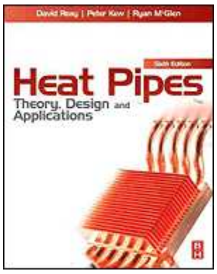


Heat Pipes: Theory, Design and Applications, Sixth Edition

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

Chapter 5: Heat Pipe Manufacture and Testing

OVERVIEW

The manufacture of conventional capillary-driven heat pipes involves a number of comparatively simple operations, particularly when the unit is designed for operation at temperatures of the order of, say 50–200°C. It embraces skills such as welding, machining, chemical cleaning and nondestructive testing, and can be carried out following a relatively small outlay on capital equipment. The most expensive item is likely to be the leak detection equipment. (Note that many procedures described are equally applicable to thermosyphons.) Tubular heat pipes are generally simpler to manufacture than flat plate forms. The tubular unit is the heat pipe (or thermosyphon) of choice for those starting to examine the performance in the laboratory.

With all heat pipes, however, cleanliness is of prime importance to ensure that no incompatibilities exist (assuming that the materials selected for the wick, wall and working fluid are themselves compatible), and to make certain that the wick and the wall will be wetted by the working fluid. As well as affecting the life of the heat pipe, negligence in assembly procedures can lead to inferior performance, due, for example, to poor wetting. Atmospheric contaminants, in addition to those likely to be present in the raw working fluid, must be avoided. Above all, the heat pipe must be leak-tight to a very high degree. This can involve outgassing of the metal used for the heat pipe wall, end caps, etc., although this is not essential for simple low-temperature operations.

Quality control cannot be overemphasised in heat pipe manufacture, and in the following discussion of assembly methods, this will be frequently stressed.

A substantial part of this chapter is allocated to a review of life test procedures for heat pipes. The life of a heat pipe often requires careful assessment in view of the many factors that can affect long-term performance, and most establishments seriously involved in heat pipe design and manufacture have extensive life test programmes in progress. As discussed later, data available from the literature can indicate satisfactory wall/wick/working fluid combinations, but the assembly procedures used differ from one manufacturer to another, and this may introduce an unknown factor that will necessitate investigation. The outcomes of life tests using a wide variety of fluids are given in Chapter 3.

Measuring the performance of heat pipes is also a necessary part of the work leading to an acceptable product, and the interpretation of the results may prove difficult. Test procedures for heat pipes destined for use in orbiting satellites have their own special requirements brought about by the need to predict performance in zero gravity by testing in earth's gravity. There are numerous examples in the literature of measured temperature profiles along heat pipes that show much greater temperature drops than one would anticipate if operation was within limits and no non-condensable gases were present. One needs to examine where temperature measurements were made and the thermal resistances between the inside of the condenser (for example) and the heat sink in order to fully understand the possibly high overall resistance.

While the vast majority of heat pipes manufactured today are conventional wicked circular (or near circular) cross-section units, there is an increasing trend towards miniaturisation and the use of microgroove type structures as wicks. The implications of these trends for manufacturing procedures are highlighted in appropriate parts of this chapter.

Although the manufacture of special types such as loop, oscillating or microheat pipes are outside the scope of this book, again there are features unique to these types that require close attention during manufacture and assembly, and these are identified and referenced, where it is believed appropriate.

The use of 3D printing, of which selective laser re-melting is one form of construction, is new to the heat pipe manufacturing field, and is described later (Section 5.1.15). Imagine being able to construct a heat pipe, together with a composite wick, as a single assembly from a CAD drawing via a 3D printing machine!

5.1 MANUFACTURE AND ASSEMBLY

5.1.1 Container Materials

The heat pipe container, including the end caps and filling tube, is selected on the basis of several properties of the material used and these are listed in Chapter 3. (Unless stated otherwise, the discussion in this chapter assumes that the heat pipes are tubular in geometry.) However, the practical implications of the selection are numerous.

Of the many materials available for the container, three are by far the most common in use, namely copper, aluminium and stainless steel. Copper is eminently satisfactory for heat pipes operating between 0°C and 200°C in applications such as electronics cooling. While commercially pure copper tube is suitable, the oxygen-free high-conductivity type is preferable. Like aluminium and stainless steel, the material is readily available and can be obtained in a wide variety of diameters and wall thicknesses in its tubular form.

Aluminium is less common as a material in commercially available heat pipes but has received a great deal of attention in aerospace applications, because of its obvious weight advantages. It is generally used in alloy form, typically 6061-T6, the nearest British equivalent being aluminium alloy HT30. Again this is readily available and can be drawn to suit by the heat pipe manufacturer, or extruded to incorporate, for example, a grooved wick.

Stainless steel unfortunately cannot generally be used as a container material with water where a long life is required, owing to gas generation problems, but it is perfectly acceptable with many other working fluids, and is in many cases the only suitable container, as for example, with liquid metals such as mercury, sodium and potassium. Types of stainless steel regularly used for heat pipes include 302, 316 and 321. (Comments on compatibility with water are made in Chapter 3.) Mild steel may be used with organic fluids, and, again, reference to Chapter 3 can be made for a discussion on its possible compatibility with water.

In the assembly of heat pipes, provision must be made for filling, and the most common procedure involves the use of an end cap with a small diameter tube attached to it, as shown in Fig. 5.1. The other end of the heat pipe contains a blank end cap. End cap and filling tube materials are generally identical to those of the heat pipe case, although for convenience a copper extension may be added to a stainless steel filling tube for cold welding (see Section 5.1.9). It may be desirable to add a valve to the filling tube where, for example, gas analysis may be carried out following life tests (see Section 5.2). The valve material must, of course, be compatible with the working fluid.

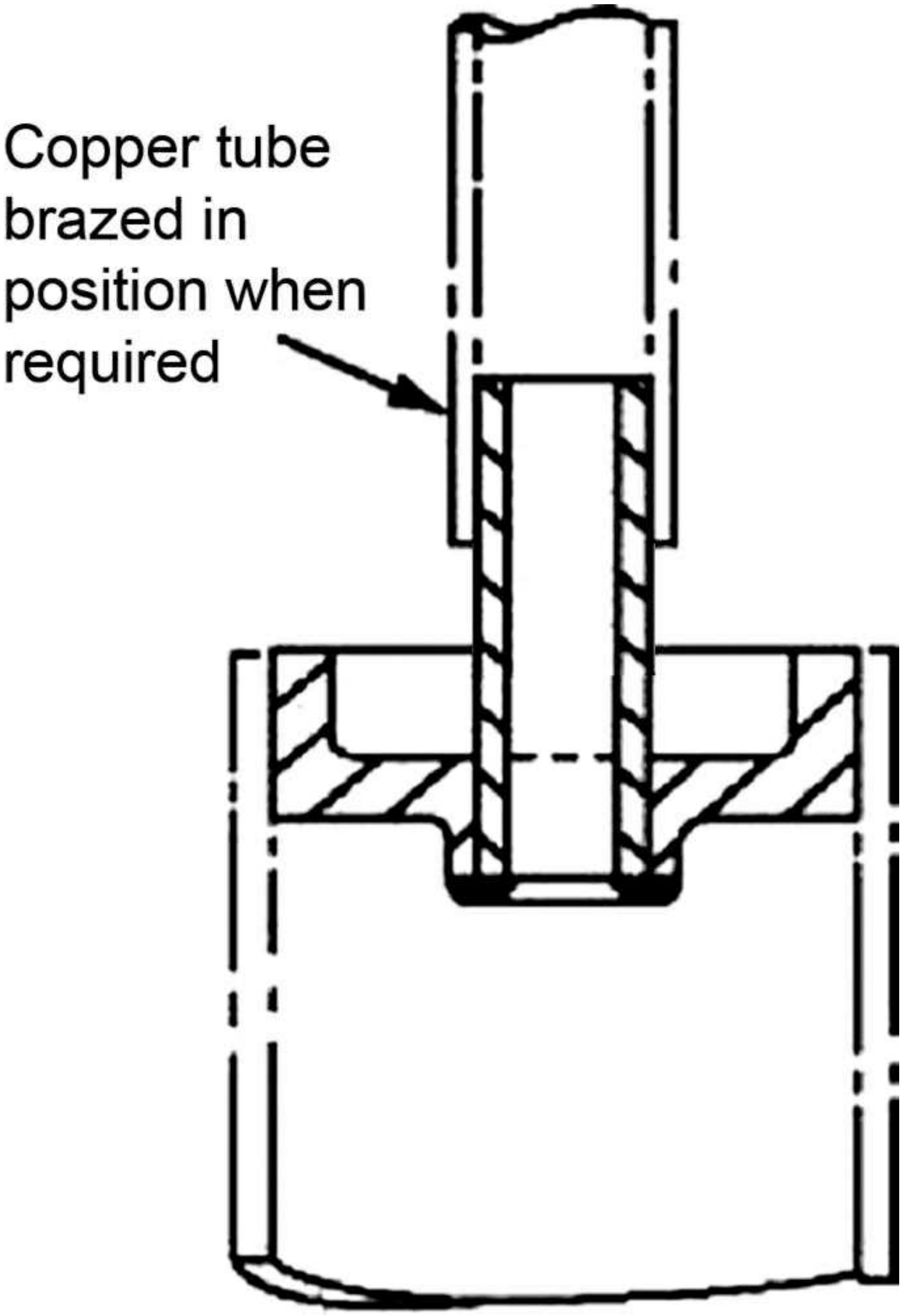


Figure 5.1: End cap and filling tube

If the heat pipe is to operate at high vapour pressures, a pressure test should be carried out to check the integrity of the vessel.

There have been a number of heat pipes and thermosyphons constructed using polymers. Polymer thermal diodes have been used to transfer solar thermal energy through the walls of buildings, and flexible sections in some early tubular heat pipes were formed from polymers. Sealing of polymers has been a problem, however.

A group in Taiwan, one of several working on polymer heat pipes, has employed polyethylene terephthalate (PET) plastic film in a flat plate heat pipe that used methanol as the working fluid with a copper mesh wick [1]. The PET sheets can be bonded together using hot lamination. As with flat plate heat pipes in general (but more so with polymer ones) one has to be careful to ensure that the vapour pressure does not become too great. In the case of the PET unit, it was found that delamination could occur at higher pressures, so a limit of just over 14 kPa was put on the internal pressure. The group concluded that the device was a viable alternative (and a low-cost one) in some electronics cooling applications.

5.1.2 Wick Materials and Form

The number and form of materials that have been tested as wicks in heat pipes is very large. Reference has already been made to some of these in analysis of the liquid pressure drop, presented in Chapter 2, and in the discussion on selection criteria in Chapter 3.

5.1.2.1 Wire Mesh

The most common form of wick is a woven wire mesh or twill which can be made in many metals. Stainless steel, monel and copper are woven to produce meshes having very small pore sizes (see Table 3.4) and 400-mesh stainless steel is available 'off the shelf' from several manufacturers. Aluminium is available, but because of difficulties in producing and weaving fine aluminium wires, the requirements of small pore wicks cannot be met.

Stainless steel is the easiest material to handle in mesh form. It can be rolled and retains its shape well, particularly when a coarse mesh is used. The inherent springiness in the coarse meshes assists in retaining the wick against the heat pipe wall, in some cases obviating the need for any other form of wick location. In heat pipes where a 400 mesh is used, a coarse 100-mesh layer located at the inner radius can hold the finer mesh in shape. Stainless steel can also be diffusion bonded, giving strong permanent wick structures attached to the heat pipe wall. The diffusion bonding of stainless steel is best carried out in a vacuum furnace at a temperature of 1150–1200°C.

The spot welding of wicks is a convenient technique for preserving shape or for attaching the wick to the wall in cases where the heat pipe diameter is sufficiently large to permit insertion of an electrode. Failing this, a coil spring can be used.

It is important to ensure that whatever the wick form it is in very close contact with the heat pipe wall, particularly at the evaporator section, otherwise local hot spots will occur. With mesh the best way of making certain that this is the case is to diffusion bond the assembly.

The manufacture of heat pipes for thermal control of the chips in laptop computers and the like conventionally involves wicked copper heat pipes. Here copper or nickel mesh may be employed instead of stainless steel, depending upon the choice of the working fluid.

5.1.2.2 Sintering

A similar structure having an intimate contact with the heat pipe wall is a sintered wick. Sintering is often used to produce metallic filters, and many components of machines are now produced by this process as opposed to die casting or moulding.

The process involves bonding together a large number of particles in the form of a packed metal powder. The pore size of the wick thus formed can be arranged to suit by selecting powders having a particular size. The powder, which is normally spherical, is placed in containers giving the shape required and then either sintered without being further compacted or, if a temporary binder is used, a small amount of pressure may be applied. Sintering is normally carried out at a temperature 100–200°C below the melting point of the sintering material.

The simplest way of making wicks by this method is to sinter the powder in the tube that will form the final heat pipe. This has the advantage that the wick is also sintered to the tube wall and thus makes a stronger structure. In order to leave the central vapour channel open, a temporary mandrel has to be inserted in the tube. The powder is then placed in the annulus between mandrel and tube. In the case of copper powder, a stainless steel mandrel is satisfactory as the copper will not bond to stainless steel and thus the bar can easily be removed after sintering. The bar is held in a central position at each end of the tube by a stainless steel collar.

A typical sintering process is described below. Copper was selected as the powder material and also as the heat pipe wall. The particle size chosen was −150+300 grade, giving particles of 0.05–0.11 mm diameter. The tube was fitted with the mandrel and a collar at one end. The powder was then poured in from the other end.

No attempt was made to compact the powder apart from tapping the tube to make sure there were no gross cavities left. When the tube was full the other collar was put in place and pushed up against the powder. The complete assembly was then sintered by heating in hydrogen at 850°C for 1/2 h. After the tube was cooled and removed and the tube, without the mandrel, was then resintered. (The reason for this was that when the mandrel was in place the hydrogen could not flow easily through the powder and as a result sintering may not have been completely successful since hydrogen is necessary to reduce the oxide film that hinders the process.) After this operation, the tube was ready for use. Figure 5.2 shows a cross section of a completed tube and Fig. 5.3 shows a magnified view of the structure of the copper wick. The porosity of the finished wick is of the order of 40–50%.

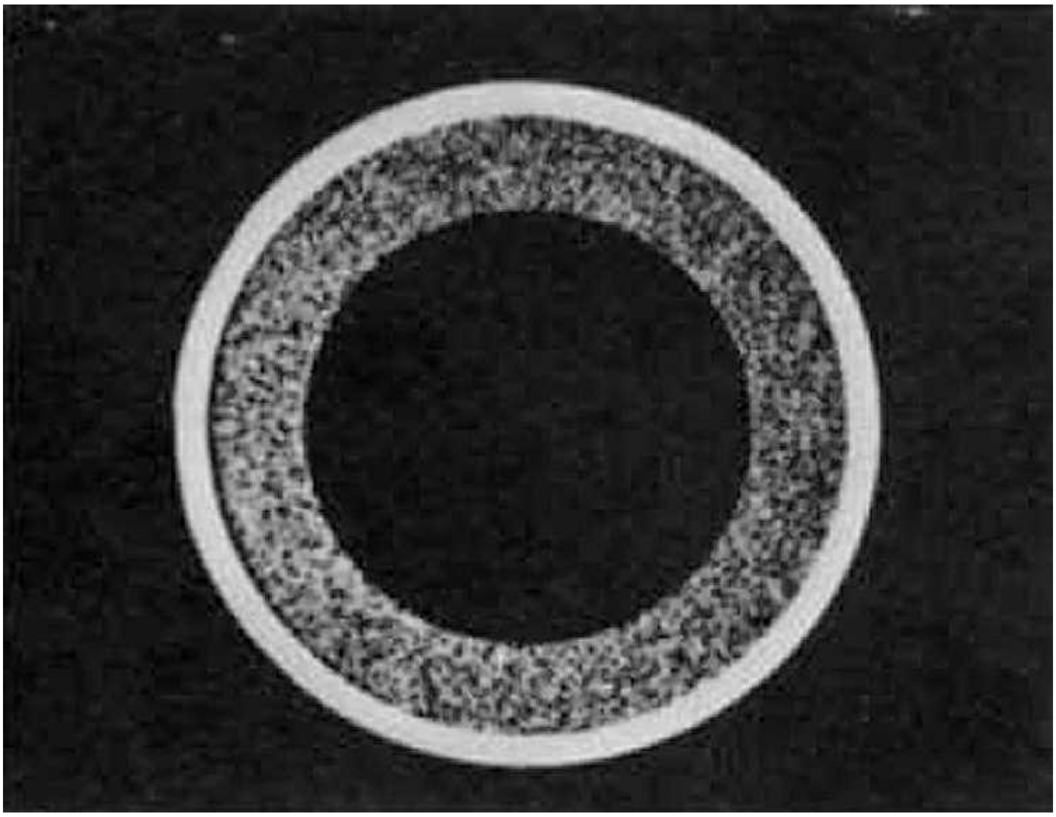


Figure 5.2: Sintered wick cross section (copper)

