil bath.

Preparation of the aluminium alloy was as follows: initial soak in a hot alkaline cleaner followed by deoxidation in a solution of 112 g sodium sulphate and 150 ml concentrated nitric acid in 850 ml water for 20 min at 60°C. In addition, the aluminium was either machined or abraded in the area of the welds. A mesh wick of commercially pure aluminium was inserted in the heat pipes. The capsules were TIG-welded under helium in a vacuum-purged inert gas welding chamber. Leak detection followed welding, and the capsules were also pressure tested to 70 bar. A leak check also followed the pressure test.

The type 321 stainless steel container was cleaned before fabrication by soaking in hot alkaline cleaner and pickling for 15 min at 58°C in a solution of 15% by volume of concentrated nitric acid, 5% by volume of concentrated hydrochloric acid and 80% water. In addition the stainless steel was passivated by soaking for 15 min at 65°C in a 15% solution of nitric acid. Type 316 stainless steel was used as the wick. The capsule was TIG-welded in air with argon purging[2].

The boiling-off technique was used to purge the test capsules of air.

In the case of methyl alcohol, reaction was noted during the filling procedure, and a full life test was obviously not worth proceeding with.

Sealing of the capsules was by a pinch-off, followed by immersion of the pinched end in an epoxy resin for final protection.

The following results were obtained:

- *n*-Pentane: Tested for 750 h at 150°C. Short-term instabilities noted with random fluctuation in temperature of 0.2°C. On examination of the capsule, very light brownish areas of discolouration were noted on the interior wall but the screen wick appeared clean. No corrosion evidence was found. The liquid removed from the capsule was found to be slightly brown in colour.

- *n*-Heptane: Tested for 600 h at 160°C. Slight interior resistances noted after 465 h, but on opening the capsule at the end of the tests, the interior, including the screen, was clear, and the working fluid clean.

- Benzene: Tested for 750 h at 150°C plus vapour pressure 6.7 bar. Very slight local areas of discolouration found on the wall, the wick was clean, there was no evidence of corrosion and the liquid was clear. It was concluded that benzene was very stable with the chosen aluminium alloy.

- Toluene: Test run for 600 h at 160°C. A gradual decrease in condenser section temperature was noted over the first 200 h of testing but no change was noted following this. On opening the capsule, slight discolouration was noted locally on the container wall. This seemed to be a surface deposit, with no signs of attack on the aluminium. The screen material was clean and the working fluid clear at the end of the test.

- Water (stainless steel): Tested at 150°C plus for 750 h. Vapour pressure 6.7 bar. Large concentration of hydrogen was found when analysis of the test pipe was performed. This was attributed in part to poor purging procedure as there was discolouration in the area of the welds, and the authors suggest that oxidation of the surfaces had occurred. A brown precipitate was also found in the test heat pipe.

- CP-32: Tested for 550 h at 158°C. A brownish deposit was found locally on interior surfaces. Screen clean, but the working fluid was darkened.

- CP-34: Tested for 550 h at 158°C. Gas generation was noted. Also extensive local discolouration on the capsule wall near the liquid surface. No discolouration on the screen. The fluid was considerably darkened.

- Ammonia: Tested at 70°C for 500 h. Some discolouration of the wall and mesh was found following the tests. This was attributed to some non-volatile impurity in the ammonia which could have been introduced when the capsule was filled. In particular, the lubricant on the valve at the filling position could have entered with the working fluid. (This was the only test

pipe on which the filling was performed through a valve.)

- *n*-Butane: Tested for 500 h at 68°C. It was considered that there could have been non-condensable gas generation, but the fall off in performance was attributed to some initial impurity in the *n*-butane prior to filling. The authors felt that this impurity could be isobutane. Further tests on purer *n*-butane gave better results, but the impurity was not completely removed.

Gerrels and Larson argued thus concerning the viability of their life tests: 'It should be emphasised that the present tests were planned to investigate the compatibility of a particular working fluid-material combination for long-term (5 years) use in vapour chamber radiator under specified conditions. The reference conditions call for a steady state temperature of 143°C for the primary radiator fluid at the inlet to the radiator and a 160°C short-term peak temperature. The actual temperature to which the vapour chamber working fluid is exposed must be somewhat less than the primary radiator fluid temperature, since some temperature drop occurs from the primary radiator fluid to the evaporative surface within the vapour chamber. It is estimated that in these capsule tests the high temperature fluids were exposed to temperatures at least 10°C higher than the peak temperature and at least 20°C greater than long-term steady state temperatures that the fluids would experience in the actual radiator. Although the time of operation of these capsule tests is only about 1% of the planned radiator lifetime, the conditions of exposure were much more severe. It seems reasonable then, to assume that if the fluid-material combination completed the capsule tests with no adverse effects, it is a likely candidate for a radiator with a 5 year life.'

On the basis of the above tests, Gerrels and Larson selected the following working fluids:

- 6061 Aluminium at temperatures not exceeding 150°C:

    - Benzene

    - *n*-Heptane

    - *n*-Pentane

- 6061 Aluminium at temperatures not exceeding 65°C:

    - Ammonia

    - *n*-Butane

- The following fluids were felt not to be suitable:

    - Water (in type 321 stainless steel)

    CP-32
    CP-34   } in 6061 aluminium
    Methyl alcohol
    Toluene

Gerrels and Larson point out that Los Alamos Laboratory obtained heat pipe lives in excess of 3000 h without degradation using a combination of water and type 347 stainless steel.

Other data [80] suggest that alcohols in general are not suitable with aluminium.

Summarising the data of Gerrels and Larson, ammonia was recommended as the best working fluid for vapour chambers operating below 65°C and *n*-pentane, the best for operation above this temperature, assuming that aluminium is the container material.