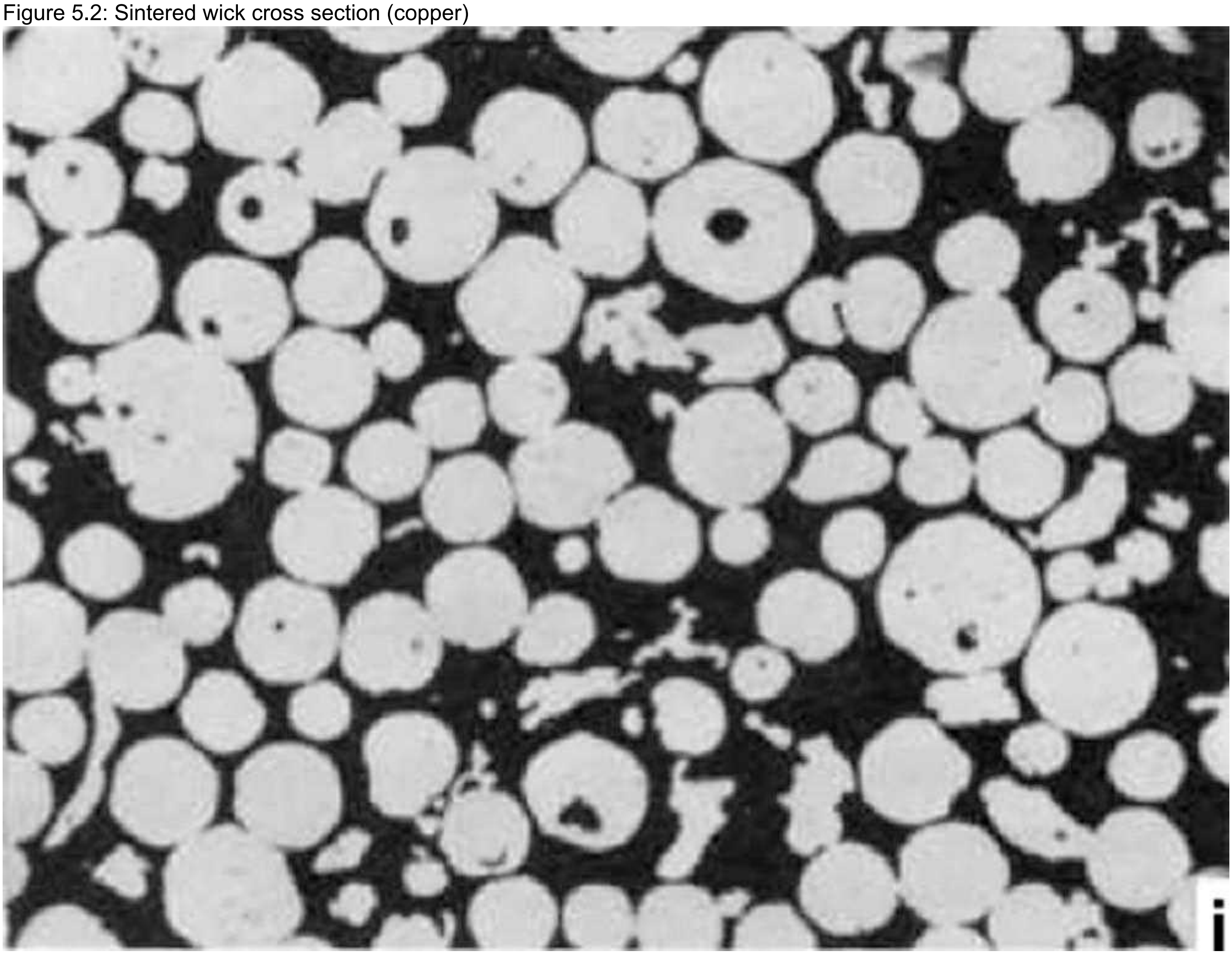


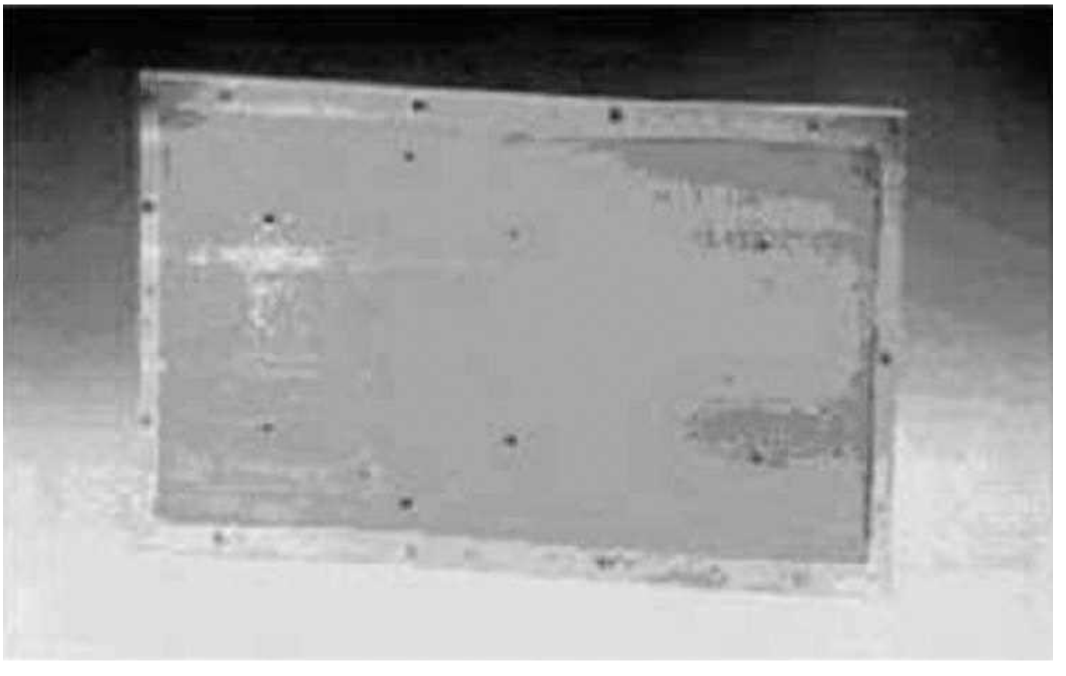
Figure 5.3: Magnified view of sinter structure

A second type of sintering may be carried out to increase the porosity. This necessitates the incorporation of inert filler material to act as pore formers. This is subsequently removed during the sintering process, thus leaving a very porous structure. The filler used was a perspex powder that is available as small spheres. This powder was sieved to remove the −150+300 (0.050–0.100 mm) fraction. This was mixed with an equal volume of very fine copper powder (−200 μm). On mixing, the copper uniformly coats the plastic spheres. This composite powder then shows no tendency to separate into its components.

The wick is now made up exactly as the previous tube with the exception that more compaction is required in order to combat the very high shrinkage that takes place during sintering. During the initial stages of the sintering, the plastic is vaporised and diffused out of the copper compact, thus leaving a skeletal structure of fine copper powder with large interconnected pores. The final porosity is probably of the order of 75–85%.

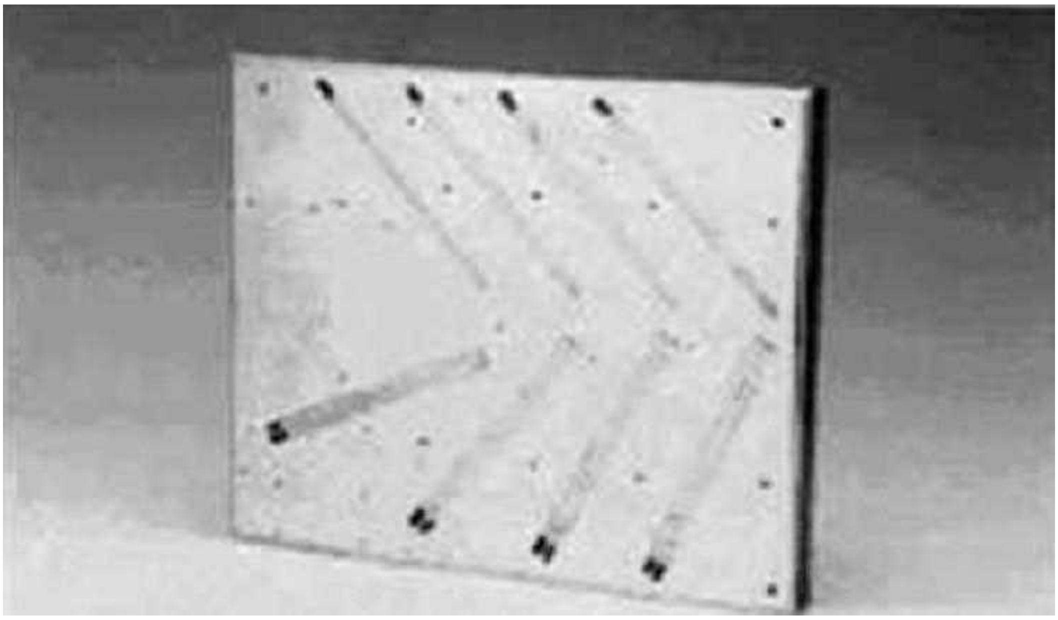
It is obvious that there are many possible variations of the wicks made by sintering methods. Porosity, capillary rise and volume flow can all be optimised by the correct choice of metal powder size, filler size, filler proportion and by incorporation of channel forming fillers.

Flat plate heat pipes, sometimes called vapour chambers (where the role of the wick may be solely for liquid distribution across the evaporator), most commonly use sintered wick structures. The Thermacore 'Therma-Base' unit [2] uses a copper-sintered wick, the unit being illustrated in Fig. 5.4. An alternative method for achieving something approaching uniform heat distribution across plate is to embed heat pipes of tubular form within it, as shown in the Thermacore unit in Fig. 5.5.



(Courtesy Thermacore International Inc.).

Figure 5.4: The Thermacore 'Therma-Base' flat plate heat pipe, employing a sintered wick



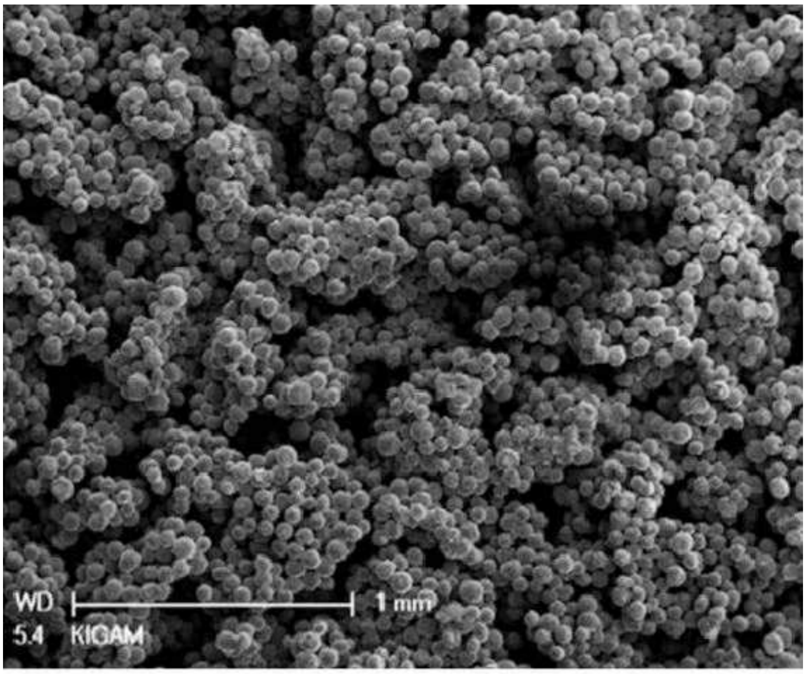
(Courtesy Thermacore International Inc.).

Figure 5.5: An alternative approach to 'spreading the heat' over a flat surface – the Therma-core heat spreader

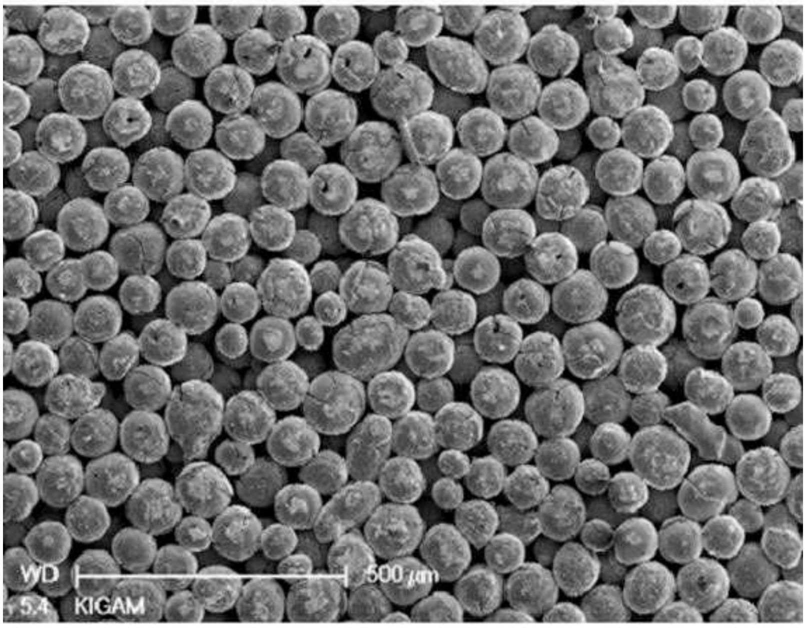
Not all flat plate heat pipes are designed to operate against gravity, hence the fact that the equipment can operate with relatively simple wick structures. One heat pipe that was mounted vertically was used in the thermal control of thermoelectric refrigeration units [3]. Although subject to further development, the use of a sintered copper (40 μm particles) wick with longitudinal channels – a graded wick structure or composite structure – was interesting. As highlighted elsewhere, the impact of the fluid fill on the heat pipe performance was shown to be significant. Results showed that as the fluid loads was varied between 5 and 40 g, the thermal resistance initially decreased from 0.25 K/W at 5 g inventory to a minimum of 0.15 K/W at 20 g, before rising to over 0.3 K/W at 40 g. Careful assessment for fluid inventory in wicked heat pipes of all types is essential.

A French heat pipe manufacturer, Atherm (see Appendix 3), has recently reported on 'industrial manufacturing' of the wicks used in LHPs. These are sintered structures but the geometry/dimensions differ from those in conventional tubular heat pipes. In the Atherm case, the LHP evaporator wick was 30 mm long, with an outside diameter of 10 mm and a 2 mm diameter cylindrical hole in the centre. In order to achieve the close tolerances needed for the LHP unit, which could not tolerate shrinkage of the sintered wick, nickel and bronze preformed sintered parts were machined, and the machining methods such as drilling, turning and milling were found not to block the surface pores and satisfactory capillary action was achieved [4]. The sintered structure had a porosity of 65–70% and a pore diameter of 8–9 μm.

Work on bi-porous wicks (a new term for what are called composite wicks in other chapters) has been reported by Byon et al. in Korea [5]. Illustrated in Fig. 5.6, the wicks were formed from spherical copper particles (supplied by ACupowder, Inc.) sintered into a porous medium in a high-temperature furnace with a reducing atmosphere of nitrogen and hydrogen. The sintered porous medium was ground into clusters, sieved into specific sizes, and again sintered onto a copper disk (10-mm diameter, 5-mm thick). In order to carry out experiments to compare the performances of the two wick structures, the wick thickness was defined to be 1 mm and set to be 1 mm. The diameter of the spheres in the mono-porous wick was 45–200 μm and the same diameter particles were used in the bi-porous wick, but before final sintering, these were sintered into clusters of 250–675 μm diameter – and the assembly resulting from this is shown in Fig. 5.6(a).



(a) Bi-porous wick (45/675 μm)



(b) Mono-porous wick (100 μm)

Figure 5.6: Scanning electron microscope images of the (a) bi- and (b) mono-porous sintered wicks [5]

5.1.2.3 Vapour Deposition

Sintering is not the only technique whereby a porous layer can be formed which is in intimate contact with the inner wall of the heat pipe. Other processes include vapour coating, cathode sputtering and flame spraying. Brown Boveri, in UK Patent 1313525, describes a process known as 'vapour plating' that has been successfully used in heat pipe wick construction. This involves plating the internal surface of the heat pipe structure with a tungsten layer by reacting tungsten hexafluoride vapour with hydrogen, the porosity of the layer being governed by the surface temperature, nozzle movement and distance of the nozzle from the surface to be coated.

5.1.2.4 Microlithography and other Techniques

The trend towards microheat pipes (see also Chapter 6) has led to the use of manufacturing techniques for such units that copy some of the methods used in the microelectronics area that these devices are targeting. Sandia National Laboratory is one of a number of laboratories using photolithographic methods, or similar techniques, for making heat pipes, or more specifically the wick. Workers at Sandia [6] wanted to make a microheat pipe that could cool multiple heat sources, keep the favourable permeability characteristics of longitudinally grooved wicks and allow fabrication using photolithography.

Full arguments behind the selection of the anisotropic wick concept, based upon longitudinal liquid flow while minimising transverse movement, are given in the referenced paper, but the wick made was of rectangular channels of width 40 μm and height 60 μm, formed using an electroplating process that plates the copper wick material onto the flat 150 mm substrate wafers.

Final assembly comprised cutting the wick parts, putting in spacers and the fill tube and electron beam welding around the periphery. (Support posts inside were resistance welded.)

Even in the 2-year period since this work was reported, the progress in microfabrication technology, including direct writing (3D printing) methods such as selective laser melting (SLM) is such that a 3D wick structure of almost any form could be fabricated by a rapid prototyping method in several laboratories around the world.

5.1.2.5 Grooves

A type of wick, which is widely used in spacecraft applications but which is unable to support significant capillary heads in earth gravity, is a grooved system. The simplest way of producing longitudinal grooves in the wall of a heat pipe is by extrusion or by broaching. Aluminium is the most satisfactory material for extruding, where grooves may be comparatively narrow in width, but possess a greater depth. An example of a copper grooved heat pipe wick is shown in Fig. 5.7. The external cross section of the heat pipe can also be adapted for a particular application. If the heat pipe is to be mounted on a plate, a flat surface may be incorporated on the wall of the heat pipe to give better thermal contact with the plate.

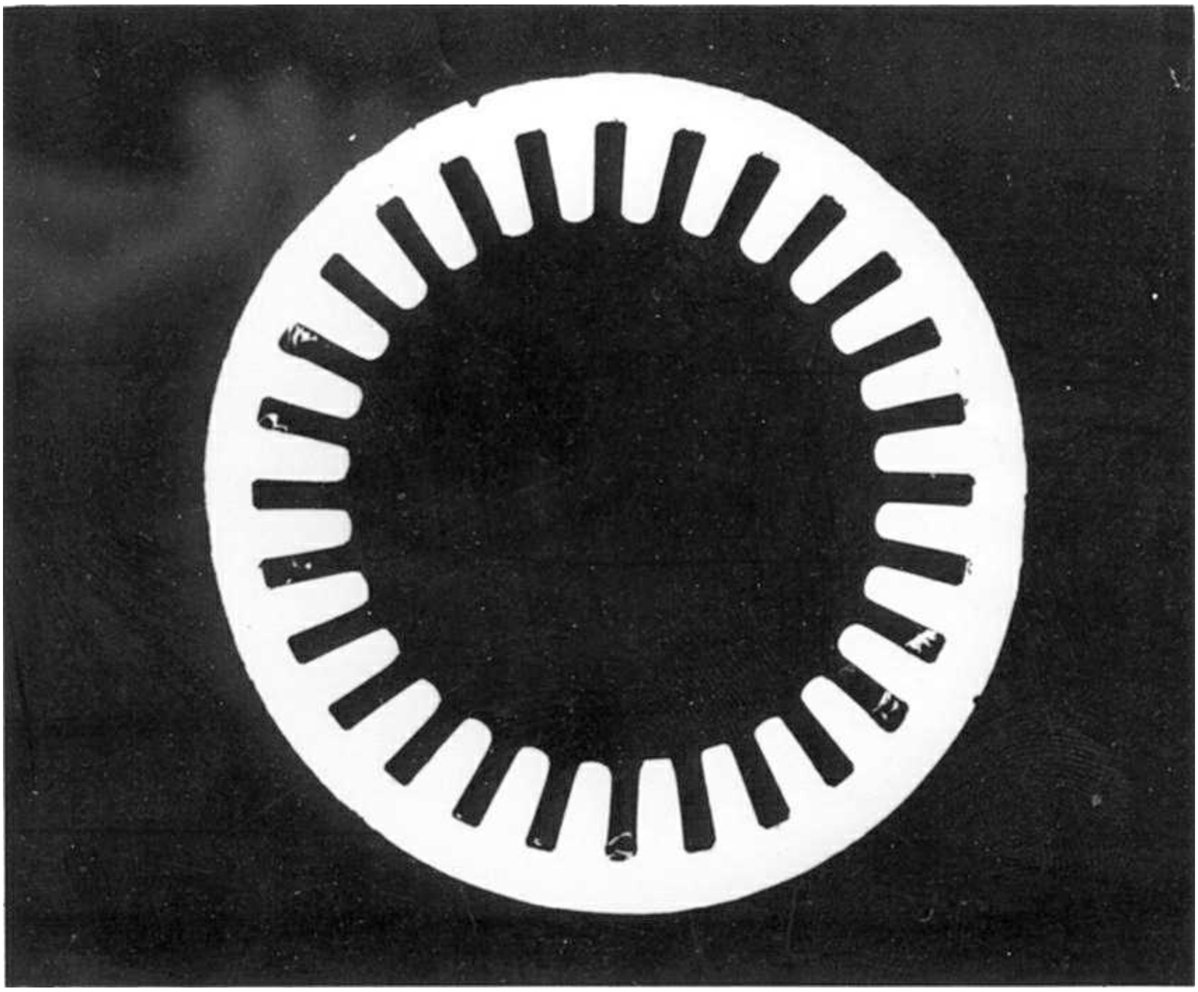


Figure 5.7: Grooved wick in a copper tube, obtained by mandrel drawing

An alternative groove arrangement involves ‘threading’ the inside wall of the heat pipe using taps or a single-point cutting tool to give a thread pitch of up to 40 threads per centimetre. Threaded arteries are attractive for circumferential liquid distribution, and may be used in conjunction with a different artery system for axial liquid transport.

Longitudinal grooves may be used as arteries (see Chapter 4 for example) and Fig. 5.8(a) shows such an artery set, machined in the form of six grooves in a former for insertion down the centre of a heat pipe. Prior to insertion, the arteries are completed by covering them with diffusion-bonded mesh to the outer surface. Figure 5.8(b) shows diffusion-bonded mesh.

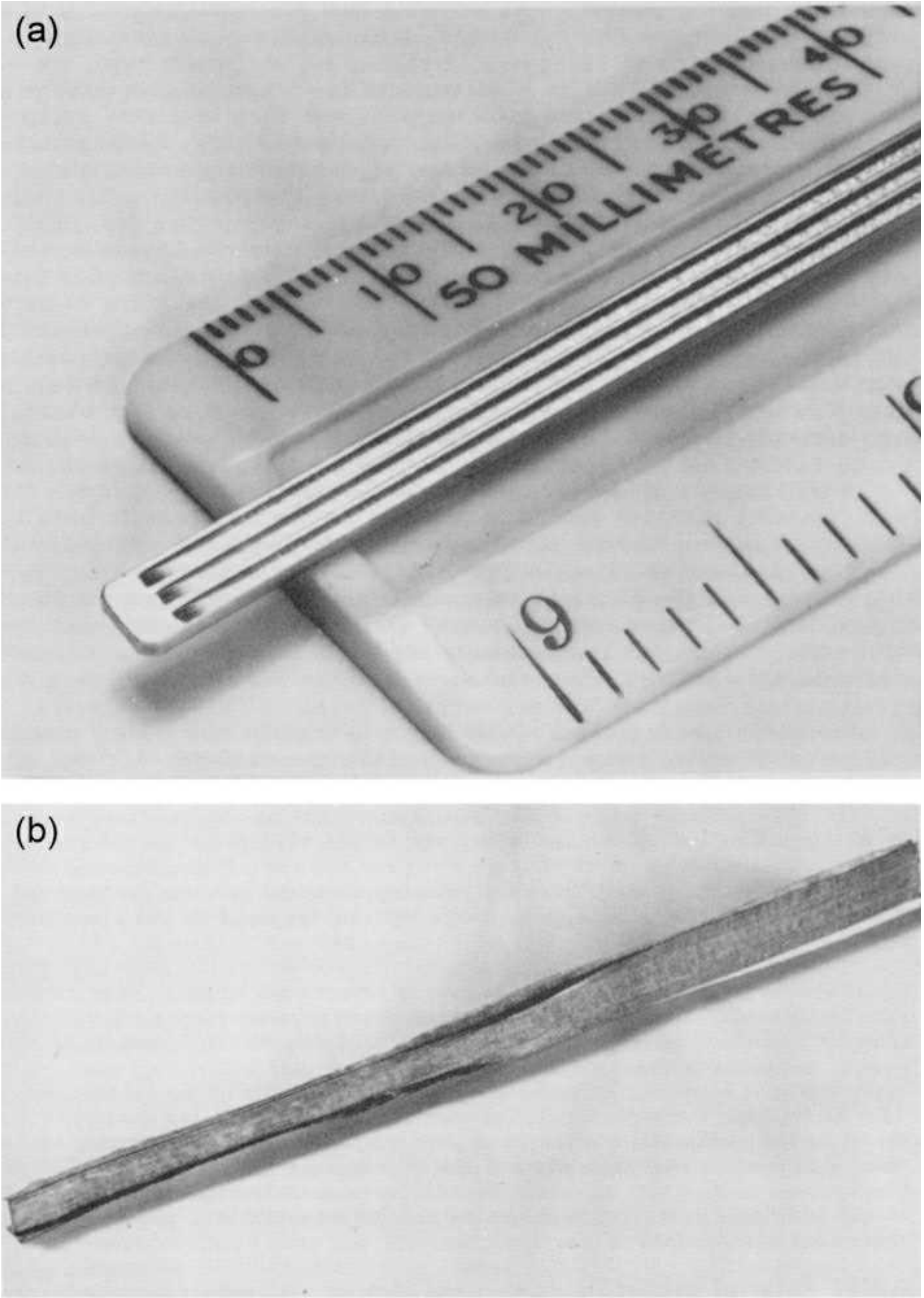


Figure 5.8: (a) Artery set prior to covering with mesh. (b) Diffusion-bonded mesh as used to cover arteries

Triangular-shaped grooves have been fabricated in silicon for electronics cooling duties. Work at INSA in France [7,8] used two processes – anisotropic chemical etching followed by direct silicon wafer bonding – for microheat pipe fabrication. In one unit, 55 triangular parallel microheat pipes were constructed (230 μm wide and 170 μm deep) and ethanol was used as the working fluid. A section through the array is shown in Fig. 5.9(a), while a second unit, shown in Fig. 5.9(b), uses arteries, fabricated in an identical manner, in a third layer of silicon.

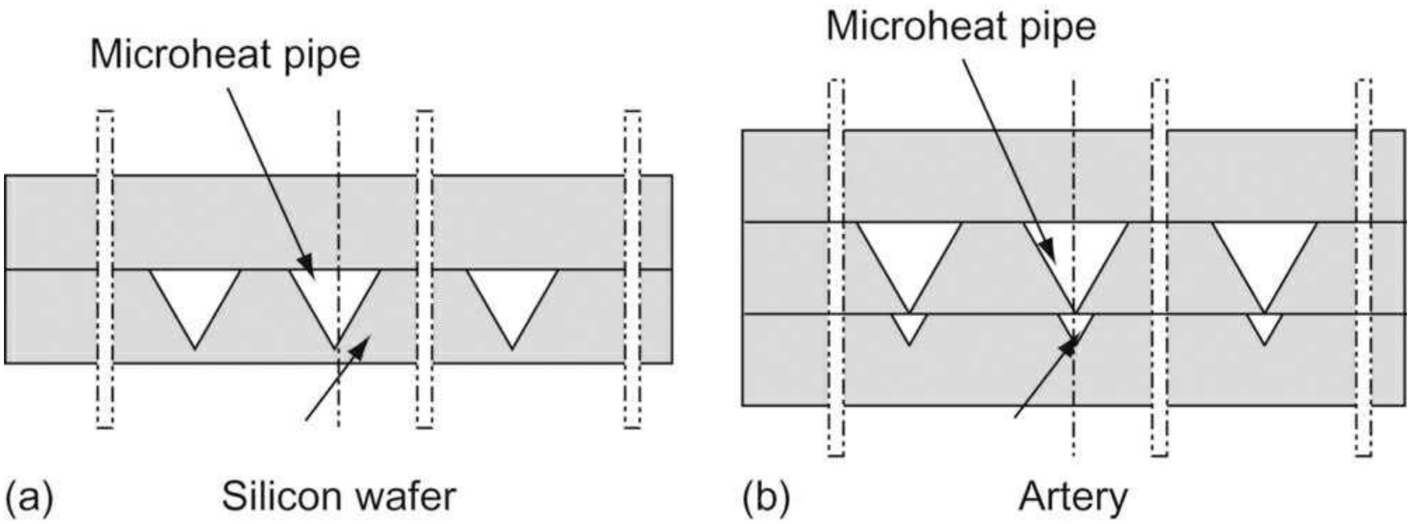


Figure 5.9: Cross sections of two microheat pipe arrays fabricated in silicon: (a) without and (b) with artery [8]

5.1.2.6 Felts and Foams

Several companies are now producing metal and ceramic felts and metal foam which can be effectively used as heat pipe wicks, particularly where units of noncircular cross section are required. The properties of some of these materials are given in Table 3.3. Foams are available in nickel, stainless steel and copper, and felt materials include stainless steel and woven ceramic fibres (Refrasil). Foams are available in sheet and rod forms, and can be supplied in a variety of pore sizes. Metallic felts are normally produced in sheets and are much more pliable than foams. An advantage of the felt is that by using mandrels and applying a sintering process, longitudinal arteries could be incorporated inside the structure, providing low-resistance flow paths. The foam, however, may double as a structural component.

Knitted ceramic fibres are available with very small pore sizes and are inert to most common working fluids. Because of their lack of rigidity, particularly when saturated with a liquid, it is advisable to use them in conjunction with a wire mesh wick to retain their shape and desired location. The ceramic structure can be obtained in the form of multilayer sleeves, ideal for immediate use as a wick, and a range of diameters of sleeves is available. Some stretching of the sleeve can be applied to reduce the diameter, should the exact size is not available.

5.1.3 Cleaning of Container and Wick

All the materials used in a heat pipe must be clean. Cleanliness achieves two objectives. It ensures that the working fluid will wet the materials and that no foreign matter is present which could hinder capillary action or create incompatibilities.

The cleaning procedure depends upon the material used, the process undergone in manufacturing and locating the wick, and the requirements of the working fluid, some of which wet more readily than others. In the case of wick/wall assemblages produced by processes such as sintering or diffusion bonding, carried out under an inert gas or vacuum, the components are cleaned during the bonding process, and provided that the time between this process and final assembly is short, no further cleaning may be necessary.

If the working fluid is a solvent, such as acetone, no extreme precautions are necessary to ensure good wetting, and an acid pickle followed by a rinse in the working fluid appears to be satisfactory. However, cleaning procedures become more rigorous as one moves up the operating temperature range to incorporate liquid metals as working fluids.

The pickling process for stainless steel involves immersing the components in a solution of 50% nitric acid and 5% hydrofluoric acid. This is followed by a rinse in demineralised water. If the units are to be used in conjunction with water, the wick should then be placed in an electric furnace and heated in air to 400°C for 1 h. At this temperature, grease is either volatised or decomposed, and the resulting carbon burnt off to form carbon dioxide. Since an oxide coating is required on the stainless steel, it is not necessary to use an inert gas blanket in the furnace.

Nickel may undergo a similar process to that described above for stainless steel but pickling should be carried out in a 25% nitric acid solution. Pickling of copper demands a 50% phosphoric acid and 50% nitric acid mixture.

Cleanliness is difficult to quantify, and the best test is to add a drop of demineralised water to the cleaned surface. If the drop immediately spreads across the surface, or is completely absorbed into the wick, good wetting has occurred, and satisfactory cleanliness has been achieved.

Stainless steel wicks in long heat pipes sometimes create problems in that furnaces of sufficient size, which contain the complete wick may not be readily available. In this case, a flame cleaning procedure may be used, whereby the wick is passed through a Bunsen flame as it is fed into the container.

An ultrasonic cleaning bath is a useful addition for speeding up the cleaning process but is by no means essential for low-temperature heat pipes. As with this process or any other associated with immersion of the components in a liquid to removed contaminants, the debris will float to the top of the bath and must be skimmed off before removing the parts being treated. If this is not done, the parts could be recontaminated as they are removed through this layer. Electropolishing may also be used to aid cleaning of metallic components.

Ceramic wick materials are generally exceptionally clean when received from the manufacturer, owing to the production process used to form them, and therefore need no treatment, provided that the handling during assembly of the heat pipe is under clean conditions.

It is important, particularly when water is used as the working fluid, to avoid skin contact with the heat pipe components. Slight grease contamination can prevent wetting, and the use of surgical gloves for handling is advisable. Wetting can be aided by additives (wetting agents) [9] applied to the working fluid, but this can introduce compatibility problems and also affect surface tension.

5.1.4 Material Outgassing

When the wick or wall material is under vacuum, gases will be drawn out, particularly if the components are metallic. If not removed prior to sealing of the heat pipe, these gases could collect in the heat pipe vapour space. The process is known as outgassing.

While outgassing does not appear to be a problem in low-temperature heat pipes for applications that are not too arduous, high-temperature units (>400°C) and pipes for space use should be outgassed in the laboratory prior to filling with working fluid and sealing.

The outgassing rate is strongly dependent on temperature, increasing rapidly as the component temperature is raised. It is advisable to outgas components following cleaning, under vacuum at a baking temperature of about 400°C. Following baking the system should be vented with dry nitrogen. The rate of outgassing depends on the heat pipe operating vapour pressure, and if this is high the outgassing rate will be restricted.

If the heat pipe has been partially assembled prior to outgassing, and the end caps fitted, it is necessary to make sure that no welds, etc., leak, as these could produce misleading results to outgassing rate. It will generally be found that analysis of gases escaping through a leak will show a very large air content, whereas those brought out by outgassing will contain a substantial water vapour content. A mass spectrometer can be used to analyse these gases. Leak detection is covered in Section 5.1.6.

The outgassing characteristics of metals can differ considerably. The removal of hydrogen from stainless steel, for example, is much easier to effect than its removal from aluminium. Aluminium is particularly difficult to outgas and can hold comparatively large quantities of non-condensables. In one test, it was found [10] that gas was suddenly released from the aluminium when it approached red heat under vacuum. Two hundred grams of metal gave 89.5 cc of gas at NTP, 88 cc being hydrogen and the remainder carbon dioxide. It is also believed that aluminium surfaces can retain water vapour even when heated to 500°C or dried over phosphorous pentoxide. This could be particularly significant because of the known incompatibility of water with aluminium. (See Section 5.1.12 for high-temperature heat pipes.)

5.1.5 Fitting of Wick and End Caps

Cleaning of the heat pipe components is best carried out before insertion of the wick, as it is easy to test the wick for wettability. Outgassing may be implemented before assembly or while the heat pipe is on the filling rig (see Section 5.1.8).

In cases where the wick is an integral part of the heat pipe wall, as in the case of grooves, sintered powders, or diffusion-bonded meshes, cleaning of the heat pipe by flushing through with the appropriate liquid is convenient, prior to the welding of the end caps.

If a mesh wick is used, and the mesh layers are not bonded to one another or to the heat pipe wall, particularly when only a fine mesh is used, a coiled spring must be inserted to retain the wick against the wall. This is readily done by coiling the spring tightly around a mandrel giving a good internal clearance in the heat pipe. The mandrel is inserted into the pipe, the spring tension released and the mandrel then removed. The spring will now be holding the wick against the wall. Typically the spring pitch is about 1 cm. (In instances where two mesh sizes may be used in the heat pipe, say two layers of 200 mesh and one layer of 100 mesh, the liquid–vapour interface must always be in the 200 mesh to achieve maximum capillary rise. It is therefore advisable to wrap the 200 mesh over the end of the 100 mesh, as shown in Fig. 5.10. It is possible to locate the fine mesh against the wall, where it will suppress boiling.)

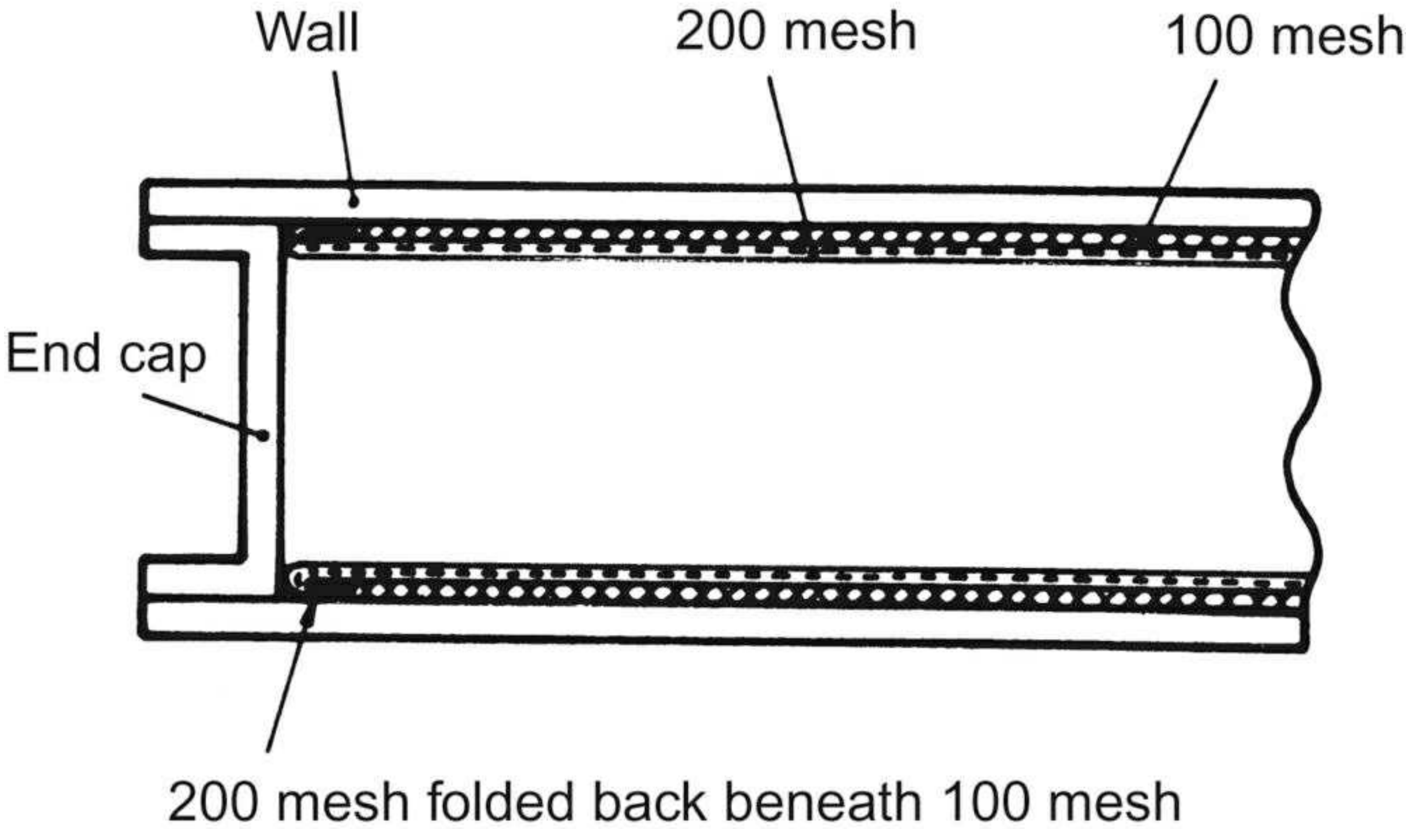


Figure 5.10: Sealing of mesh at the end of heat pipe

The fitting of end caps is normally carried out by argon-arc welding. This need not be done in a glove box and is applicable to copper, stainless steel and aluminium heat pipes. The advantage of welding over brazing or soldering is that no flux is required, therefore the inside of cleaned pipes do not suffer from possible contamination. However, possible inadequacies of the argon shield, in conjunction with the high temperatures involved, can lead to local material oxidation which may be difficult to remove from the heat pipe interior. Assembly in a glove box filled with argon would overcome this but would be expensive. The use of a thermal absorbent paste such as Rocol HS to surround the area of heat pipe local to the weld can considerably reduce the amount of oxide formed.

Electron beam welding may also be used for heat pipe assembly, but this added expense cannot be justified in most applications.

5.1.6 Leak Detection

All welds on heat pipes should be checked for leaks. If quality control is to be maintained, a rigorous leak check procedure is necessary because a small leak that may not affect heat pipe performance initially could make itself felt over a period of months.

The best way to test a heat pipe for leaks is to use a mass spectrometer that can be used to evacuate the heat pipe to a very high vacuum, better than 10^{-5} torr, using a diffusion pump. The weld area is then tested by directing a small jet of helium gas onto it. If a leak is present, the gauge head on the mass spectrometer will sense the presence of helium once it enters the heat pipe. After an investigation of the weld areas and location of the general leak area(s), if present, a hypodermic needle can then be attached to the helium line and careful traversing of the suspected region can lead to very accurate identification of the leak position, possibly necessitating only a very local rewelding procedure to seal it.