At the other end of the temperature scale, long lives have been reported [19] for heat pipes with lithium or silver as the working fluid. With a tungsten rhenium (W-26 Re) container, a life of many years was forecast with lithium as the working fluid, operating at 1600°C. At 1700°C significant corrosion was observed after 1 year, while at 1800°C the life was as short as 1 month. W-26 Re/silver heat pipes were considered capable of operating at 2000°C for 10 900 h. Some other results are presented in Table 3.6 updated using information summarised in Ref. [81].

Table 3.6: Compatibility Data – Life Tests on High-Temperature Heat Pipes

Working	Material		Vapour Temperature (°C)	Duration (h)
	Wall	Wick		
Caesium	Ti		400	>2000

Table 3.6: Compatibility Data – Life Tests on High-Temperature Heat Pipes

Working	Material		Vapour Temperature (°C)	Duration (h)
	Wall	Wick		
	Nb+1%Zr		1000	8700
Potassium	Ni		600	>6000
	Ni		600	16 000
	Ni		600	24 500
	304, 347 ss		510, 650	6100
Sodium	Hastelloy X		715	>8000
	Hastelloy X		715	>33 000
	316 ss		771	>4000
	Nb+1%Zr		850	>10 000
	Nb+1%Zr		1100	1000
	304, 347 ss		650–800	7100
Bismuth	Ta		1600	39
	W		1600	118
Lithium	Nb+1%Zr		1100	4300
	Nb+1%Zr		1500	>1000
	Nb+1%Zr		1600	132
	Ta		1600	17
	W		1600	1000
	SGS-Ta		1600	1000
	TMZ		1500	9000
	W+26%Re		830–1000	7700
Lead	Nb+1%Zr		1600	19
	SGS-Ta		1600	1000
	W		1600	1000
	Ta		1600	>280
Silver	Ta		1900	100
	W		1900	335
	W		1900	1000
	Re	W	2000	300

Sodium is the working fluid of choice for many high-temperature applications, and the 10-year sodium heat pipe life text carried out by Thermacore Inc (see Appendix 4), in conjunction with Sest Inc., a company that has dynamically modelled the Stirling Converter and is adept at life predictions, gave most encouraging results [82]. One application for which such heat pipes are proposed (as when liquid–metal heat pipes were first examined over 50 years ago) is for thermal control in space nuclear power plants, which are believed to be making a comeback. the Thermacore study revolved around a Stirling-cycle based Space Power Converter heat pipe using Inconel 718 as the container material and a stainless steel wick. Examination after 10 years showed that a 30 µm thick layer of the container inner wall had been depleted of nickel, as a result of the long-term operation at 700°C, but it was concluded that this did not seem to affect the operation of the heat pipe.

The work also involved variable conductance sodium heat pipes (see Chapter 5 for a discussion of the VCHP) using Haynes 230 alloy as the container material [83].

Confirmation on the importance of the purity of the working fluid in contributing to a satisfactory life with lithium heat pipes is given by the work at the Commissariat à l'Energie Atomique in Grenoble [84]. In pointing out that failures in liquid metal heat pipes most commonly arise due to impurity-driven corrosion mechanisms, a rigorous purifying procedure for the lithium is carried out. This involves forced circulation on a cold and on a hot trap filled with Ti–Zr alloy as a getter to lower the oxygen and nitrogen content, respectively. The lithium is then distilled under vacuum before filling the heat pipe.

Data on extended tests on units using lead at more modest temperatures (around 1340°C) have been obtained over 4800 h at Los Alamos Laboratory [85]. Using one heat pipe fabricated from a molybdenum tube with a Ta-10% W wall and a W wick, no degradation in performance was noted over the test period.

One subject of much argument is the method of conducting life tests and their validity when extrapolating likely performance

over a period of several years. For example, on satellites, where remedial action in the event of failure is difficult, if not impossible, to implement, a life of 7 years is a standard minimum requirement[3]. It is therefore necessary to accelerate the life tests so that reliability over a longer period can be predicted with a high degree of accuracy.

Life tests on heat pipes are commonly regarded as being primarily concerned with the identification of any incompatibilities that may occur between the working fluid and wick and wall materials. However, the ultimate life test would be in the form of a long-term performance test under likely operating conditions. However, if this is carried out, it is difficult to accelerate the life test by increasing, say, the evaporator heat flux, as any significant increase is likely to cause dryout as the pipe will be operating well in excess of its probable design capabilities. Therefore, any accelerated life test that involves heat flux increases of the order of, say, four over that required under normal operating conditions must be carried out in the reflux mode, with regular performance tests to ensure that the design capability is still being obtained.

An alternative possibility as a way of accelerating any degradation processes, and one that may be carried out with the evaporator up if the design permits, is to raise the operating temperature of the heat pipe. One drawback of this method is the effect that increased temperature may have on the stability of the working fluid itself. Acetone cracking, for example, might be a factor where oxides of metals are present, resulting in the formation of diacetone alcohol that has a much higher boiling point than pure acetone.

Obviously there are many factors to be taken into account when preparing a life test programme, including such questions as the desirability of heat pipes with valves, or completely sealed units as used in practice. This topic is of major importance, and life test procedures are discussed more fully in Chapter 4.

One of the most comprehensive life test programmes was that carried out by Hughes Aircraft Co. [86]. Additional experience had been gained with some of the material combinations discussed above and a summary of recommendations based on these tests is given in Table 3.7.

Table 3.7: Hughes Aircraft Compatibility Recommendations

	Recommended	Not Recommended
Ammonia	Aluminium	Copper
	Carbon steel	
	Nickel	
	Stainless steel	
Acetone	Copper	
	Silica	
	Aluminium[1]	
	Stainless steel[1]	
Methanol	Copper	Aluminium
	Stainless steel	
	Silica	
Water	Copper	
	Monel	
	347 Stainless steel[2]	Stainless steel
		Aluminium
		Silica
		Inconel
		Nickel
		Carbon steel
Dowtherm A	Copper	
	Silica	
	Stainless steel[3]	
Potassium	Stainless steel	Titanium
	Inconel	
Sodium	Stainless steel	Titanium
	Inconel	

Note Type 347 stainless steel as specified in AISI codes does not contain tantalum. AISI type 348, which is otherwise identical except for a small tantalum content, should be used in the United Kingdom (Authors). Work on water in steel heat pipes is also discussed later in this chapter.

Table 3.7: Hughes Aircraft Compatibility Recommendations

	Recommended	Not Recommended
[1]The use of acetone with aluminium and/or stainless steel presented problems to the authors, but others have had good results with these materials. The problem may be temperature-related; use with caution.		
[2]Recommended with reservations.		
[3]This combination should be used only where some non-condensable gas in the heat pipe is tolerable, particularly at higher temperatures.		
Note Type 347 stainless steel as specified in AISI codes does not contain tantalum. AISI type 348, which is otherwise identical except for a small tantalum content, should be used in the United Kingdom (Authors). Work on water in steel heat pipes is also discussed later in this chapter.		

The lack of support given to a nickel–water combination is based on an Arrhenius-type accelerated life test carried out by Anderson [87]. Work carried out on nickel wicks in water heat pipes, generally with a copper wall, has, in the authors' experience, not created compatibility problems, and this area warrants further investigation. With regard to water–stainless steel combinations, for some years the subject of considerable study and controversy, the Hughes' work suggests that type 347 stainless steel is acceptable as a container with water. Tests had been progressing since December 1973 on a 347 stainless steel container, copper wicked water heat pipe operating at 165°C, with no trace of gas generation. (Type 347 stainless steel contains no titanium but does contain niobium.) Surprisingly, a type 347 wick caused rapid gas generation. The use of Dowtherm A (equivalent to Thermex, manufactured by ICI) is recommended for moderate temperatures only, breakdown of the fluid progressively occurring above about 160°C. With careful materials preparation Thermex appears compatible with mild steel and the Hughes data are limited somewhat by the low operating temperature conditions.

Hughes emphasised the need to carry out rigorous and correct cleaning procedures, and also stressed that the removal of cleaning agents and solvents prior to filling with working fluid is equally important.

3.5.2 Compatibility of Water and Steel – a Discussion

Water is an ideal working fluid for heat pipes, because of its high latent heat, thus requiring a relatively low inventory, its low cost and its high 'figure of merit'. As shown already in this chapter, water is compatible with a number of container materials, the most popular being copper. However, ever since heat pipes were first conceived, experimenters have experienced difficulty in operating a water–steel (be it mild, boiler or stainless steel) heat pipe without obtaining the generation of hydrogen in the container. This gas generation always manifests itself as a cold plug of gas at the condenser section of the heat pipe – blocking off surface for heat rejection. There is a sharply defined interface between the water vapour and the non-condensable gas, making the presence readily identifiable. The effect is similar to that when air is present in a conventional domestic radiator system but of course the reasons may be different.

The earlier description in Chapter 1 of the Perkins tube and its derivatives, which used iron or steel with water as the working fluid, shows that the fluid–wall combination has demonstrated a significant life, although gas generation did occur.

3.5.2.1 The Mechanism of Hydrogen Generation and Protective Layer Formation

The reaction responsible for the generation of hydrogen is:

$$Fe + 2H_2O \rightarrow Fe(OH)_2 + H_2$$
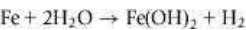
Corrosion of steel is negligible in the absence of oxygen. Therefore, in a closed system such as a steel heat pipe with water as the working fluid, the corrosion only takes place until all the free oxygen is consumed. When oxygen is deficient, low alloy steels develop a hydrated magnetite layer in neutral solutions, by decomposition of the ferrous hydroxide. Further dehydration, or a chemical reaction of iron with water, occurs.

$$3Fe(OH)_2 \rightarrow Fe_3O_4 + 2H_2O + H_2$$

The conversion of $Fe(OH)_2$ leads to a protective layer of Fe_3O_4 especially with mild/carbon steels. In high-temperature water, this Fe_3O_4 layer is responsible for the good corrosion resistance of boiler steels in power generation plant boilers.

A number of different methods have been developed to obtain non-porous and adhesive magnetite layers, and these are discussed below.

In addition, several other observations have been made concerning factors which influence the long-term compatibility of steel with water:

- The pH value of the water should be greater than 9 (some researchers quote a range of 6–11 as being satisfactory – see below for a discussion). This value can be adjusted by conditioning of the water. The high pH value has also been reported to favour the growth of effective passive layers.

- The water must be fully degassed and desalted (or demineralised) before conditioning.

- The protective layer can be destroyed if the metal is locally overheated above 570°C (thus the passivation reaction is best carried out once the container has been welded or subjected to any other high-temperature procedures during assembly).

3.5.2.2 Work Specifically Related to Passivation of Mild Steel

There are a number of potential/active heat pipe applications where the advantages of using water with mild steel is attractive. For example, in domestic radiators attempts have been made to construct two-phase units with more rapid responses than those of a single-phase heating system. Japanese and Korean companies have marketed such products, and research in the United Kingdom has also investigated such combinations.

Work some years ago in the then Czechoslovakia [88] discusses three approaches to the prevention of hydrogen generation:

1. Preparation of heat pipes with an inhibitor added to the working fluid.

2. Preparation of pipes provided with a protective oxide layer.

3. Preparation of heat pipes involving a protective layer in conjunction with an inhibitor.

All the tests were carried out with the condenser above the evaporator, and with the evaporator in a sand bath heated to 200°C. The test period was 6000 h.

Measurements were made of the temperature difference along the pipes (higher values are poor), and the gases inside were analysed for hydrogen. All results are compared in Table 3.8. A steel heat pipe without any treatment was tested to form the basis for comparison – pipe (X). As can be seen from Table 3.8, this exhibited a high-temperature drop along its length, indicating gas generation.