Obviously, if a very large leak is present, the pump on the mass spectrometer may not even manage to obtain a vacuum better than 10^{-2} or 10^{-3} torr. Porosity in weld regions can create conditions leading to this, and may point to impure argon or an unsuitable welding filler rod.

It is possible, if the leak is very small, for water vapour from the breath to condense and block, albeit temporarily, the leak. It is therefore important to keep the pipe dry during leak detection.

5.1.7 Preparation of the Working Fluid

It is necessary to treat the working fluid used in a heat pipe with the same care as that given to the wick and container.

The working fluid should be the most highly pure available, and further purification may be necessary following purchase. This may be carried out by distillation. In the case of low-temperature working fluids such as acetone, methanol and ammonia the presence of water can lead to incompatibilities, and the minimum possible water content should be achieved.

Some brief quotations from a treatise on organic solvents [11] highlight the problems associated with acetone and its water content:

> Acetone is much more reactive than is generally supposed. Such mildly basic materials as alumina gel cause aldol condensation to 4-hydroxy-4-methyl-2-pentanone (diacetone alcohol), and an appreciable quantity is formed in a short time if the acetone is warm. Small amounts of acidic material, even as mild as anhydrous magnesium sulphate, cause acetone to condense.
>
> Silica gel and alumina increased the water content of the acetone, presumably through the aldol condensation and subsequent dehydration. The water content of acetone was increased from 0.24 to 0.46% by one pass over alumina. All other drying agents tried caused some condensation.

Ammonia has a very great affinity for water, and it has been found that a water content of the order of <10 ppm is necessary to obtain satisfactory performance. Several chemical companies are able to supply high-purity ammonia but exposure to air during heat pipe filling must be avoided.

The above examples are extreme but serve to illustrate the problems that can arise when the handling procedures are relaxed.

A procedure that is recommended for all heat pipe working fluids used up to 200°C is freeze-degassing. This process removes all dissolved gases from the working fluid, and if the gases are not removed they could be released during heat pipe operation and collected in the condenser section. Freeze-degassing may be carried out on the heat pipe filling rig described in Section 5.1.8 and is a simple process. The fluid is placed in a container in the rig directly connected to the vacuum system and is frozen by surrounding the container with a flask containing liquid nitrogen. When the working fluid is completely frozen the container is evacuated and resealed and the liquid nitrogen flask removed. The working fluid is then allowed to thaw and dissolved gases will be seen to bubble out of the liquid. The working fluid is then refrozen and the process repeated. All gases will be removed after three or four freezing cycles.

The liquid will now be in a sufficiently pure state for insertion into the heat pipe.

5.1.8 Heat Pipe Filling

A flow diagram for a rig that may be used for heat pipe filling is shown in Fig. 5.11. The rig may also be used to carry out the following processes:

- Working fluid degassing
- Working fluid metering
- Heat pipe degassing
- Heat pipe filling with inert gas.

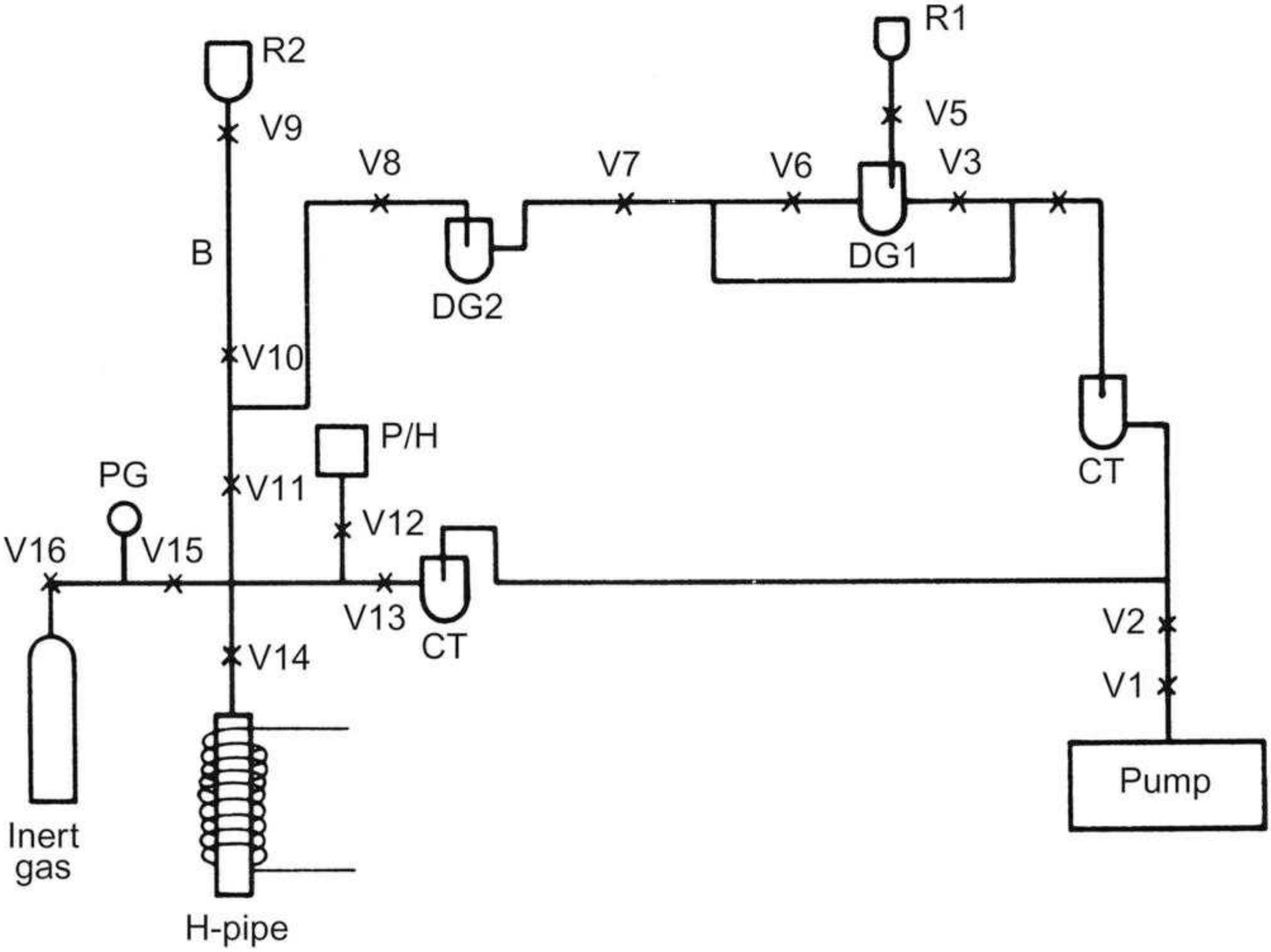


Figure 5.11: A heat pipe filling rig layout

Before describing the rig and its operation, it is worth mentioning the general requirements when designing vacuum rigs. The material of construction for pipework is generally either glass or stainless steel. Glass has advantages when handling liquids in that the presence of liquid droplets in the ductwork can be observed and their vaporisation under vacuum noted. Stainless steel has obvious strength benefits and must be used for all high-temperature work, together with high-temperature packless valves such as Hoke bellows valves. The rig described below is for low-temperature heat pipe manufacture.

Valves used in vacuum rigs should preferably have ‘O’ ring seals, and it is important to ensure that the ductwork is not too long or has a small diameter, as this can greatly increase evacuation times.

The vacuum pump may be the diffusion type or a sorption pump containing a molecular sieve that produces vacuums as low as 10^{-4} torr. It is, of course, advisable to refer to experts in the field of high-vacuum technology when considering designing a filling rig.

5.1.8.1 Description of Rig

The heat pipe filling rig described below is made using glass for most of the pipework. Commencing from the right-hand side, the pump is of the sorption type, which is surrounded by a polystyrene container of liquid nitrogen when a vacuum is desired. Two valves are fitted above the pump, the lower one being used to disconnect the pump when it becomes saturated. (The pump may be cleaned by baking out in a furnace for a few hours.) Above the valve V2, a glass-to-metal seal is located and the rest of the pipework is glass. Two limbs lead from this point, both interrupted by cold traps, in the form of small glass flasks, which are used to trap stray liquid and any impurities which could affect other parts of the rig or contaminate the pump. The cold traps are formed by surrounding each flask with a container of liquid nitrogen.

The upper limb includes provision for adding working fluid to the rig and two flasks are included (DG1 and DG2) for degassing the fluid. The section of the rig used for adding fluid can be isolated once a sufficient quantity of fluid has been passed to flask DG2 and thence to the burette between valves V9 and V10.

The lower limb incorporates a Pirani head that is used to measure the degree of vacuum in the rig. The heat pipe to be filled is fitted below the burette, and provision is also made to electrically heat the pipe to enable outgassing of the unit to be carried out on the rig (see also Section 5.1.4). An optional connection can be made via valve V15 to permit the loading of inert gas into the heat pipe for variable conductance types.

5.1.8.2 Procedure for Filling a Heat Pipe

The following procedure may be followed using this rig for filling, for example, a copper/ethanol heat pipe.

i. Close all valves linking rig to atmosphere (V5, V9, V14, V15).

ii. Attach sorption pump to rig via valves V1 and V2, both of which should be closed.

iii. Surround the pump with liquid nitrogen, and also top up the liquid nitrogen containers around the cold traps. It will be found that the liquid N_2 evaporates quickly initially, and regular topping up of the pump and traps will be necessary.

iv. After approximately 30 min, open valves V1 and V2, commencing rig evacuation. Evacuate to about 0.010 mmHg, the time to achieve this depending on the pump capacity, rig cleanliness and rig volume.

v. Close valves V4 and V6, and top up reservoir R1 with ethanol.

vi. Slowly crack valve V5 to allow ethanol into flask DG1. Reclose V5 and freeze the ethanol using a flask of liquid N_2 around DG1.

vii. When all the ethanol is frozen, open V4 and evacuate. Close V4 and allow ethanol to melt. All gas will bubble out of the ethanol as it melts. The ethanol is then refrozen.

viii. Open V4 to remove gas.

ix. Close V4, V3 and V8; open V6 and V7. Place liquid N_2 container around flask DG2.

x. Melt the ethanol in DG1 and drive it into DG2. (This is best carried out by carefully heating the frozen mass using a hair dryer. Warming of the ductwork between DG1 and DG2 and up to V4 will assist.)

xi. The degassing process may be repeated in DG2 until no more bubbles are released. V4 and V6 are now closed, isolating DG1.

xii. Close V7 and V11; open V8 and V10, and drive the ethanol into the burette as in (x). Close V10 and V8 and open V11. The lower limb and upper limb back to V8 are now brought to a high vacuum (≈0.005 mmHg).

The heat pipe to be filled should now be attached to the rig. In cases where the heat pipe does not have its own valve, the filling tube may be connected to the rig below V14 using thick-walled rubber tubing, or in cases where this may be attacked by the working fluid, another flexible tube material or a metal compression or ‘O’ ring coupling. If a soft tube material is used, the joints should be covered with a silicone-based vacuum grease to ensure no leaks.

The heat pipe may be evacuated by opening valve V14. Following evacuation that should take only a few minutes, depending on the diameter of the filling tube, the heat pipe may be outgassed by heating. This can be done by surrounding the heat pipe with electric heating tape, and applying heat until the Pirani gauge returns to the maximum vacuum obtained before heating commenced. (It is worth emphasising the fact that, depending on the diameter of the heat pipe and filling tube, the pressure recorded by the Pirani is likely to be less than that in the heat pipe. It is preferable from this point of view to have a large diameter filling tube.)

To prepare the heat pipe for filling, the lower end is immersed in liquid nitrogen so that the working fluid, which flows towards the coldest region, will readily flow to the heat pipe base. Valve V10 is then cracked and the correct fluid inventory (in most cases enough to saturate the wick plus a small excess) is allowed to flow down into the heat pipe. Should the fluid stray into valve seats or other parts of the rig, local heating of these areas using the hot air blower will evaporate any liquid, which should then condense and freeze in the heat pipe. A further freeze-degassing process may be carried out with the fluid in the heat pipe, allowing it to thaw with V14 closed, refreezing and then opening V14 to evacuate any gas. The heat pipe may then be sealed.

5.1.9 Heat Pipe Sealing

Unless the heat pipe is to be used as a demonstration unit, or for life testing, in which case, a valve may be retained on one end, the filling tube must be permanently sealed.

With copper, this is conveniently carried out using a tool that will crimp and cold weld the filling tube. A typical crimp obtained with this type of tool is shown in Fig. 5.12 and the force to operate this is applied manually. The tool is illustrated in Fig. 5.13.

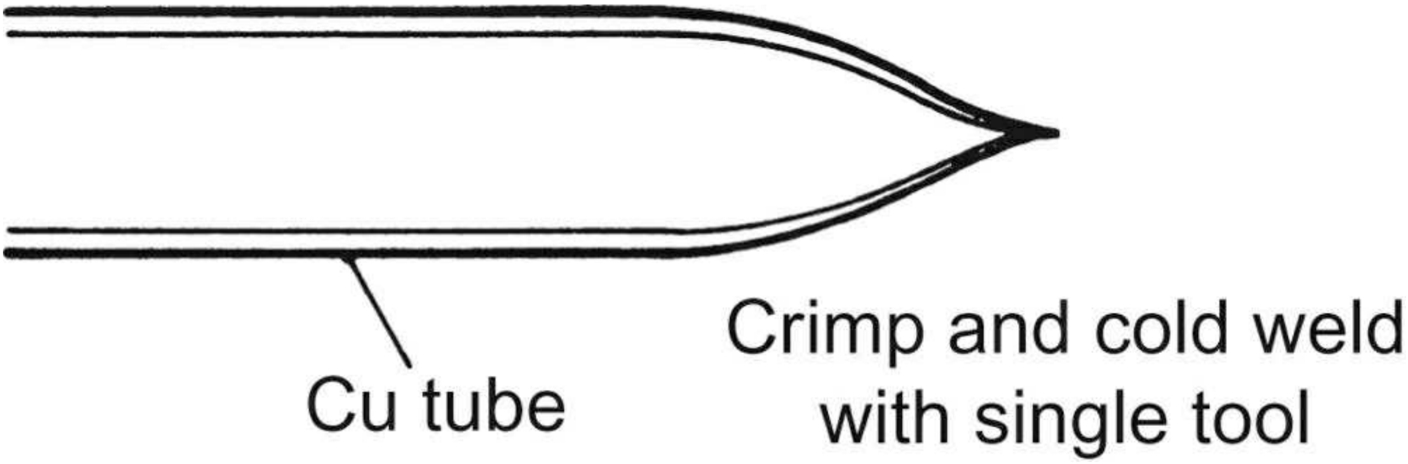


Figure 5.12: Crimped and cold-welded seal

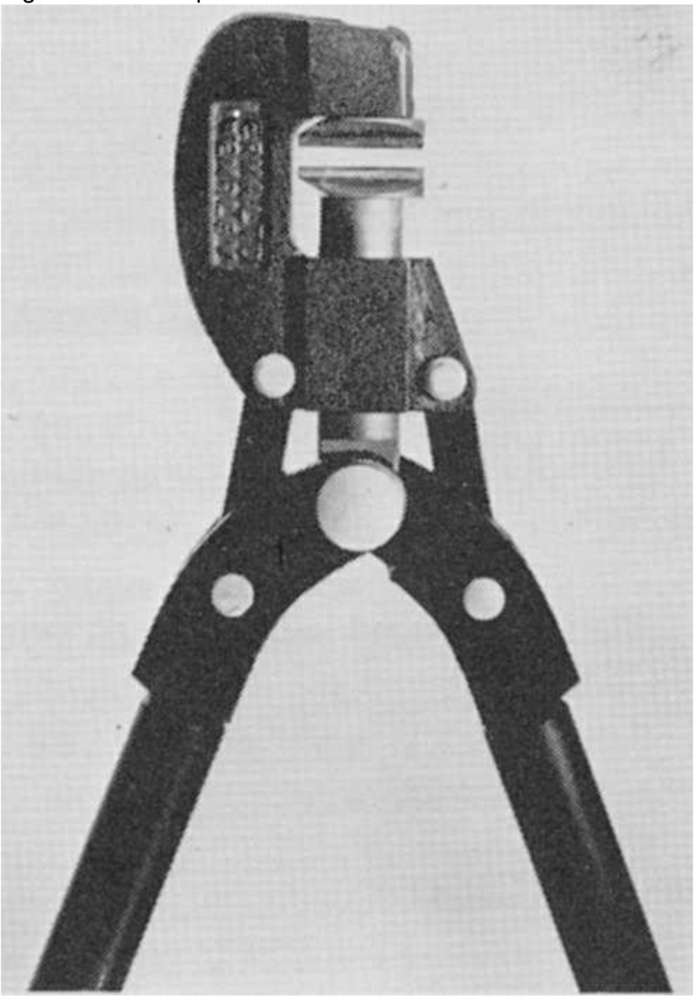


Figure 5.13: Crimp and cold welding tool

If stainless steel or aluminium is used as the heat pipe filling tube material, crimping followed by argon-arc welding is a more satisfactory technique. Once the desired vacuum has been attained and the fluid injected, two 0.5 in. (12.7 mm) jaws are brought into contact with the evacuating tube and the latter is flattened. The heat pipe is then placed between two 0.25 in. thick jaws located at the lower half of the 0.5 in. flattened section. Sufficient load is placed on the evacuating tube to temporarily form a vacuum-tight seal and the remaining 0.25 in. flattened section is simultaneously cut through and welded using an argon-arc torch. The 0.25 in. (6.3 mm) crimping tool, which fits between the jaws of a standard vice, is shown in Fig. 5.14. Results obtained are shown in Fig. 5.15.