Table 3.8: Heat Pipe Specification and Analytical Results After 6000 h

Code	Surface Treatment	Working Fluid	pH	Inhibitor Concentration	Temperature Difference (°C)	Amount of H_2
X	None	Water	8.32	None	33.2	Maximum
A	None	+Inhibitor	10.52	0.04	6	Trace
b	Oxidation+vapour at 550°C	Water	8.01	None	10	Trace
c_1	Oxidation+vapour at 550°C	+Inhibitor	9.05	0.03	3	None
c_2	Oxidation+vapour+catalyst at 550°C	+Inhibitor	7.01	0.45	13	Trace

3.5.2.3 Use of an Inhibitor

The inhibitor selected was an anodic type based on a chromate, to minimise oxidation. K_2CrO_4 was selected and used in a concentration of 5 g for 1l of water, with a pH of 7.87. The pipe internal surface had been previously degassed. The inhibitor acts to decelerate the anodic partial reaction ($Fe \rightarrow Fe^{2+}+2e$). The chromate anion is first adsorbed on the active sites of the metal surface and the film formed is chromium III oxide, Cr_2O_3, or chromium III hydroxide-chromate, $Cr(OH)CrO_4$. The passivating concentration varies from 0.1% to 1.0%.

The pipe (A) with an inhibitor and no protective oxide layer exhibited a temperature difference along its length of 6°C and traces of hydrogen were found on analysis of the gases in the heat pipe.

3.5.2.4 Production of a Protective Layer

As discussed above, the natural ageing process of mild steel leads to a protective layer of magnetite being formed, which reduces hydrogen generation rates. It was found in tests on naturally passivated steel in the laboratory that while the performance stabilised after 2000 h of operation, there was in the intervening period sufficient generation of hydrogen to reduce significantly the performance, again evident in an increased temperature drop along the length.

Therefore, it was decided to accelerate the passivation process prior to filling and sealing the heat pipe by oxidising the pipe surface with superheated steam vapour. The efficiency of this process is determined by the thickness and porosity of the magnetite layer formed. Optimum thickness of the layer was found to be 3–5 µm. Both of these properties are a function of temperature and the time of oxidation, and can also be positively influenced by adding an oxidation catalyst, ammonium molybdate $(NH_4)_2MoO_4$ to the water vapour. This leads to molybdenum trioxide being deposited on the surfaces being treated. Note that the stability of magnetite reduces above 570°C and this temperature should not be exceeded during the process (as mentioned above).

The heat pipe tested (*b*) with vapour oxidation carried out at 550°C had, at the end of the test period, working fluid with a pH of 8.01 and had a temperature difference along its length of 10°C, larger than that with the inhibitor alone. Only a trace of hydrogen was found on analysis.

3.5.2.5 Pipes with Both Inhibitor and Oxide Layers

A combination of magnetite layer and inhibitor introduced into the working fluid was then tested. It was pointed out that the pH of the inhibitor solution should be maintained in the range 6<pH<11 so that the inhibitor did not break down the magnetite layer.

The optimum performance was achieved with pipe c_1, which was passivated using superheated steam without addition of the oxidation catalyst, and also contained an inhibitor. The catalyst led to inferior performance in the pipe c_2, which again had an inhibitor present. The poor performance of this latter heat pipe was attributed to faults in the protective layer due to the exceeding of a limiting layer thickness and by dissolution of MoO_3 in the aqueous solution of potassium chromate.

The temperature drop in pipe c_1 was 3°C, and there was no indication of hydrogen formation. An analysis of the working fluid showed that the pH is strongly shifted towards the alkaline region after the 6000 h test.

(Note that the temperature difference is that measured along the condenser section of the heat pipe.)

In a further communication [89], the Czech research team reported on the extension of the tests to 18 000 h. They concluded, on the basis of the very small (1°C) increase in temperature difference for pipes (*a*) and (c_1) measured over the additional 12 000 h, that the inhibitor stabilises the performance of water–steel heat pipes, but a superior performance is achieved with the combination of inhibitor and oxidation. However, this latter process was substantially more costly.

The use of inhibitors tested for up to 35 000 h has been reported from the Ukraine [90]. The steel used was Steel 10 GOST 8733-87. Best results with only a minor increase in thermal resistance were achieved with a chromate-based inhibitor. Although the vapour temperature was only 90°C, the authors recommended that accelerated life tests should be done for at least 35 000 h at 200–250°C.

Work in China [91] on long-term compatibility of steel–water units, with a carbon content slightly higher than the steel used in the RRR (0.123%), gave similar results to those of Novotna et al. The Chinese tests were carried out over a period of 29 160 h, with temperature drops along the heat pipes with passivation, with or without an inhibitor, never exceeding 6°C, and frequently being substantially less. Since this, carbon steel–water heat pipes have become a regular feature of heat recovery plant in China, with one company producing over 1000 heat exchangers [92].

Reported in 2003, the extensive activities in China on steel–water heat pipes have continued [93]. Tests in heat recovery duties where exhaust gases are up to 700°C have been carried out safely. Typified by the data in Ref. [94], the National Technological Supervision Administration of China has, with others, formulated standards for the technical specification of carbon steel–water heat pipe heat exchangers and boiler heat pipe economisers.

Further work in France, following an almost identical path to that in Czechoslovakia, confirms the above results. The authors [95] concluded: 'In accordance with other studies, the addition of chromates in a neutral solution of distilled water and the formation of a magnetite layer are sufficient conditions to prevent corrosion and hydrogen release in water/mild steel heat pipes at any operating temperature.'

The importance of deoxygenation of the water even in systems that are not sealed to such a high integrity as heat pipes is demonstrated by work on district heating pipeline corrosion [96]. Effective passivation was achieved in conjunction with deaerated water with an oxygen content of 40µg/kg, whereas if normal water with an oxygen content of 4 mg/kg was used, pitting on the steel surfaces appeared.