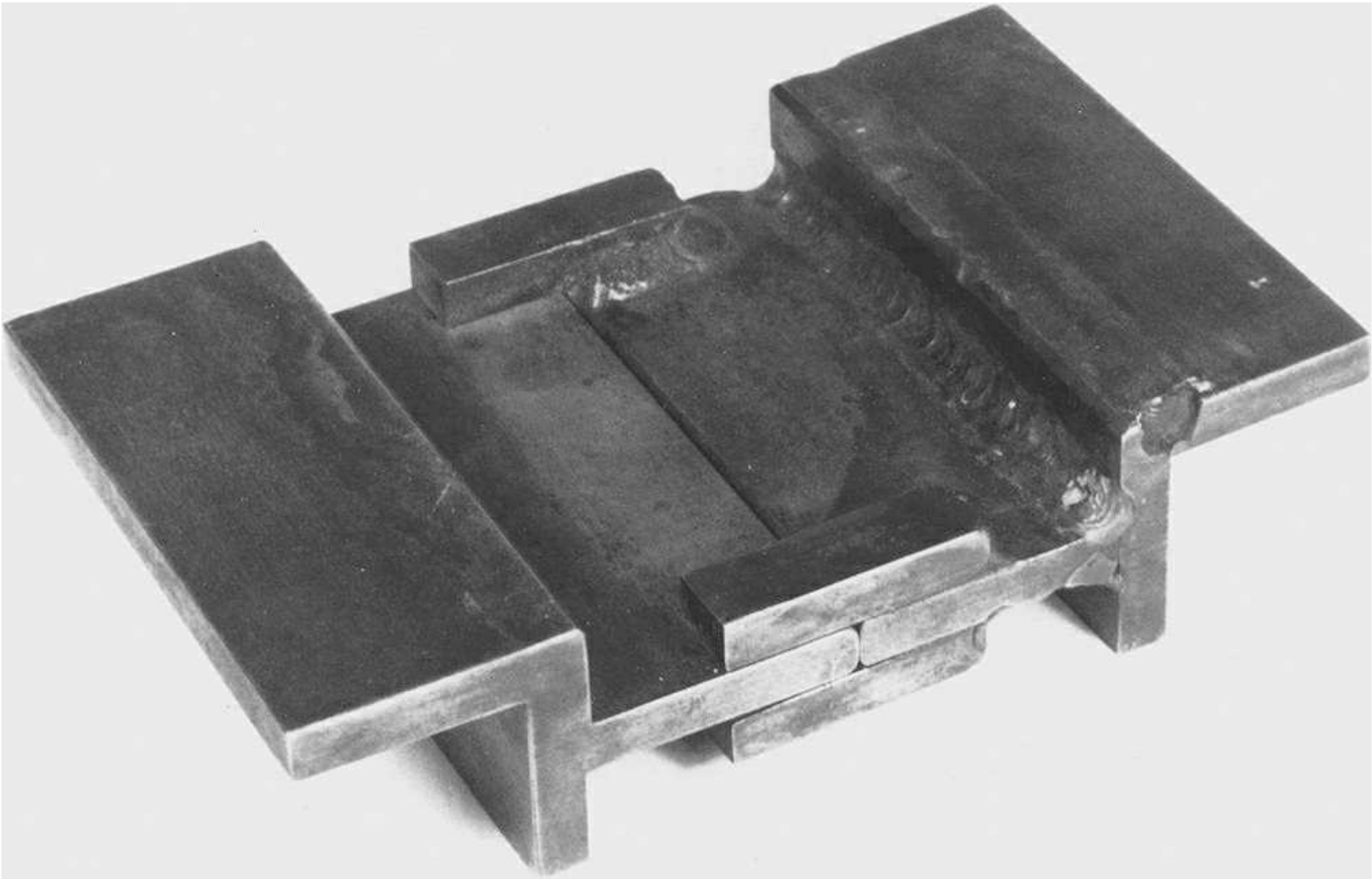


Figure 5.14: Jaws for crimping prior to welding

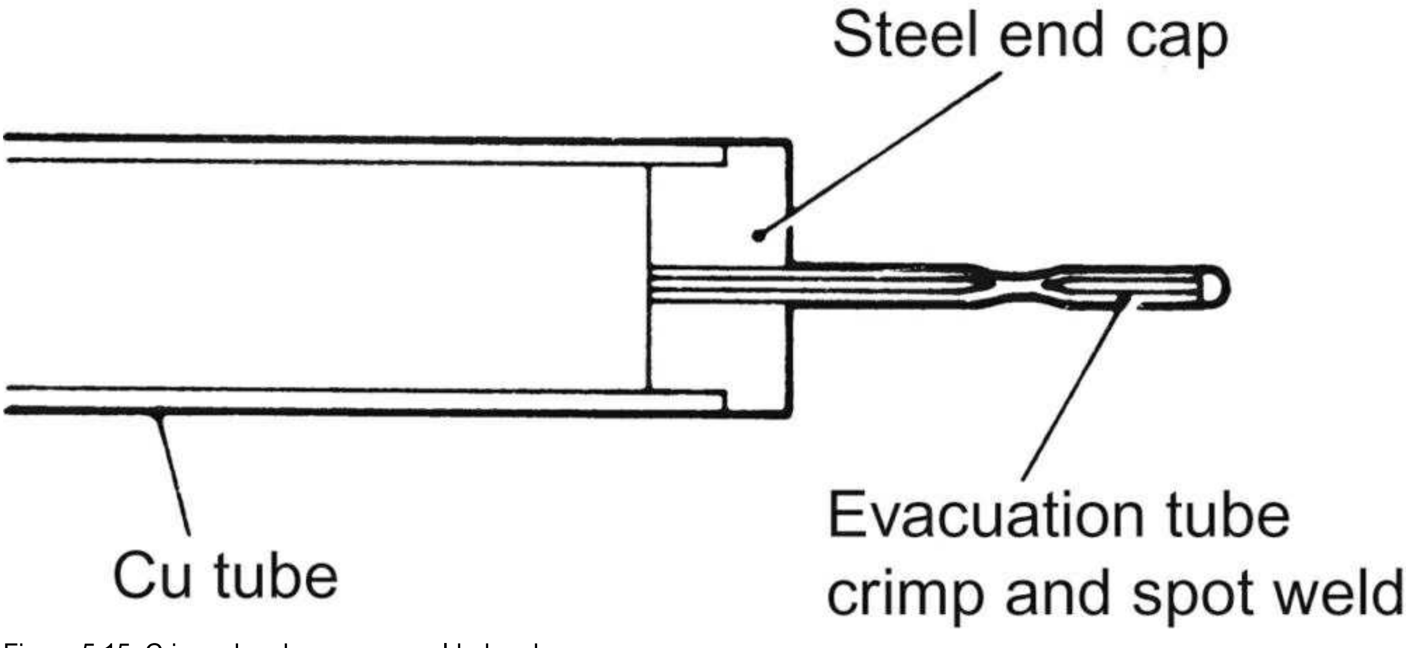


Figure 5.15: Crimped and argon-arc welded end

Following sealing the filling tube may be protected by a cap having an outer diameter the same as that of the heat pipe wall. The cap may be filled with solder, a metal-loaded resin or any other suitable material.

5.1.10 Summary of Assembly Procedures

The following is a list of the procedures described above, which should be followed during heat pipe assembly:

i. Select container material

ii. Select wick material and form

iii. Fabricate wick and end caps, etc.

iv. Clean wick, container and end caps

v. Outgas metal components

vi. Insert wick and locate

vii. Weld end caps

viii. Leak check welds

ix. Select working fluid

x. Purify working fluid (if necessary)

xi. Degas working fluid

xii. Evacuate and fill heat pipe

xiii. Seal heat pipe.

It may be convenient to weld the blank end cap before wick insertion, and in cases of sintered and diffusion-bonded wicks, the outgassing may be done with the wick in place in the container.

For the manufacturer considering the production of a considerable number of identical heat pipes, for example 50 or more units following prototype trials, a number of the manufacturing stages may be omitted. Outgassing of metal components may be unnecessary, and it may be found that, depending upon the filling and evacuation procedure used, the fluid degassing may be eliminated as a separate activity.

5.1.11 Heat Pipes Containing Inert Gas

Heat pipes of the variable conductance type (see Section 6.1) contain an inert gas in addition to the normal working fluid, and an additional step in the filling process must be carried out. The additional features on the filling rig to cater for inert gas metering are shown in Fig. 5.11.

The working fluid is inserted into the heat pipe in the normal way, and then the system is isolated and the line connecting the heat pipe to the inert gas bottle is opened and the inert gas bled into the heat pipe. The pressure increases as the inert gas quantity in the heat pipe is raised, as indicated by the pressure gauge in the gas line. The pressure appropriate to the correct gas inventory may be calculated, taking into account the partial pressure of the working fluid vapour in the heat pipe (see earlier editions for mass calculation) and when this is reached, the heat pipe is sealed in the normal manner.

Two aspects of variable conductance (gas-loaded) heat pipes need to be accounted for in manufacture and test procedures. Firstly, most theories for VCHPs are based on the assumption that the gas–vapour interface is sharp and diffusion between the two regions is not present. In practice this is not the case, and in some designs it is necessary to take diffusion into account.

A second more serious phenomenon resulting from the introduction of inert gas control into a heat pipe occurs when gas bubbles enter the wick structure via the working fluid.

These two features are briefly discussed below.

5.1.11.1 Diffusion at the Vapour–Gas Interface

It has been demonstrated that in some gas-buffered heat pipes the energy and mass diffusion between the vapour and the non-condensable gas could have an appreciable effect on heat transfer in the interface region and the temperature distribution along the heat pipe.

The diffusion coefficient of the inert gas has an effect on the extent of the diffuse region, gases having higher diffusion coefficients being less desirable, reducing the maximum heat transport capability of the heat pipe by reducing local condenser temperature. It must be noted that the diffusion coefficient is inversely proportional to density, and therefore at lower operating temperatures, particularly during start-up of the heat pipe, the diffuse region may be extensive and of even greater significance. It is therefore important to cater for this during any transient performance analysis, and it should be noted during inert gas selection.

5.1.11.2 Gas Bubbles in Arterial Wick Structures

Although in simple heat pipes containing only the working fluid, freeze-degassing of the liquid can remove any dissolved gases; in a VCHP inert gas is always present. If the gas dissolves in the working fluid, or finds its way in bubble form into arteries carrying liquid, the performance of the heat pipe can be adversely affected.

Saaski [12] carried out theoretical and experimental work on the isothermal dissolution of gas in arterial heat pipes, examining effects of solubility and diffusivity of helium and argon in ammonia, and methanol.

One of the significant factors determined by Saaski was the venting time of bubbles in working fluids (the time for a bubble to disappear).

The venting time t_v may be calculated from the equation:

$$t_v = \frac{R_0^2}{3\alpha D}$$

where R_0 is the bubble radius (initial); a the Ostwald coefficient, given by the ratio of the solute concentration in the liquid phase to the concentration in the gaseous phase [13] and D the diffusion coefficient.

Predicted values of t_v are given in Table 5.1.

Table 5.1: Venting Time of Gas Bubbles in Working Fluids (R_0=0.05 cm)

		t_v (s)	
Fluid	**Temperature**	**Helium**	**Argon**
Ammonia	−40	1200	107
	20	63	6.7
	60	7	1.6
Methanol	−40	1030	154
	20	133	55
	60	50	26
Water	22	1481	1215

Table 5.1 shows that the venting times can be considerable when the working fluid is at a low temperature, but in general argon is more easily vented than helium.

The equation above is not valid when non-condensable gas pressure is significant compared to the value of $2\sigma_l/R_0$, where σ_l is the surface tension of the working fluid. Saaski stated that the venting time increases linearly with non-condensable gas pressure, other factors being equal, and showed that if, as in a typical gas-controlled heat pipe, the helium pressure is about equal to the ammonia working fluid vapour pressure, the vent time can be 9 days. This is a very long time when compared with the transients to be expected in a VCHP; by changing the working fluid and/or control gas, relatively long venting times may still be obtained.

Having established venting times for spherical bubbles, Saaski developed a theory to cater for elongated bubbles, the type most likely to form in arteries. He obtained the results in Table 5.2 for the half-lives of elongated arterial bubbles in a VCHP at 20°C (artery radius 0.05 cm, non-condensable gas partial pressure equal to vapour pressure).

Table 5.2: Half-lives of Arterial Bubbles in Various Working Fluids

Fluid	**$t_{1/2}$ (Helium)**	**$t_{1/2}$ (Argon)**
Ammonia	7 days	17 h
Methanol	4.8 h	1.7 h
Water	3 h	2.5 h

The models used to calculate these values were confirmed experimentally, and it was concluded that the venting times are of sufficient length that repriming of an arterial heat pipe containing gas may be possible only if some assistance in releasing gas occlusions can be given during start-up or steady state operation, either by internal phenomena or by external interference.

Kosson et al. [14] introduced another factor affecting VCHPs, namely variations in pressure within the pipe due to oscillations in the diffusion zone. These pressure variations are of the same order as the capillary pressure and can cause vapour flashing within the artery, with accompanying displacement of liquid from the artery.

In order to overcome this and occlusion problems, subcooling of the liquid in the artery was carried out by routing the fluid to the condenser wall so that it experienced sink conditions before returning to the evaporator. As shown in Saaski's results, lowering the liquid temperature improved venting time. It was also found to reduce the sensitivity of the artery to vapour formation caused by the pressure oscillations described above.

Work recently reported by Lockheed Martin Space Systems [15] suggests that it is possible to model the effect of accelerations on heat pipes. This is particularly important in spacecraft applications – and these may occur in orbit or during the launch phase. This can involve depriming of the wick and repriming of the form discussed above is relevant and of course necessary. The work by Ambrose studied the acceleration forces that may be encountered while the units containing heat pipes are in orbit, and more specifically relates to the effect of thrusts that may be used to re-orientate the spacecraft or change orbit. Predictions were made of heat pipe thermal responses to acceleration pulses and of the wick rewetting behaviour. In the case of rewetting of the evaporators in a Lunar Reconnaissance Orbiter, located on the heat pipe avionics radiator (involving over 20 heat pipes), the predicted adiabatic rewetting was found to be in good agreement with the 2–4 min recovery time measured in practice.

5.1.12 Liquid Metal Heat Pipes

The early work on liquid metal heat pipes was concerned with the application to thermionic generators. For this application, there are two temperature ranges of interest, the emitter range of 1400–2000°C and the collector range of 500–900°C. In both temperature ranges, liquid metal working fluids are required and there is a considerable body of information on the fabrication and performance of such heat pipes. More recently, heat pipes operating in the lower temperature range have been used to transport heat from the heater to the multiple cylinders of a Stirling engine and for industrial ovens. A large range of material combinations have been found suitable in this temperature range and compatibility and other problems are well understood. The alkali metals are used with containment materials such as stainless steel, nickel, niobium–zirconium alloys and other refractory metals. Lifetimes of greater than 20 000 h are reported [16]. Grover [17] reports on the use of a lightweight pipe made from beryllium and using potassium as the working fluid. The beryllium was inserted between the wick and wall of a pipe both made from niobium–1% zirconium. The pipe operated at 750°C for 1200 h with no signs of attack, alloying or mass transport.

The use of Inconel 600 as a container material with sodium working fluid was investigated by Japanese researchers, with a view to show its long-term durability compared to stainless steel type 316. Standard assembly procedures were used, and results of life tests showed some superiority of Inconel 600 over 316 stainless steel, but grain boundary examination suggested that after 60 000 h of operation, pitting would lead to pin holes of corrosion [18].

High-performance, long life, liquid metal heat pipes can be constructed with some confidence; they are, however, expensive. Hence, before commencing the design of a liquid metal heat pipe, it is important to decide what is to be required from it. It frequently happens that an application does not require the pipe to pump against a gravity head so that a thermal syphon will be adequate. This greatly reduces the importance of working fluid purity. Again short operation life at low rating will enable cheaper and less time-consuming fabrication methods to be adopted. If gas buffering is possible a simpler crimped seal arrangement can be used.

Two examples of heat pipes using liquid sodium as the working fluid are shown in Figs 5.16 and 5.17. These heat pipes, manufactured by Transterm in Romania, are tubular and annular units, respectively. The unit in Fig. 5.16 is destined for a chemical reactor, while the second unit, an isothermal oven, may be used for crystal growing.

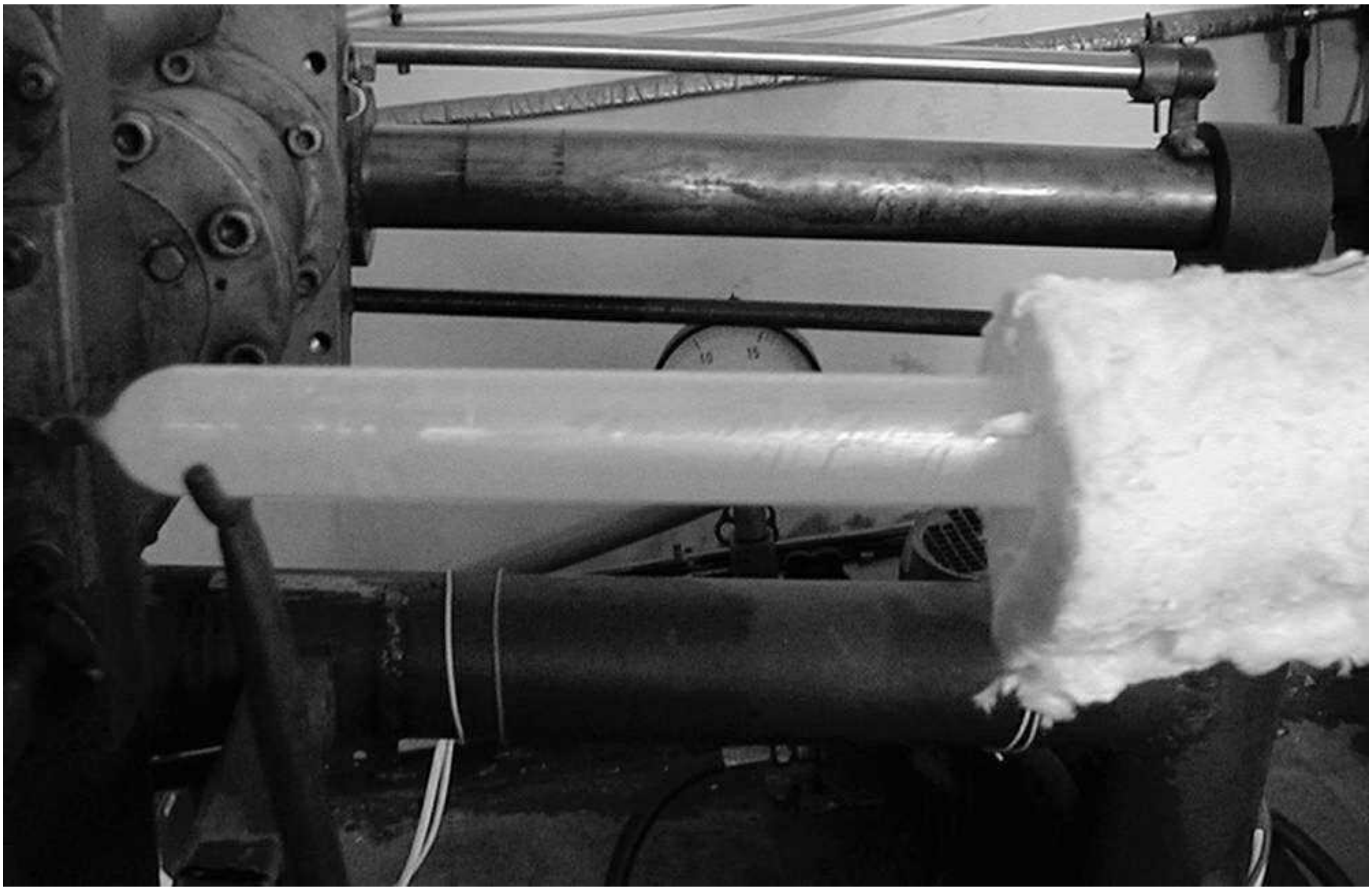


Figure 5.16: Sodium heat pipe during manufacturing process. Dimensions: length, 2800 mm; outside diameter, 38 mm; inside diameter, 32 mm; destination: catalytic reactors

Figure 5.17: Isothermal oven for growing crystals experiments. Working fluid: sodium; dimensions: length, 500 mm; outside diameter, 51 mm; inner working space diameter 25 mm

5.1.13 Liquid Metal Heat Pipes for the Temperature Range 500–1100°C

In this temperature range potassium and sodium are the most suitable working fluids and stainless steel is selected for the container. The construction and fabrication of a sodium heat pipe [19] will be described to indicate the processes involved. The heat pipe container was made from type 321 (EN58B) stainless steel tube 2.5 cm diameter and 0.9 mm wall thickness. The capillary structure was two layers of 100-mesh stainless steel having a wire diameter of 0.1016 mm and an aperture size of 0.152 mm. The pipe was 0.9 m in length and the wick welded by spot welds using a special tool built for the purpose.

5.1.13.1 Cleaning and Filling

The following cleaning process was followed:

i. Wash with water and detergent.

ii. Rinse with demineralised water.

iii. Soak for 30 min in 1:1 mixture of hydrochloric acid and water.

iv. Rinse with demineralised water.

v. Soak for 20 min in an ultrasonic bath filled with acetone and repeat with a clean fluid.

After completion of the welds and brazes this procedure was repeated. Argon-arc welding was used throughout, and after leak testing, the pipe was outgassed at a temperature of 900°C and a pressure of 10^{-5} torr for several hours in order to remove gases and vapours.

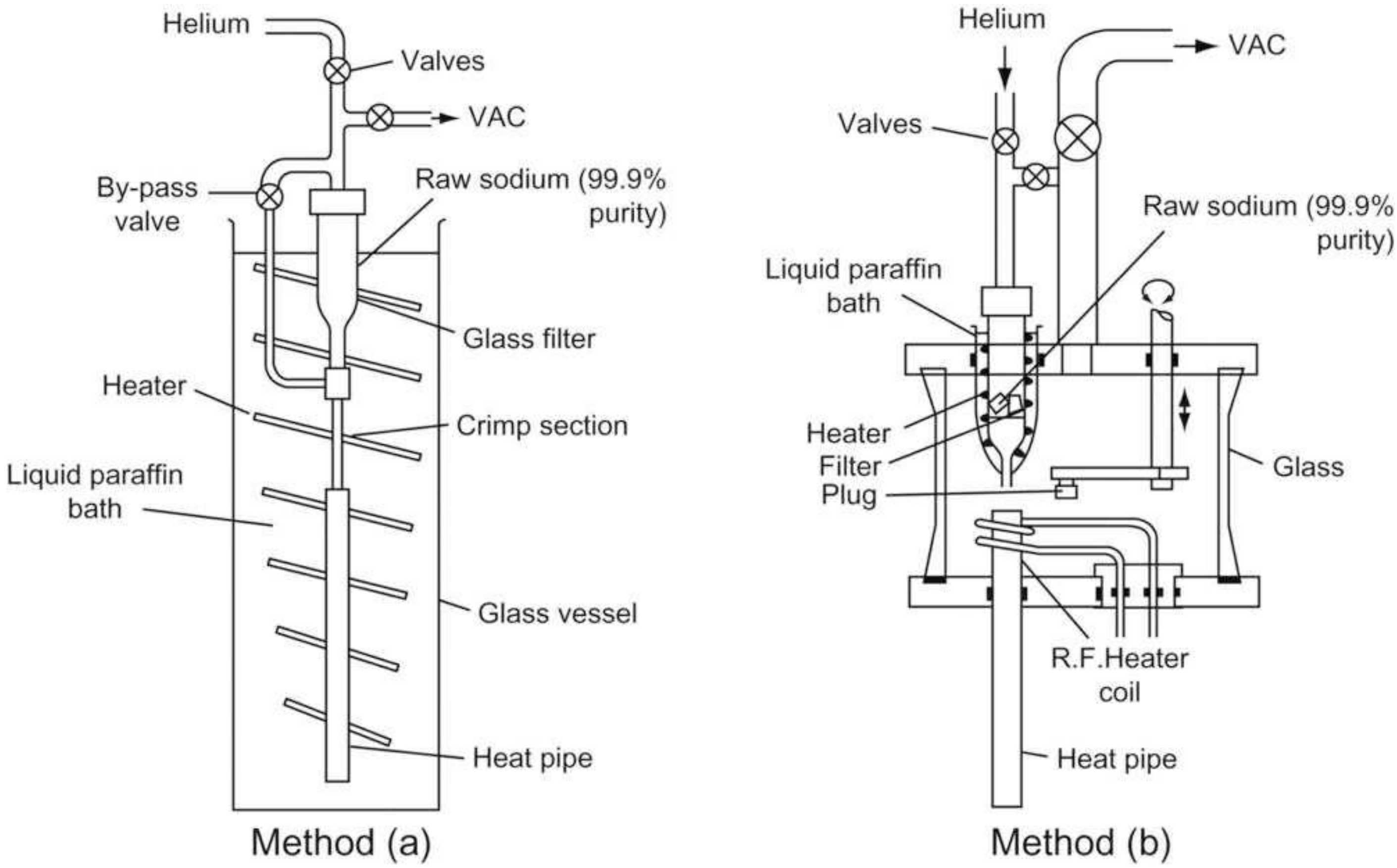
Various methods may be used to fill the pipe with liquid metal including:

i. distillation, sometimes from a getter sponge to remove oxygen;

ii. breaking an ampoule contained in the filler pipe by distortion of the filler pipe;

   Distillation is essential if a long life is required. The method adopted for the pipe being described was as follows:

iii. 99.9% industrial sodium was placed in a glass filter tube attached to the filling tube of the heat pipe. A bypass to the filter allowed the pipe to be initially evacuated and outgassed. The filling pipe and heat pipe were immersed in the heated liquid paraffin bath to raise the sodium above its melting point. The arrangement is shown in Fig. 5.18.



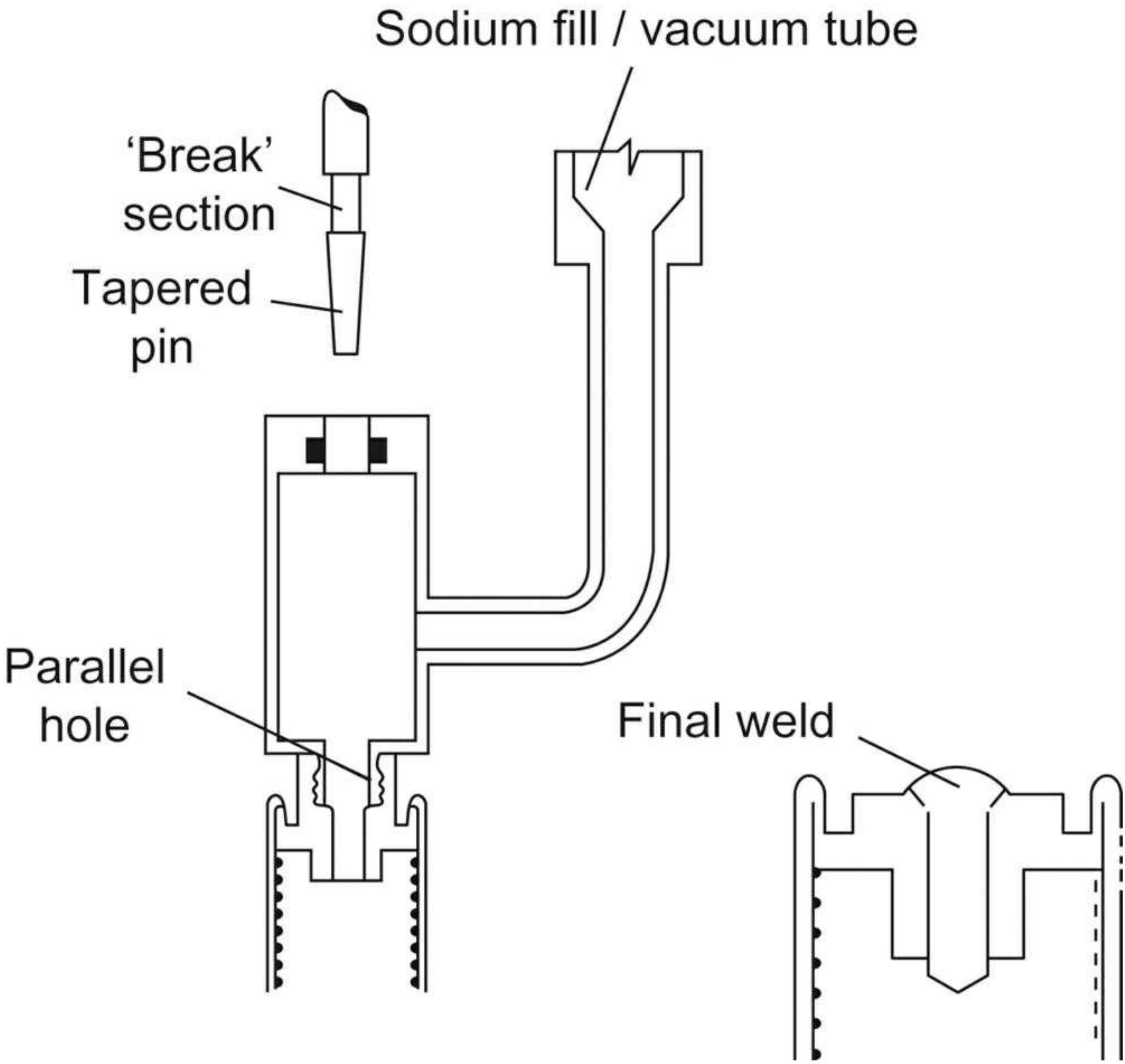
(Courtesy Reading University).

Figure 5.18: Liquid metal heat pipe filling

Finally the bypass valve is closed and a pressure applied by means of helium gas to force the molten sodium through the filter and into the heat pipe.

5.1.13.2 Sealing

For liquid metal heat pipes at Reading University, the technique of plug sealing was adopted, as shown in Fig. 5.19.



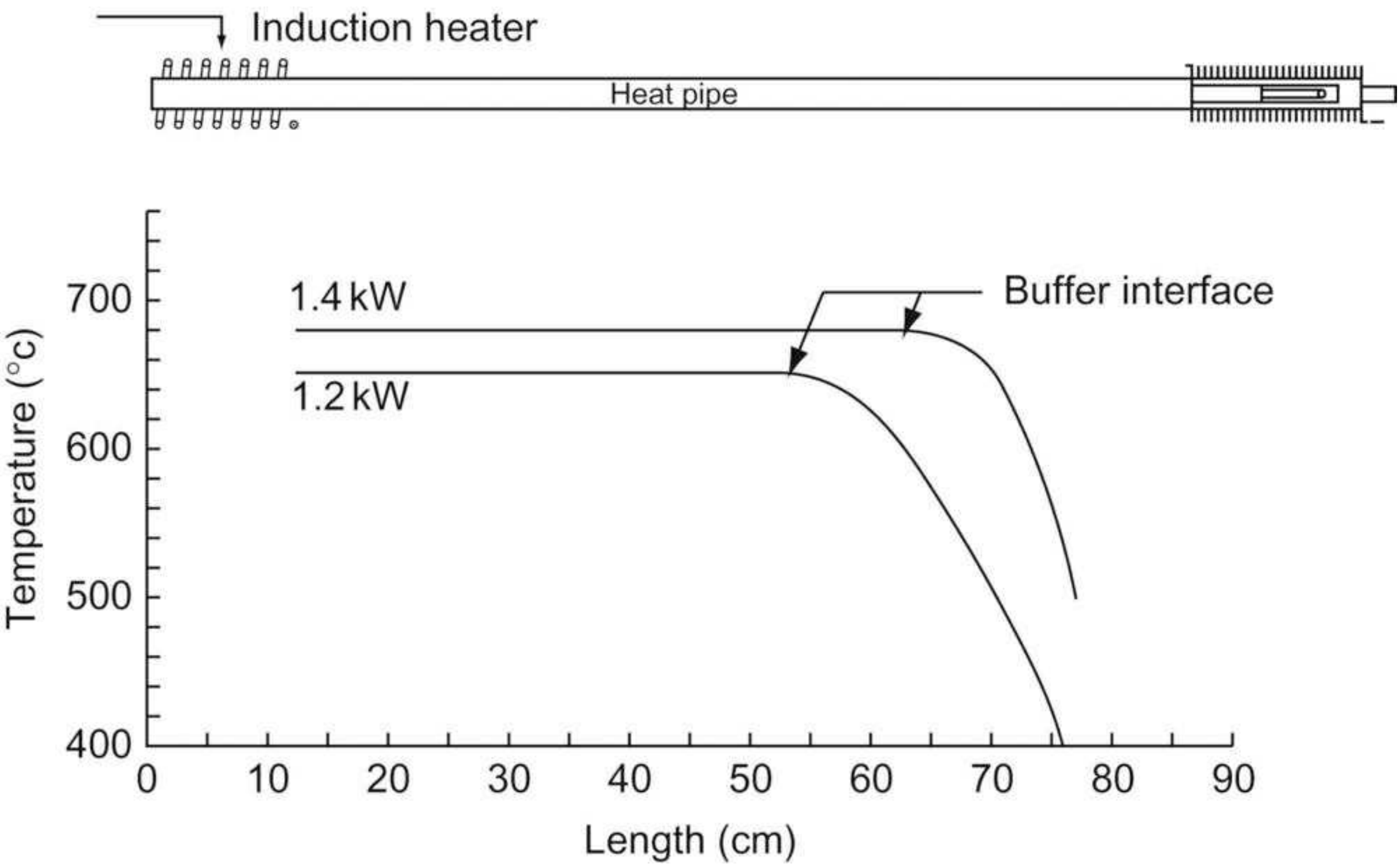
(Courtesy Reading University).

Figure 5.19: Plug sealing technique for sealing liquid metal heat pipes

A special rig has been constructed which allows for outgassing of an open-ended tube and sodium filling by the filtering method described above. On completion of the filling process, the end sealing plug, supported by a swivel arm within the filling chamber, is swung into position and placed within the heat pipe. The plug is then induction heated to effect a brazed vacuum seal. The apparatus and sequence of operation is illustrated in Fig. 5.18. The end sealing plug is finally argon-arc welded after removal of the heat pipe from the filling apparatus.

5.1.13.3 Operation

It has been found that wetting of the wick structure does not occur immediately, and it was necessary to heat the pipe as a thermal syphon for several hours at 650°C. Heating was by an RF (radio frequency) induction heater over a length of 10 cm. Temperature profiles are given in Fig. 5.20 for heat inputs of 1.2 and 1.4 kW. Before sealing, the heat pipe was filled with helium at a pressure of 20 torr to protect the copper crimp by the resulting gas buffer. It is seen that the gas buffer length is approximately proportional to the power input as might be expected.



(Courtesy Reading University).

Figure 5.20: Temperature profiles along a sodium heat pipe

The start-up of the heat pipe after conditioning was interesting. In the thermal syphon mode, that is with the pipe vertical and heated at the bottom, there were violent temperature variations associated with boiling in the evaporator zone. This was not experienced when the heater was at the top of the heat pipe. Further sodium work at Reading is described in Ref. [20].

Similar work has been reported by other authors. An interesting method for making rigid thin-walled wicked pipes is described by Vinz et al. [21]. Previous work on mesh wicks has included methods such as spot welding, drawing and sintering. The first method does not give uniform adhesion, and drawing methods cannot be used for very fine wicks (<200–400 mesh) because of damage. Vinz's method consists of winding a screen strip spirally on a mandrel and sintering it under simultaneous axial pulling and twisting. Gauze of 508×3600 mesh has been used successfully to give pore diameters of 10 μm reproducible to ±10% and with a free surface for evaporation of 15–20%.

Broached grooves can be used either alone or with gauze wicks.

5.1.13.4 High-Temperature Liquid Metal Heat Pipes >1200°C

At the lower end of the range, lithium is preferred as the working fluid and niobium–zirconium or tantalum as the container material. At higher temperatures silver may be used as the working fluid with tungsten or rhenium as the container material. Data on the compatibility and lifetime of heat pipes made from these materials are given in Chapter 3. Such refractory materials have a high affinity for oxygen and must be operated in a vacuum or inert gas.

Busse and his collaborators have carried out a considerable programme on lithium and silver working fluid heat pipes, and the techniques used for cleaning, filling, fabrication and sealing are described in Refs [22,23].

More recently [24], a lithium heat pipe system has been studied by Advanced Cooling Technologies in the United States, on behalf of Lockheed Martin and the US Air Force Research Laboratory. The system, operating at slightly lower temperatures (to 1100°C), is directed at cooling the wings of spacecraft on re-entry into the Earth's atmosphere.

5.1.13.5 Gettering

Oxides can be troublesome in liquid metal heat pipes since they will be deposited in the evaporator area. Dissolved oxygen is a particular problem in lithium heat pipes since it causes corrosion of the container material. Oxygen can arise both as an impurity in the heat pipe fluid and also from the container and wick material. A number of authors report the use of getters. For example Busse et al. [23] used a zirconium sponge from which he distilled lithium into the pipe. Calcium can also be used for gettering.

5.1.14 Safety Aspects

While there are no special hazards associated with heat pipe construction and operation, there are a number of aspects that should be borne in mind.

Where liquid metals are employed, standard handling procedures should be adopted. The affinity of alkali metals for water can give rise to problems; a fire was started in one laboratory when a sodium in stainless steel pipe distorted releasing the sodium and at the same time fracturing a water pipe.

Mercury is a highly toxic material and its saturated vapour density at atmospheric pressure is many times the recommended maximum tolerance.

One danger that is sometimes overlooked is the high pressure which may occur in a heat pipe when it is accidentally raised to a higher temperature than its design value. Water is particularly dangerous in this respect. The critical pressure of water is 220 bar and occurs at a temperature of 374°C. When water in copper heat pipe sealed by a soldered plug was inadvertently overheated, both the 30 cm long heat pipe and the plug were ejected from the clamps at very high velocity and could well have had fatal results. It is imperative that a release mechanism such as a crimp seal be incorporated in such heat pipes.

Cryogenic heat pipes employing fluids such as liquid air should have special provision for pressure release or be of sufficient strength since they are frequently allowed to rise to room temperature when not in use. The critical pressure of nitrogen is 34 bar.

Organisations using specific ‘Health and Safety at Work’ documentation and procedures will find that many aspects of heat pipe manufacture and use may need bringing to the attention of personnel, such as the toxicity/flammability of some working fluids, the high-temperature of some surfaces and the need to keep within internal pressure guidelines. (Note that pressure will not in most cases be monitored and can only be assessed from knowledge of the heat pipe temperature and the fluid used within it.)

5.1.15 3D Printed Heat Pipes

3D printed heat pipes are being developed as part of an ongoing research project in the Faculty of Engineering and Environment of Northumbria University in Newcastle upon Tyne in collaboration with the University of Liverpool and Thermacore's UK base in Northumberland. The main objective of the project is to develop an aluminium ammonia heat pipe with a sintered wick structure. Currently available ammonia heat pipes mainly use extruded grooved aluminium tubes. There have been a small number of attempts of employing sintered steel or nickel wicks in steel tubes with ammonia as the working fluid [25], but these are believed to be the first published data on aluminium heat pipes with ammonia and a sintered wick structure. The main barrier is the difficulty of sintering aluminium powders to make sintered wicks. So far, promising sintered aluminium heat pipe samples have been manufactured using the SLM technique with various wick characteristics. This new method proved to be capable of producing very complicated wick structures with different thickness, porosity, permeability and pore sizes in different regions of a heat pipe in addition to the solid (nonporous) walls while the entire heat pipe including the end cap, wall, wick and the fill tube can be produced in a single process [26].

The Selective Laser Sintering/Melting (SLS/SLM) manufacturing process utilises a laser beam to locally melt a thin layer of metal powder. By applying additional powder layers and using 3D CAD and a custom beam control software to melt a pattern across each layer, complex 3D components that are not able to be manufactured using conventional machining can be produced. There are many companies offering this facility, including for heat exchangers – see for example the web site of Within [27].

After analysing the solid and porous structures various designs were proposed for manufacturing heat pipes by SLM. In order to check the feasibility of manufacturing the proposed designs, especially the axial grooved heat pipe, a preliminary 20 mm section of heat pipe was built in titanium. Then a 60 mm long sample of the same geometry was made from Al6061. These samples were to prove the ability of SLM in manufacturing complicated wick structures. In total four different wicks structures were manufactured, axial grooved wick (porous fins), annular wick, graded wick (different thickness and porosity in the evaporator and condenser sections of the pipe) and arterial wick (small ducts fabricated into an annular porous wick to facilitate the return of the working fluid condensate from condenser). The heat pipes are built up from the end cap upwards, with the end cap, wick and wall being made together.