3.5.2.6 Comments on the Water–Steel Data

The above data suggest that, with correct treatment of the water and the internal wall of the heat pipe/thermosyphon, steel and water are compatible in terms of the rate of non-condensable gas generation.

There is a cost associated with the prevention of gas generation, both in treating the water and in achieving a suitable magnetite (or other material/form) layer on the container wall. If any subsequent manufacturing process (e.g. welding, heat treatment, enamel coating) involves a high-temperature operation downstream of passivation, this may need to be rescheduled – it is always important when considering a heat pipe procedure that involves changes to surface structures internally to remember that subsequent manufacturing processes may degrade such procedures. Similarly, the heat pipe manufacturer may have little or no control over the system installer.

[2]In both series of US tests, mixtures of materials were used. This is not good practice in life tests as any degradation may not be identified as being caused by the particular single material.

[3]ESA requirement.

3.6 HOW ABOUT WATER AND ALUMINIUM?

It is interesting to observe that there is, on the other hand, little or no data on the compatibility of aluminium and water as heat pipe combinations, and few attempts have been made by the heat pipe fraternity to overcome the perceived incompatibility using this combination.

The Ukrainian research mentioned in Ref. [90] did look at aluminium–water thermosyphons, using alloy 6060 and it was found that some corrosion could be slowed by selection of optimum pH conditions (5–6.5) and passivation method. However, long-term compatibility was not demonstrated.

Geiger and Quataert [97] have carried out corrosion tests on heat pipes using tungsten as the wall material and silver (Ag), gold (Au), copper (Cu), gallium (Ga), germanium (Ge), indium (In) and tin (Sn) as working fluids. The results from tests carried out at temperatures of up to 1650°C enable Table 3.6 to be extended above 2000°C, albeit for heat pipes having comparatively short lives. Of the above combinations, tungsten and silver proved the most satisfactory, giving a life of 25 h at 2400°C, with a possible extension if improved quality tungsten could be used.

3.7 HEAT PIPE START-UP PROCEDURE

Heat pipe start-up behaviour is difficult to predict and may vary considerably depending upon many factors. The effects of working fluid and wick behaviour and configuration on start-up performance have been studied qualitatively, and a general description of start-up procedure has been obtained [98].

During start-up, vapour must flow at a relatively high velocity to transfer heat from the evaporator to the condenser, and the pressure drop through the centre channel will be large. Since the axial temperature gradient in a heat pipe is determined by the vapour pressure drop, the temperature of the evaporator will be initially much higher than that of the condenser. The temperature level reached by the evaporator will, of course, depend on the working fluid used. If the heat input is large enough, a temperature front will gradually move towards the condenser section. During normal heat pipe start-up, the temperature of the evaporator will increase by a few degrees until the front reached the end of the condenser. At this point, the condenser temper will increase until the pipe structure becomes almost isothermal (when lithium or sodium is used as working fluids, this process occurs at temperature levels where the heat pipe becomes red hot, and the near isothermal behaviour is visible).

Heat pipes with screen-covered channels behave normally during start-up as long as heat is not added too quickly. Kemme found that heat pipes with open channels did not exhibit straightforward start-up behaviour. Very large temperature gradients were measured, and the isothermal state was reached in a peculiar manner. When heat was first added, the evaporator temperature levelled out at 525°C (sodium being the working fluid) and the front, with a temperature of 490°C, extended only a short distance into the condenser section. In order to achieve a near isothermal condition more heat was added, but the temperature of the evaporator did not increase uniformly; a temperature of 800°C being reached at the end of the evaporator farthest from the condenser. Most of the evaporator remained at 525°C and a sharp gradient existed between these two temperature regions.

Enough heat was added so that the 490°C front eventually reached the end of the condenser. Before this occurred, however, temperatures in excess of 800°C were observed over a considerable portion of the evaporator. Once the condenser became almost isothermal, its temperature rapidly increased and the very hot evaporator region quickly cooled in a pattern, which suggested that liquid return flow was in fact taking place. From this point, the heat pipe behaved normally.

In some instances during start-up, when the vapour density is low and its velocity high, the liquid can be prevented from returning to the evaporator. This is more likely to occur when open return channels are used for liquid transfer than when

porous media are used.

Further work by van Andel [99] on heat pipe start-up has enabled some quantitative relationships to be obtained which assist in ensuring that satisfactory start-up can occur. This is based on the criterion that burn-out does not occur, i.e. the saturation pressure in the heated zones should not exceed the maximum capillary force. If burn-out is allowed to occur, drying of the wick results, inhibiting the return flow of liquid.

A relationship that gives the maximum allowable heat input rate during the start-up condition is

$$(3.8) \quad Q_{max} = 0.4 \pi r_c^2 \times 0.73 L (P_E \rho_E)^{1/2}$$

where r_c is the vapour channel radius, L the latent heat of vaporisation, and P_E and ρ_E are the vapour pressure and vapour density in the evaporator section.

It is important to meet the start-up criteria when a heat pipe is used in an application that may involve numerous starting and stopping actions, for example in cooling a piece of electronic equipment or cooling brakes. One way in which the problem can be overcome is to use an extra heat source connected to a small branch heat pipe when the primary role of cooling is required, thus reducing the number of start-up operations. The start-up time of gas-buffered heat pipes is quicker.

Busse [100] has made a significant contribution to the analysis of the performance of heat pipes, showing that before sonic choking occurs, a viscous limitation that can lie well below the sonic limit can be met. This is described in detail in Chapter 2.

Where it is required to calculate transient behaviour of heat pipes during start-up and in later transient operation, time constants and other data may be calculated using equations presented in Ref. [81].

REFERENCES

[1] N. Zhang *Innovative heat pipe systems using a new working fluid Int. Commun. Heat Mass Transf.*28 82001 1025–1033

[2] Anon, Thermophysical properties of heat pipe working fluids: operating range between −60°C and 300°C. Data Item No. 80017, Engineering Sciences Data Unit, London, 1980.

[3] M. Esen *Thermal performance of a solar cooker integrated vacuum-tube collector with heat pipes containing different refrigerants Sol. Energy*76 2004 751–757

[4] H. Jouhara A.J. Robinson *Experimental investigation of small diameter two-phase closed thermosyphons charged with water, FC-84, FC-77 and FC-3283 Appl. Therm. Eng.*30 2010 201–211

[5] R.T. Dobson, Relative thermal performance of supercritical CO_2, H_2O, N_2 and He charged closed-loop thermosyphon-type heat pipes, in: Proceedings of the Sixteenth International Heat Pipe Conference, Lyon, France, 20–24 May 2012.

[6] M. Groll, H. Nguyen-Chi, H. Krähling, Heat recovery units employing reflux heat pipes as components, Final Report, Contract EE-81-133D(B), Commission of the European Communities Report EUR9166EN, 1984.

[7] M. Groll *Heat pipe research and development in Western Europe Heat Recov. Syst. CHP.*9 11989 19–66

[8] S. Roesler, D. Heine, M. Groll, Performance of closed two-phase thermosyphons with high-temperature organic working fluids, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Hemisphere, New York, NY, 1991.

[9] J. Zhang, J. Li, J. Yang, T. Xu, Analysis of heat transfer in the condenser of naphthalene thermosyphon at small inclination, Paper H3-1, in: Proceedings of Tenth International Heat Pipe Conference, Stuttgart, 21–25 September 1997.

[10] F.H. Milanez, M.B.H. Mantelli, A two-phase loop thermosyphon with naphthalene as working fluid, in: Proceedings of the Sixteenth International Heat Pipe Conference, Lyon, France, 20–24 May 2012.

[11] A. Devarakonda, J.K. Olminsky, An evaluation of halides and other substances as potential heat pipe fluids, in: Proceedings of the Second International Energy Conversion Engineering Conference, vol. 1, 2004, pp. 471–477.

[12] L.M. Libby W.F. Libby *One parameter equation of state for metals and certain other solids Proc. Natl. Acad. Sci. USA*69 111972 3305–3306

[13] W.G. Anderson, et al., Intermediate temperature heat pipe life tests, in: Proceedings of the Sixteenth International Heat Pipe Conference, Lyon, France, 20–24 May 2012.

[14] J.E. Deverall, Mercury as a heat pipe fluid, ASME Paper 70 HT/Spt-8, American Society of Mechanical Engineers, 1970.

[15] D.A. Reay, Mercury wetting of wicks, in: Proceedings of the Fourth C.H.I.S.A. Conference, Prague, September 1972.

[16] T. Yamamoto K. Nagata M. Katsuta Y. Ikeda *Experimental study of mercury heat pipes Exp. Therm. Fluid Sci.*9 1994 39–46

[17] P. Marcarino A. Merlone *Gas-controlled heat pipes for accurate temperature measurements Appl. Therm. Eng.*23 2003 1145–1152

[18] W. Bienert, Heat pipes for solar energy collectors, in: Proceedings of the First International Heat Pipe Conference, Stuttgart, Paper 12-1, October 1973.

[19] J.E. Kemme, C.A. Busse, Performance investigations of liquid metal heat pipes for space and terrestrial applications. AIAA Paper 78-431, in: Proceedings of the Third International Heat Pipe Conference, Palo Alto, CA, May 1978.

[20] D. Quataert, C.A. Busse, F. Geiger, Long time behaviour of high temperature tungsten-rhenium heat pipes with lithium or silver as the working fluid, Paper 4-4, in: Proceedings of the Third International Heat Pipe Conference, Palo Alto, CA, May 1978.

[21] J.-M. Tournier M.S. El-Genk *Startup of a horizontal lithium molybdenum heat pipe from a frozen state Int. J. Heat Mass Transf.*46 2003 671–685

[22] C.Y. Tsai H.T. Chien P.P. Ding B. Chan T.Y. Luh P.H. Chen *Effect of structural character of gold nano particles in nano fluid on heat pipe thermal performance Mater. Lett.*58 2004 1461–1465

[23] N. Putra W.N. Septiadi H. Rahman R. Irwansyah *Thermal performance of screen mesh wick heat pipes with nano fluids Exp. Therm. Fluid Sci.*40 2012 10–19

[24] A. Brusly Solomon K. Ramachandran B.C. Pillai *Thermal performance of a heat pipe with nanoparticles coated wick Appl. Therm. Eng.*36 2012 106–112

[25] K.Y. Leong R. Saidur T.M.I. Mahlia Y.H. Yau *Performance investigation of nanofluids as working fluid in a thermosyphon air preheater Int. Commun. Heat Mass Transf.*39 2012 523–529

[26] J.A. Lidbury, A helium heat pipe, Nimrod Design Group Report NDG-72-11, Rutherford Laboratory, England, 1972.

[27] M. Groll *Wärmerohre als Baudemente in der Wärme-und Kältetechnik Brennst-Waerme-kraft*25 11973 (in German)

[28] P.J. Marto, W.L. Mosteller, Effect of nucleate boiling on the operation of low temperature heat pipes, ASME Paper 69-HT-24.

[29] E.C. Phillips, Low temperature heat pipe research program, NASA CR-66792, 1970.

[30] D. Keser, Experimental determination of properties of saturated sintered wicks, in: First International Heat Pipe Conference, Stuttgart, 1973.

[31] K. Moritz R. Pruschek *Limits of energy transport in heat pipes Chem. Ing. Technik.*41 11969 2 (in German)

[32] P. Vinz, C.A. Busse, Axial heat transfer limits of cylindrical sodium heat pipes between 25 W/cm^2 and 15.5 kW/cm^2, in: Proceedings of the First International Heat Pipe Conference, Paper 2-1, Stuttgart, 1973.