In Fig. 5.21, from left to right, first a heat pipe is shown as it is modelled in CAD and it is then converted to a machine readable format using the SLM special CAD software. Then the build process is shown. Layers of powder are laid on the substrate. First layers are fully melted/fused together in a circular area to form the heat pipe end cap up to the specified thickness and then, in the following layers, powders in an annular section are fully melted and fused together to form the heat pipe wall. Adjacent to the wall the above-mentioned octahedral structure is formed by fusing the powders together along special passes up to the specified distance from the wall (wick thickness). This forms the capillary structure. Elsewhere the powder remains loose and is removed at the end by shaking the sample. In Fig. 5.22 a finished SLM arterial HP and its cross section are shown.

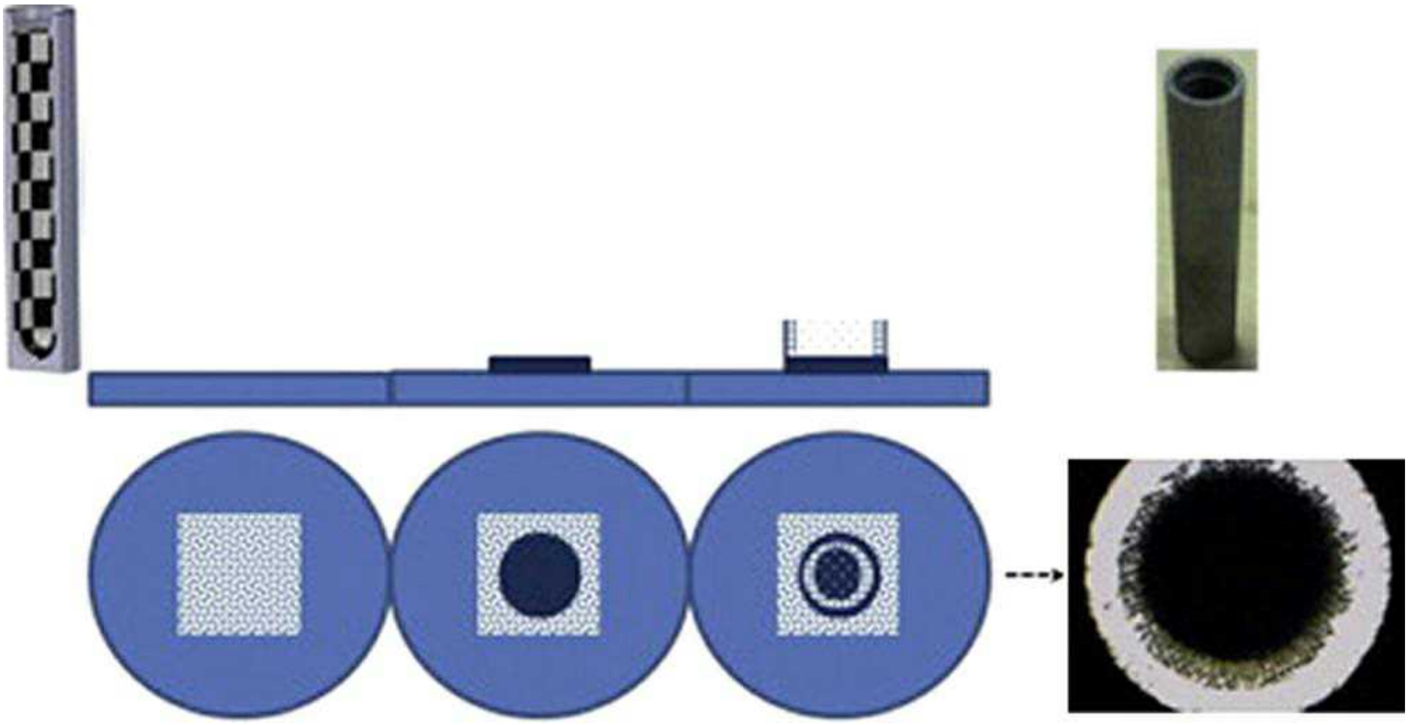


Figure 5.21: Heat pipe build process in SLM. The heat pipe is built up from the end cap upwards with the end cap, wall and wick made together on top of a substrate disk

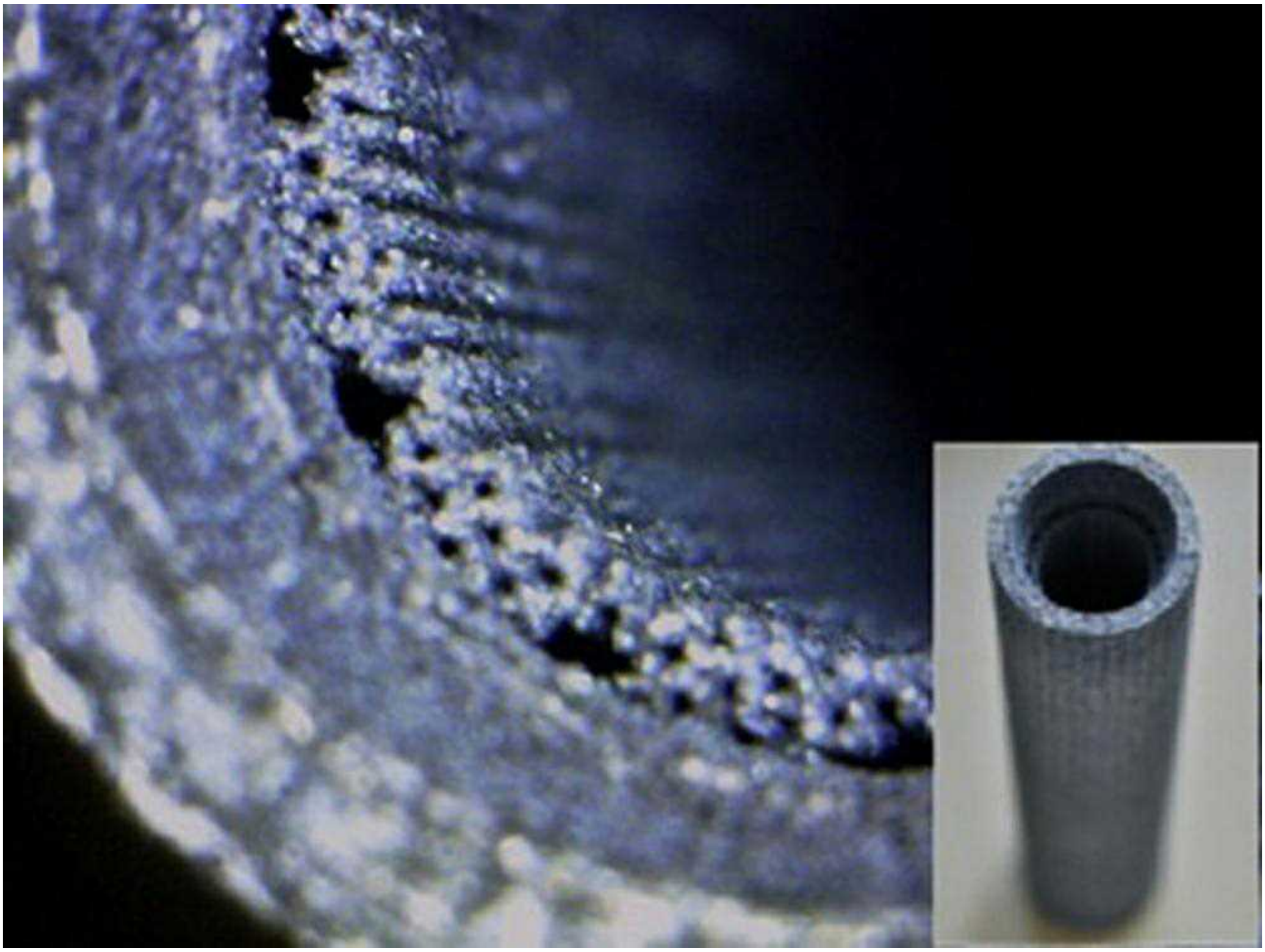


Figure 5.22: Arterial wick heat pipe made by SLM (14 mm OD and 70 mm length)

5.2 HEAT PIPE LIFE TEST PROCEDURES

Life testing and performance measurements on heat pipes, in particular when accelerated testing is required, are the most important factors in their selection.

In spacecraft, for example, the ESA stipulates [28] that heat pipes should be suitable for operation for 7–10 years in space after 5 years of ground storage and testing during spacecraft development. It is specifically stated that evidence of long-term compatibility of materials and working fluids must be available before spacecraft 'qualification' can be granted. (Requirements are presented in more detail later.)

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. The ultimate life test, however, would be in the form of a long-term performance test under conditions appropriate to those in the particular application. If this is done, it is difficult, however, in cases where the wick is pumping against gravity, to accelerate the life test by increasing, say, the evaporator heat flux, as this could well cause heat pipe failure owing to the fact that it is likely to be operating well in excess of its design capabilities. This, therefore, necessitates operation in the reflux mode. (Compatibility data are presented in Chapter 3.)

There are many factors to be taken into account when setting up a full life test programme, and the relative merits of the alternative techniques are discussed below.

5.2.1 Variables to Be Taken into Account during Life Tests

The number of variables to be considered when examining the procedure for life tests on a particular working fluid/wick/wall combination is very extensive and would require a large number of heat pipes to be fully comprehensive.

Several of these may be discounted because of existing available data on particular aspects, but one important point which must be emphasised is the fact that quality control and assembly techniques inevitably vary from one laboratory to another, and these differences can be manifested in differing compatibility data and performance.

5.2.1.1 The Working Fluid

The selection of the working fluid must take into account the following factors which can all be investigated by experiments:

i. Purity – the working fluid must be free of dissolved gases and other liquids, for example water. Such techniques as freeze-degassing and distillation are available to purify the working fluid. It is important to ensure that the handling of the working fluid following purification does not expose it to contaminants.

ii. Temperature – some working fluids are sensitive to operating temperature. If such behaviour is suspected, the safe temperature band must be identified.

iii. Heat flux – high heat fluxes can create vigorous boiling action in the wick, which can lead to erosion.

iv. Compatibility with wall and wick – the working fluid must not react with the wall and wick. This can also be a function of temperature and heat flux, the tendency for reactions to occur generally increases with increasing temperature or flux.

v. Non-condensable gas – in the case of VCHPs, where a non-condensable gas is used in conjunction with the working fluid, the selection of the two fluids must be based on compatibility and also on the solubility of the gas in the working fluid. (In general these data are available from the literature, but in specific arterial design the effect of solubility may only be apparent after experimentation.)

5.2.1.2 The Heat Pipe Wall

In addition to the interface with the heat pipe working fluid, as discussed above, the wall and associated components such as end caps have their own particular requirements with regard to life, and also interface with the wick. The successful operation of the heat pipe must take into account the following:

i. Vibration and acceleration – the structure must be able to withstand any likely vibrations and accelerations, and any qualification procedures designed to ensure that the units meet these specifications should be regarded as an integral part of any life test programme.

ii. Quality assurance – the selection of the outer case material should be based on the purity or at least the known alloy specification of the metal used.

iii. External environment – the external environment could affect the case material properties or cause degradation of the outer surface. This should also be the subject of life test investigation if any deterioration is suspected.

iv. Interface corrosion – it is possible that some corrosion could occur at metallic interfaces, particularly where dissimilar metals are used, in the presence of the working fluid.

5.2.1.3 The Wick

The heat pipe wick is subjected to the same potential hazards as the heat pipe wall, with the exception of external attack. Vibration is much more critical however, and the wick itself contains, in most cases, many interfaces where corrosion could occur (Fig. 5.23).

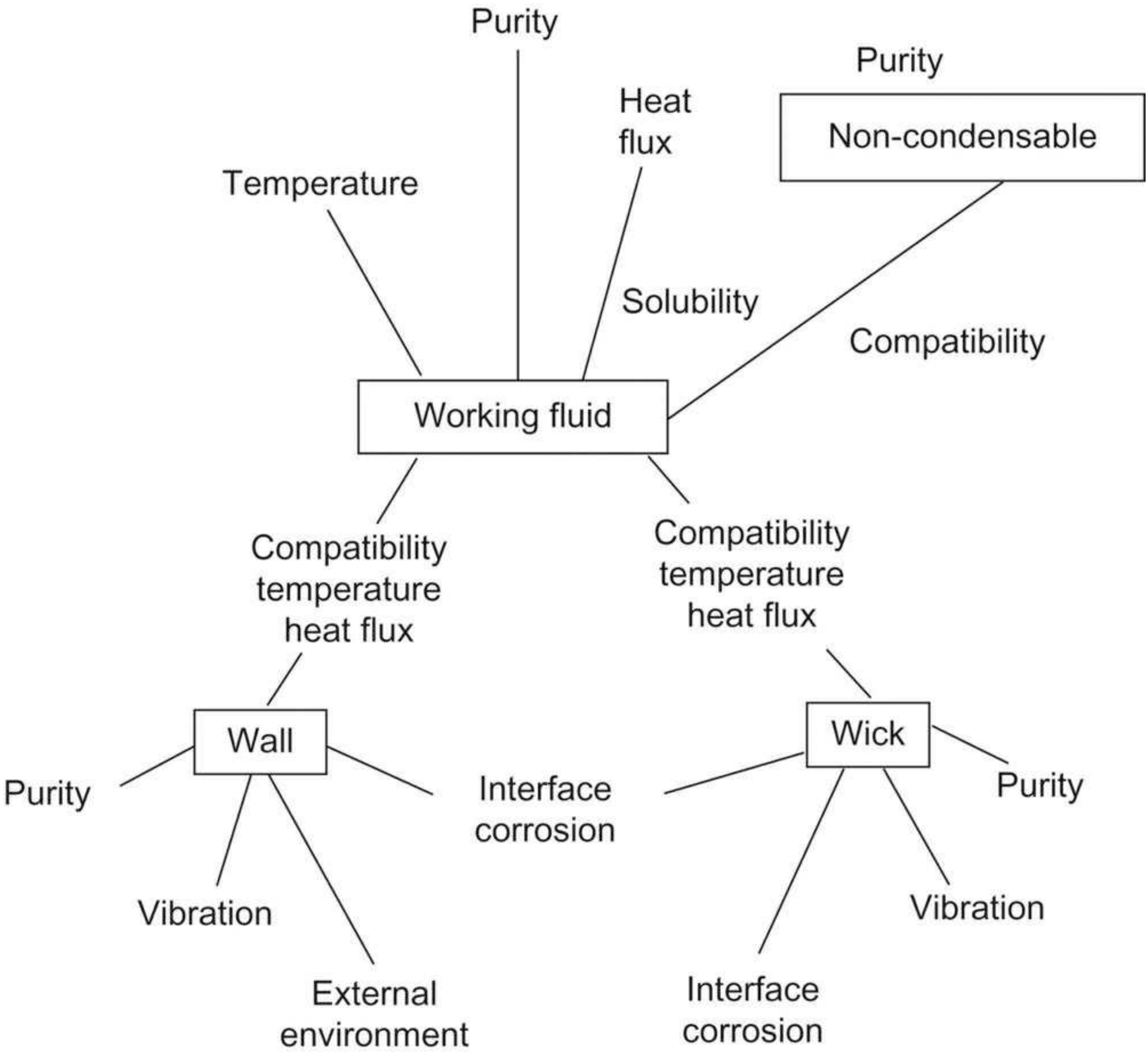


Figure 5.23: Heat pipe life test factors

5.2.2 Life Test Procedures

There are many ways of carrying out life tests, all having the same aim, namely to demonstrate that the heat pipe can be expected to last for its design life with an excellent degree of certainty.

The most difficult part of any life test programme is the interpretation of the results and the extrapolation of these results to predict long-term performance. (One technique used for extrapolating results obtained from gas generation measurements is described in Section 5.2.3.)

The main disadvantage of carrying out life tests of one particular combination of materials, be the test accelerated or at design load, is the fact that if any reaction does occur, insufficient data are probably available to enable one to explain the main causes of the degradation. For example, in some life tests carried out at IRD, diacetone alcohol was formed as a result of acetone degradation. It was not possible without further testing over a considerable period, however, to state whether this phenomenon was a function of operating temperature, as life tests on identical units operating at several different vapour temperatures will have to be carried out. It is even possible that comprehensive life test programmes may never provide the complete answer to some questions, new aspects being found during each study.

5.2.2.1 Effect of Heat Flux

The effect of heat flux on heat pipe lives and performance can only really be investigated using units in the reflux mode, where fluxes well in excess of design values may be applied.

By setting up experiments involving a number of heat pipes operating at the same vapour temperature but with differing evaporator heat fluxes, one can later examine the inner surface of the evaporator for corrosion, etc.

If carried out in a representative heat pipe, performance tests could be carried out at regular intervals during the life tests.

5.2.2.2 Effect of Temperature

Compatibility and working fluid make-up can both be affected by the operating temperature of the heat pipe. It is therefore important to be able to discriminate between any effects resulting from temperature levels.

5.2.2.3 Compatibility

As opposed to the effect of heat flux or temperature on the working fluid alone, it is necessary to investigate the compatibility of the working fluid with the wall and the wick materials.

Here one is looking for reactions between the materials which could change the surface structure in the heat pipe, generate non-condensable gas or produce impurities in the form of deposits that could affect evaporator performance. Of course, all three phenomena could occur at the same time, at differing degrees, and this can make the analysis of the degradation much more complex.

Compatibility tests can be carried out at design conditions on a heat pipe operating horizontally or under tilt against gravity. To be meaningful, such tests should continue for years, but if compatibility is shown to be satisfactory over, say, a 3-year period, some conclusions can be made concerning the likely behaviour over a much longer life. Accelerated compatibility tests could also be performed, with occasional tests in the heat pipe mode to check on the design performance.

5.2.2.4 Other Factors

The life of a heat pipe can be affected by assembly and cleaning procedures and it is important to ensure that life test pipes are fully representative as far as assembly techniques are concerned. The working fluid used must, of course, be of the highest purity.

Another feature of life testing is the desirability of incorporating valves on the pipes so that samples of gas, etc., can be taken out without necessarily causing the unit to cease functioning. One disadvantage of valves is the introduction of a possibly new incompatibility: that of the working fluid and valve material, although this can be ruled out with modern stainless steel valves.

When testing in the heat pipe mode, a valve body can be filled with working fluid that may be difficult to remove. This should be taken into account when carrying out such tests, in case depletion of the wick or artery system occurs.

5.2.3 Prediction of Long-Term Performance from Accelerated Life Tests

One of the major drawbacks of accelerated life tests has been the uncertainty associated with the extrapolation of the results to estimate performance over a considerably longer period of time. Baker [29] has correlated data on the generation of hydrogen in stainless steel heat pipes, using an Arrhenius plot, with some success, and this has been used to predict non-condensable gas generation over a 20-year period.

The data were based on life tests carried out at different vapour temperatures over a period of 2 years, the mass of hydrogen generated being periodically measured. Vapour temperatures of 100, 200 and 300°F were used, five heat pipes being tested at each temperature.

Baker applied Arrhenius plots to these results, which were obtained at the Jet Propulsion Laboratory, in the following way.

The Arrhenius model is applicable to activation processes, including corrosion, oxidation, creep and diffusion. Where the Arrhenius plot is valid, the plot of the log of the response parameter (F) against the reciprocal of absolute temperature is a straight line.