[33] V.A. Busse, Heat pipe research in Europe, Euratom Report, EUR 4210 f, 1969.

[34] D. Quataert, C.A. Busse, F. Geiger, Long term behaviour of high temperature tungsten–rhenium heat pipes with lithium or silver as working fluid, in: First International Heat Pipe Conference, Paper 4-4, Stuttgart, 1973.

[35] A.M. Schroff M. Armand *Le Caloduc Rev. Tech. Thomson-CSF*1 41969 (in French)

[36] R.A. Farran, K.E. Starner, Determining wicking properties of compressible materials for heat pipe applications, in: Proceedings of Aviation and Space Conference, Beverley Hills, CA, June 1968.

[37] J.K. Ferrell, J. Alleavitch, Vaporisation heat transfer in capillary wick structures, Department of Chemical Engineering

Report, North Carolina University, Raleigh, CA, 1969.

[38] R.A. Freggens, Experimental determination of wick properties for heat pipe applications, in: Fourth Intersociety Energy Conference Engineering Conference, Washington DC, 22–26 September 1969, pp. 888–897.

[39] E.C. Phillips, J.D. Hinderman, Determination of properties of capillary media useful in heat pipe design, ASME Paper 69-HT-18, 1969.

[40] H. Birnbreier, G. Gammel, Measurement of the effective capillary radius and the permeability of different capillary structures, in: First International Heat Pipe Conference, Paper 5-4, Stuttgart, October 1973.

[41] L.S. Langston, H.R. Kunz, Liquid transport properties of some heat pipe wicking materials, ASME Paper 69-HT-17, 1969.

[42] B.G. McKinney, An experimental and analytical study of water heat pipes for moderate temperature ranges, NASA-TM-X53849, Marshall Space Flight Center, AL, June 1969.

[43] A.T. Calimbas, R.H. Hulett, An avionic heat pipe, ASME Paper 69-HT-16, New York, NY, 1969.

[44] S. Katzoff, Heat pipes and vapour chambers for thermal control of spacecraft, AIAA Paper 67-310, 1967.

[45] C.J. Hoogendoorn, S.G. Nio, Permeability studies on wire screens and grooves, in: First International Heat Pipe Conference, Paper 5-3, Stuttgart, October 1973.

[46] K.R. Chun, Some experiments on screen wick dry-out limits, ASME Paper 71-WA/HT-6, 1971.

[47] M.N. Ivanovskii et al *Investigation of heat and mass transfer in a heat pipe with a sodium coolant High Temp.*8 21970 299–304

[48] R.W. Williams D.K. Harris *The heat transfer limit of step-graded metal felt heat pipe wicks Int. J. Heat Mass Transf.*48 2005 293–305

[49] M.G. Semena A.P. Nishchik *Structure parameters of metal fibre heat pipe wicks J. Eng. Phy.*35 51957 1268–1272

[50] A.G. Kostornov et al *A study of heat transfer in heat pipe evaporators with metal fibre capillary structures J. Enhanced Heat Transf.*19 12012 43–52

[51] T. Takaoka et al *Development of long heat pipes and heat pipe applied products Fujikura Tech. Rev.* 1985 77–93

[52] A. Schimizu, et al., Characteristics of a heat pipe with carbon fibre wick, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Hemisphere, New York, NY, 1991.

[53] J.V. Kaudinga, et al., Experimental investigation of a heat pipe with carbon fibre wick, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Hemisphere, New York, NY, 1991.

[54] C. Byon S.J. Kim *Capillary performance of bi-porous sintered metal wicks Int. J. Heat Mass Transf.*55 2012 4096–4103

[55] C. Figus L. Ounougha P. Bonzom W. Supper C. Puillet *Capillary fluid loop developments in Astrium Appl. Therm. Eng.*23 2003 1085–1098

[56] L. Ottenstein, D. Butler, J. Ku, Flight testing of the capillary pumped loop 3 experiment in: Proceedings of the 2002 International Two-phase Thermal Control Technology Workshop, Mitchellville, MA, 24–26 September 2002.

[57] T.D. Swanson G.C. Birur *NASA thermal control technologies for robotic spacecraft Appl. Therm. Eng.*23 2003 1055–1065

[58] F. Dobran *Heat pipe research and development in the Americas Heat Recov. Syst. CHP.*9 11989 67–100

[59] D.A. Reay *Heat transfer enhancement – a review of techniques Heat Recov. Syst. CHP.*11 11991 1–40

[60] T. Zhang P. deBock E.W. Stautner T. Deng C. Immer *Demonstration of liquid nitrogen wicking using a multi-layer metallic wire cloth laminate Cryogenics*52 2012 301–305

[61] R.L. Gorring S.W. Churchill *Thermal conductivity of heterogeneous materials Chem. Eng. Prog.*57 71961

[62] R. Kempers D. Ewing C.Y. Ching *Effect of number of mesh lasers and fluid loading on the performance of screen mesh*

*wicked heat pipes Appl. Therm. Eng.*26 2006 589–595

[63] K. Kar, A. Dybbs, Effective thermal conductivity of fully and partially saturated metal wicks, in: Proceedings of the Sixth International Heat Transfer Conference, vol. 3, Toronto, Canada, 1978, pp. 91–97.

[64] J.C. Maxwell third ed. *A treatise on electricity and magnetism*vol. 1 1954 OUP Reprinted by Dover, New York, NY, 1981

[65] H. Kozai, et al., The effective thermal conductivity of screen wick, in: Proceedings of the Third International Heat Pipe Symposium, Tsukuba, Japan Association for Heat Pipes, Sagamihara, Japan, 1988.

[66] J. Xu Y. Zou D. Fan L. Cheng *Effect of pore parameters on thermal conductivity of sintered LHP wicks Int. J. Heat Mass Transf.*55 2012 2703–2706

[67] P. Joy, Optimum cryogenic heat pipe design, ASME Paper 70-HT/SpT-7, 1970.

[68] P.E. Eggers, A.W. Serkiz, Development of cryogenic heat pipes, ASME Paper 70-WA/Ener-1, New York, NY, 1970.

[69] N. Kosowski, R. Kosson, Experimental performance of grooved heat pipes at moderate temperatures, AIAA Paper 71-409, 1971.

[70] Anon, Heat pipes – properties of common small-pore wicks, Data Items No. 79013, Engineering Sciences Data Unit, London, 1979.

[71] M.G. Semena V.K. Zaripov *Influence of the diameter and length of fibres on material heat transfer of metal fibre wicks of heat pipes Therm. Eng.*24 41977 69–72

[72] A. Acton *Correlating equations for the properties of metal felt wicks. Advances in heat pipe technology Proc. Fourth Int. Heat Pipe Conf.* 1981 Pergamon Press Oxford

[73] P.H.D. Santos E. Bazzo A.A.M. Oliveira *Thermal performance and capillary limit of a ceramic wick applied to LHP and CPL Appl. Therm. Eng.*41 2012 91–103

[74] X. Yang Y.Y. Yan D. Mullen *Recent developments of lightweight, high performance heat pipes Appl. Therm. Eng.*33–34 2012 1–14

[75] S. Van Oost, B. Aalders, Cryogenic heat pipe ageing, Paper J-6, in: Proceedings of the Tenth International Heat Pipe Conference, Stuttgart, 21–25 September 1997.

[76] A. Basiulis, M. Filler, Operating characteristics and long life capabilities of organic fluid heat pipes, AIAA Paper 71-408, in: Sixth AIAA Thermophysics Conference, Tullahoma, TN, April 1971.

[77] H. Kreeb, M. Groll, P. Zimmermann, Life test investigations with low temperature heat pipes, in: First International Heat Pipe Conference, Stuttgart, Paper 4-1, October 1973.

[78] C.A. Busse, A. Campanile, J. Loens, Hydrogen generation in water heat pipes at 250°C, in: First International Heat Pipe Conference, Stuttgart, Paper 4-2, October 1973.

[79] E.E. Gerrels, J.W. Larson, Brayton cycle vapour chamber (heat pipe) radiator study, NASA CR-1677, General Electric Company, Philadelphia, PA, NASA, February 1971.

[80] T.F. Freon, E.I. Solvent, Dupont de Nemours and Company Inc., Technical Bulletin FSR-1, 1965.

[81] Anon, Heat pipes – general information on their use, operation and design, Data Item No. 80013, Engineering Sciences Data Unit, London, 1980.

[82] J.H. Rosenfeld, J.L. Sanzl, Analysis results of a ten year sodium heat pipe life test.

[83] C. Tarau, W.G. Anderson, Sodium variable conductance heat pipe for radioisotope. Stirling systems – design and experimental results, in: Proceedings of the Eighth Annual International Energy Conversion Engineering Conference, AIAA Paper 2010-6758 – Nashville, TN, July 2010.

[84] A. Bricard, et al., High temperature liquid metal heat pipes, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Hemisphere, New York, NY, 1991.

[85] M.A. Merrigan, An investigation of lead heat pipes, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Hemisphere, New York, NY, 1991.

[86] A. Basiulis, R.C. Prager, T.R. Lamp. Compatibility and reliability of heat pipe materials, in: Proceedings of the Second International Heat Pipe Conference, Bologna, ESA Report SP 112, 1976.

[87] W.T. Anderson, Hydrogen evolution in nickel–water heat pipes, AIAA Paper 73-726, 1973.

[88] I. Novotna, et al., Compatibility of steel–water heat pipes, in: Third International Heat Pipe Symposium, Japan Association for Heat Pipes, Tsukuba, Japan, 1988.

[89] I. Novotna, et al., A contribution to the service life of heat pipes, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Begel Corporation, 1995.

[90] B.M. Rassamakin, N.D. Gomelya, N.D. Khairnasov, N.V. Rassamakina, Choice of the effective inhibitors of corrosion and the results of the resources tests of steel and aluminium thermosyphon with water, Paper J-1, in: Proceedings of the Tenth International Heat Pipe Conference, Stuttgart, 21–25 September 1997.

[91] Zhao Rong Di, et al., Experimental investigation of the compatibility of mild carbon steel and water heat pipes, in: Proceedings of the Sixth International Heat Pipe Conference, Grenoble, 1988.

[92] Ya Ming Liang, et al., Applications of heat pipe heat exchangers in energy saving and environmental protection, in: Proceedings of the International Conference on Energy and Environment, Shanghai, 8–10 May 1995.

[93] H. Zhang J. Zhuang *Research, development and industrial application of heat pipe technology in China Appl. Therm. Eng.*23 2003 1067–1083

[94] Anon, Technology specification for carbon steel–water gravity heat pipe, Su Q/B-25-86, Approved by Jiangsu Province Standard Bureau, 1986.

[95] A. Bricard, et al., Recent advances in heat pipes for hybrid heat pipe heat exchangers, in: Proceedings of the Seventh International Heat Pipe Conference, Minsk, 1990, Begel Corporation, 1995.

[96] Anon *On the influence of the overshoot of oxygen on corrosion of carbon steels in heat supply systems Teploenergetika*12 1992 36–38

[97] F. Geiger, D. Quataert, Corrosion studies of tungsten heat pipes at temperatures up to 2650°C, in: Proceedings of the Second International Heat Pipe Conference, Bologna, ESA Report SP 112, 1976.

[98] J.E. Kemme, Heat pipe capability experiments, Los Alamos Scientific Laboratory, Report LA-3585, August 1966.

[99] E. Van Andel, Heat pipe design theory, Euratom Center for Information and Documentation, Report EUR No. 4210 e, f, 1969.

[100] C.A. Busse *Theory of the ultimate heat transfer limit of cylindrical heat pipes Int. J. Heat Mass Transf.*16 1973 169–186