The response parameter is defined by the equation:

(5.1) $F = \text{Const.} \times \exp. - A/kT$

where A is the reaction activation energy, k the Boltzmann constant (1.38×10^{-23} J/K) and T the absolute temperature. For the case of the heat pipe, Baker described the gas generation process as:

(5.2) $\dot{m}(t,T) = f(t)F(T)$

where m is the mass generation rate, t denotes time and $F(t)$ is given in Eq. (5.1).

By plotting the mass of hydrogen generation in each heat pipe against time, with results at different temperatures, one can use these figures to obtain a universal curve, presenting the mass of hydrogen generated as a function of time×shift factor, which will be a straight line on logarithmic paper. Finally, the shift factors are plotted against the reciprocal of absolute temperature for each temperature examined, and the slope of this curve gives the activation energy A in Eq. (5.1).

The mass of hydrogen generated at any particular operating temperature can then be determined using the appropriate value of shift factor. Baker concluded that stainless steel/water heat pipes could operate for many years at temperatures of the order of 60°F, but at 200°F the gas generation would be excessive.

It is probable that this model could be applied to other wall/wick/working fluid combinations, the only drawback being the large number of test units needed for accurate predictions. The minimum is of the order of 12, results being obtained at three vapour temperatures, four heat pipes being tested at each temperature.

Another study was concerned with the evolution of hydrogen in nickel/water heat pipes. Anderson used a corrosion model to enable him to predict the behaviour of heat pipes over extended periods, based on accelerated life tests, following Baker's method [30].

He argued that oxidation theory predicts that passivating film growth occurs with a parabolic time dependence and an exponential temperature dependence.

Anderson gives the following values for A, the reaction activation energy:

Stainless steel (304)/water	8.29×10^{-20} J
Nickel/water	10.3×10^{-20} J

and confirms Baker's model.

Later, work in Japan [31,32] concentrated on a statistical treatment of life test data from accelerated tests on copper/water heat pipes. This has been directed in part at investigating the formation of small quantities of non-condensable gas (CO_2) in such pipes where lifetimes of 20 years or more are required.

The investigations were carried out on axially grooved heat pipes, some of which used commercial phosphorous, deoxidised copper and other oxygen-free copper (OFC).

High-temperature ageing was done for periods of 20, 40 and 150 days. Analysis was by X-ray microscopy and infrared spectroscopy. The infrared absorption spectra showed absorption caused by benzene rings, phenyl groups, an O–H link and a C–O–C link. It was therefore concluded that the products were organic. After the full ageing period, corrosion was observed on the inside of the commercial copper, while the OFC showed only slight corrosion. It was concluded that phosphorous used during refining of the copper had a profound effect on its corrosion properties.

With regard to the generation of CO_2, on the basis of the criterion that the active–inactive (i.e. buffered) boundary in the vapour space is where the temperature drop becomes one half of the total temperature drop, it was possible to estimate the gas column length and temperature drop achieved after 20 years of use of the heat pipe.

After 1000 days a temperature difference of about 2.5°C was yielded at 160°C. Ageing for 470 days at 393 K corresponds, according to data in [31] to a 20-year use at 333 K, and it was thus concluded that commercially available heat pipes using this phosphorous-containing material could be used satisfactorily if a temperature drop of 3°C is acceptable.

5.2.4 A Life Test Programme

A life test programme must provide detailed data on the effects of temperature, heat flux and assembly techniques on the working fluid, and the working fluid/wall and wick material compatibility.

The alternative techniques for testing have been discussed in Section 5.2.2 and it now remains to formulate a programme that will enable sufficient data to be accumulated to enable the life of a particular design of heat pipe to be predicted accurately.

Each procedure may be given a degree of priority (numbered 1–3, in decreasing order of importance) and these are presented in Table 5.3 together with the *minimum* number of units required for each test. The table is self-explanatory.

Table 5.3: Heat Pipe Life Test Priorities

Priority	Minimum No. Units to Be Tested	Number with Valves	Test Specification
1	–	–	Cleanliness of materials
1	–	–	Purity of working fluid
1	–	–	Sealing of case
1	–	–	Outgassing
2	2	2	Refluxing – vapour temperature at maximum design
1	4 at each temperature	All	Refluxing – temperature range up to maximum design (to include) bonding temperatures
3	2	2	Refluxing – heat flux at maximum design
2	2	1	Heat pipe mode – intermittent tests between refluxing
1	2	1	Heat pipe mode – long-term continuous performance test
1[1]	2	0	Heat pipe mode – vibration test with intermittent performance tests
1	2	2	VCHP – solubility of gas in working fluid and effect on artery

[1]Where applicable.

This programme should provide sufficient data to enable one to confidently predict the long-term performance of a heat pipe, based on an Arrhenius plot, and the maximum allowable operating temperature, based on fluid stability. The programme involves a considerable amount of testing, but the cost should be weighed against satisfactory heat pipe performance over its life in applications where reliability is of prime importance.

5.2.5 Spacecraft Qualification Plan

The use of heat pipes in spacecrafts, as discussed earlier, makes heavy demands on heat pipe technology. The qualification plan set out by the ESA, and illustrated in Fig. 5.24, involves the construction of 15 sample heat pipes, the majority of which are eventually opened up for detailed physical analysis. Of the heat pipes included in the qualification programme, it is stipulated that at least 10%, but not less than three units, should be subjected to life tests of 8000 h. The qualification procedure guidelines set out the temperature and heat load requirements of these 'ageing' tests and it is pointed out that these tests, by themselves, do not necessarily prove the longevity of the heat pipes for 7–10 years of operation in space.

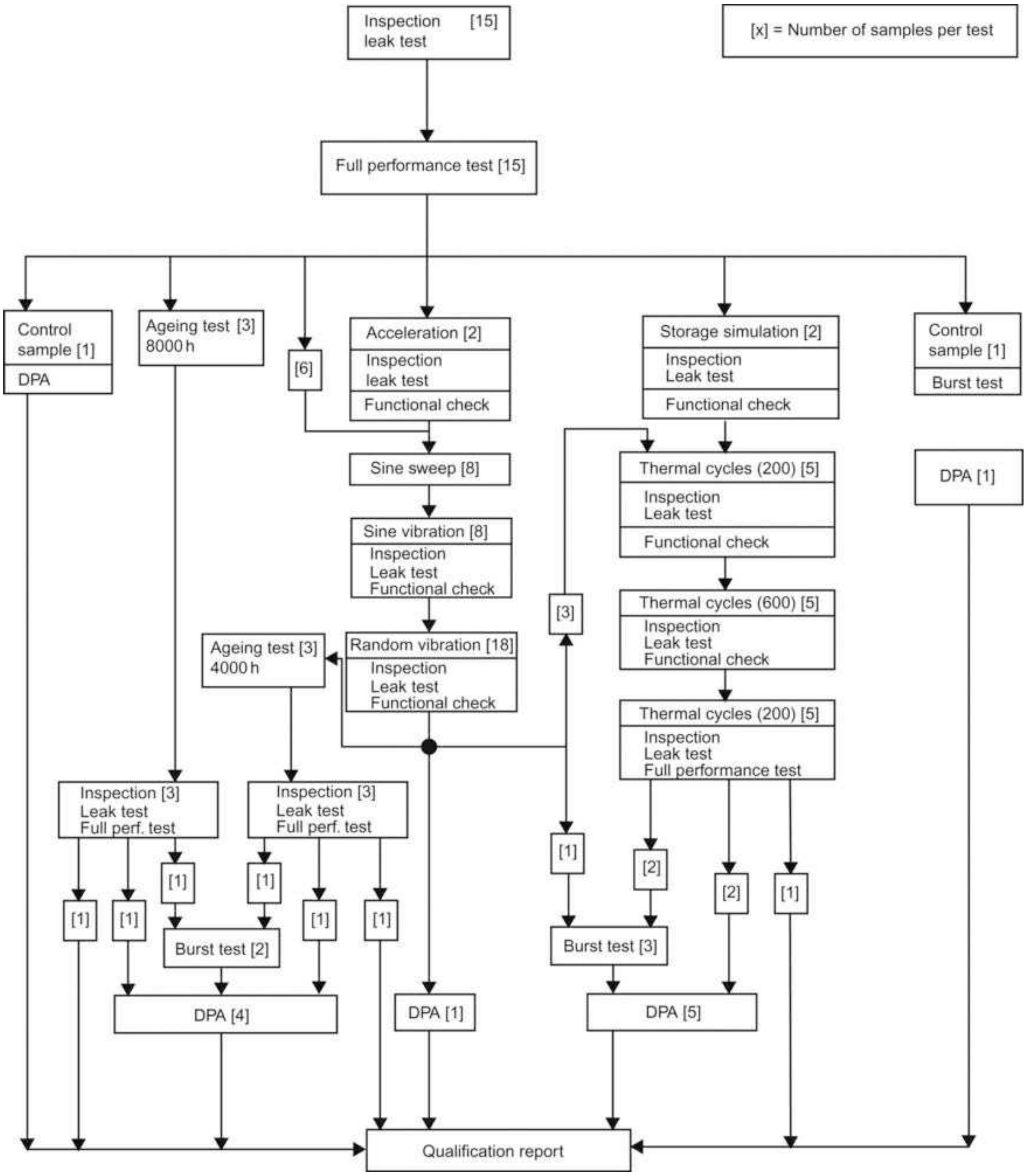


Figure 5.24: ESA heat pipe qualification plan [28]

An example of the qualification procedures for a specific ESA heat pipe type is given in Ref. [33]. Alcatel Space [34] present data of value to those developing heat pipes for spacecraft in the referenced paper summarising a 'roadmap'. This sets out the objectives and the technical challenges of a development programme, in particular for aluminium/ammonia heat pipes, but applicable more broadly.

The company, interestingly, outlines the facilities that enable it to produce typically 2000 heat pipes per annum. These include:

- Filling stations
- Automatic welding machine
- Testing benches – proof pressure, ageing and thermal cycling
- Performance test benches

- Bending machines.

The thermal tests carried out on the bench include burnout (maximum heat transport capability), heat flux tests and precise measurement of the thermal conductance. The ability to incline the pipe (a necessity for space qualification procedures) is also incorporated in the test bench.

Other countries use ESA criteria for space qualification. In Ukraine [35], this led to the following tests being proposed:

- Inspection and physical measurement
- Proof pressure testing – leak test
- Performance testing
- Burst test
- Random vibration
- Storage simulation test
- Thermal cycles/shock test
- Ageing test (life test)
- Non-condensable gas definition test.

A number of other tests to measure various aspects of the heat pipe performance were recommended:

- Definition of heat pipe thermal resistance
- Definition of maximum heat transport capability
- Definition of the temperature distribution along the length of the heat pipe
- Definition of heat pipe priming time after full evaporator dryout
- Definition of start-up capability when 80% of maximum heat transport capability is applied, over a range of vapour temperatures.

With alternative configurations of heat pipes being applied in spacecraft, different qualification procedures sometimes need to be applied. LHPs have been used in spacecraft for well over a decade, but as has been emphasised in the context of heat pipe life testing, it is important to carry out qualification of the manufacturing methods and materials as well as the LHP performance in its application. Dos Santos and Riehl [36] reported on the qualification procedures adopted for these aspects at the Brazilian National Institute for Space Research. The authors emphasise that the procedures are focused on the fabrication methods for the LHPs, the material evaluation and certification, and the processes used in all stages of manufacture, culminating in life tests.

After successful completion of these procedures, an LHP can, it is claimed, be built as a certified device for space applications. The target at the time was a 10-year life for uses in geostationary satellites.

5.3 HEAT PIPE PERFORMANCE MEASUREMENTS (SEE ALSO SECTION 5.1.12)

The measurement of the performance of heat pipes is comparatively easy and requires in general equipment available in any laboratory engaged in heat transfer work.

Measurements are necessary to show that the heat pipe meets the requirements laid down during design. The limitations to heat transport, described in Chapter 2, and presented in the form of a performance envelope, can be investigated, as can the degree of isothermalisation. A considerable number of variables can be investigated by bench testing, including orientation with respect to gravity, vapour temperature, evaporator heat flux, start-up, vibrations and accelerations.

5.3.1 The Test Rig

A typical test rig is shown diagrammatically in Fig. 5.25. The rig has the following features and facilities:

i. Heater for evaporator section
ii. Wattmeter for power input measurement

iii. Variac for power control

iv. Condenser for heat removal

v. Provision for measuring flow and temperature rise of condenser coolant

vi. Provision for tilting heat pipe

vii. Thermocouples for temperature measurement and associated readout system

viii. Thermal insulation.

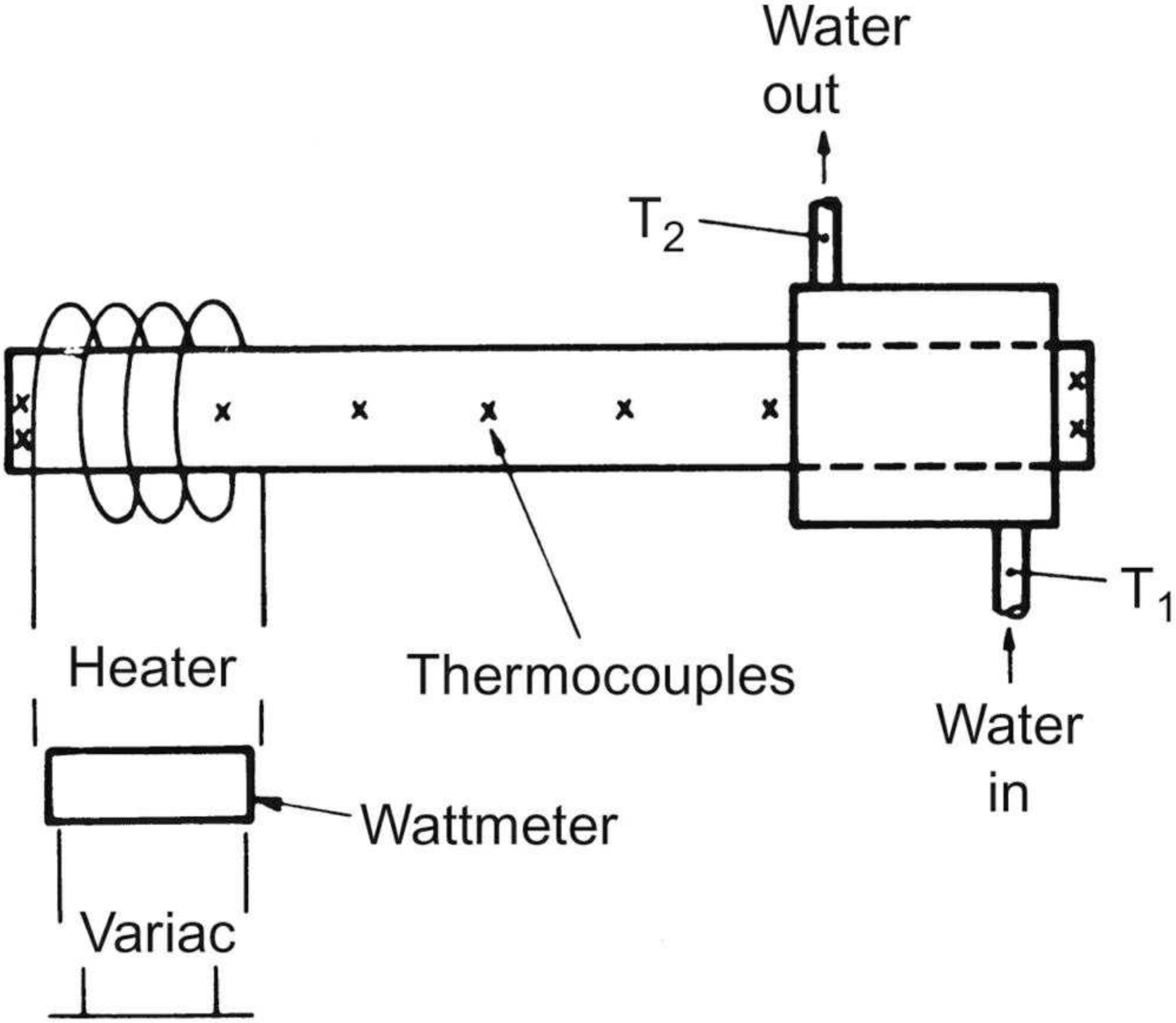


Figure 5.25: Heat pipe performance test rig

The heater may take several forms, as long as heat is applied uniformly and the thermal resistance between the heater and the evaporator section is low. This can be achieved using rod heaters mounted in a split copper block clamped around the heat pipe or by wrapping insulated heater wire directly on the heat pipe. For many purposes eddy current heating is convenient, using the condenser as a calorimeter. Heat losses by radiation and convection to the surroundings should be minimised by applying thermal insulation to the outside of the heater. An accurate wattmeter covering the anticipated power range, and a variac for close control of power, should be incorporated in the heater circuit. Where orientation may be varied, long leads between the heater and the instruments should be used for convenience.

An effective technique for measuring the power output of heat pipes operating at vapour temperatures appropriate to most organic fluids and water is to use a condenser jacket through which a liquid is passed. For many cases this can be water. The heat given up to the water can be obtained if the temperature rise between the condenser inlet and outlet is known, together with the flow rate. The temperature of the liquid flowing through the jacket may be varied to vary the heat pipe vapour temperature. Where performance measurements are required at vapour temperatures of about 0°C, a cryostat may be used.

Cryogenic heat pipes should be tested in a vacuum chamber. This prevents convective heat exchange and a cold wall may be used to keep the environment at the required temperature. As a protection against radiation heat input, the heat pipe, fluid lines and cold wall should all be covered with superinsulation. If the heat pipe is mounted such that the mounting points are all at the same temperature (cold wall and heat sink) it can be assumed that all heat put into the evaporator will be transported by the heat pipe as there will be no heat path to the environment. Further data on cryogenic heat pipe testing can be obtaining from Refs [37,38].

An important factor in many heat pipe applications is the effect of orientation on performance. The heat transport capability of a heat pipe operating with the evaporator below the condenser (thermosyphon or reflux mode) can be up to an order of magnitude higher than that of a heat pipe using the wick to return liquid to the evaporator from a condenser at a lower height. In many cases, the wick may prove incapable of functioning when the heat pipe is tilted so that the evaporator is only a few centimetres above the condenser. Of course, wick selection is based in part on the likely orientation of the heat pipe in the particular application.

Provision should be made on the rig to rotate the heat pipe through 180°C while keeping heater and condenser in operation. The angle of the heat pipe should be accurately set and measured. In testing of heat pipes for satellites, a tilt of only 0.5 cm over a length of 1 m may be required to check heat pipe operation, and this requires very accurate rig alignment.

The measurement of temperature profiles along the heat pipe is normally carried out using thermocouples attached to the heat pipe outer wall. If it is required to investigate transient behaviour, for example during start-up, burnout or on a VCHP, automatic electronic data collection is required. For steady state operation a switching box connected to a digital voltmeter or a multichannel chart recorder should suffice, but most laboratories now possess computer-aided data collection and real-time presentation of such data.

5.3.2 Test Procedures

Once the heat pipe is fully instrumented and set up in the rig, the condenser jacket flow may be started and heat applied to the evaporator section. Preferably heat input should be applied at first in steps, building up to design capability and allowing the temperatures along the heat pipe to achieve a steady state before adding more power. When the steady state condition is reached, power input, power output (i.e. condenser flow rate and ΔT) and the temperature profile along the heat pipe should be noted.

If temperature profiles as shown in Fig. 5.26 are achieved, the heat pipe is operating satisfactorily. However, several modes of failure can occur, all being recognisable by temperature changes at the evaporator or condenser.

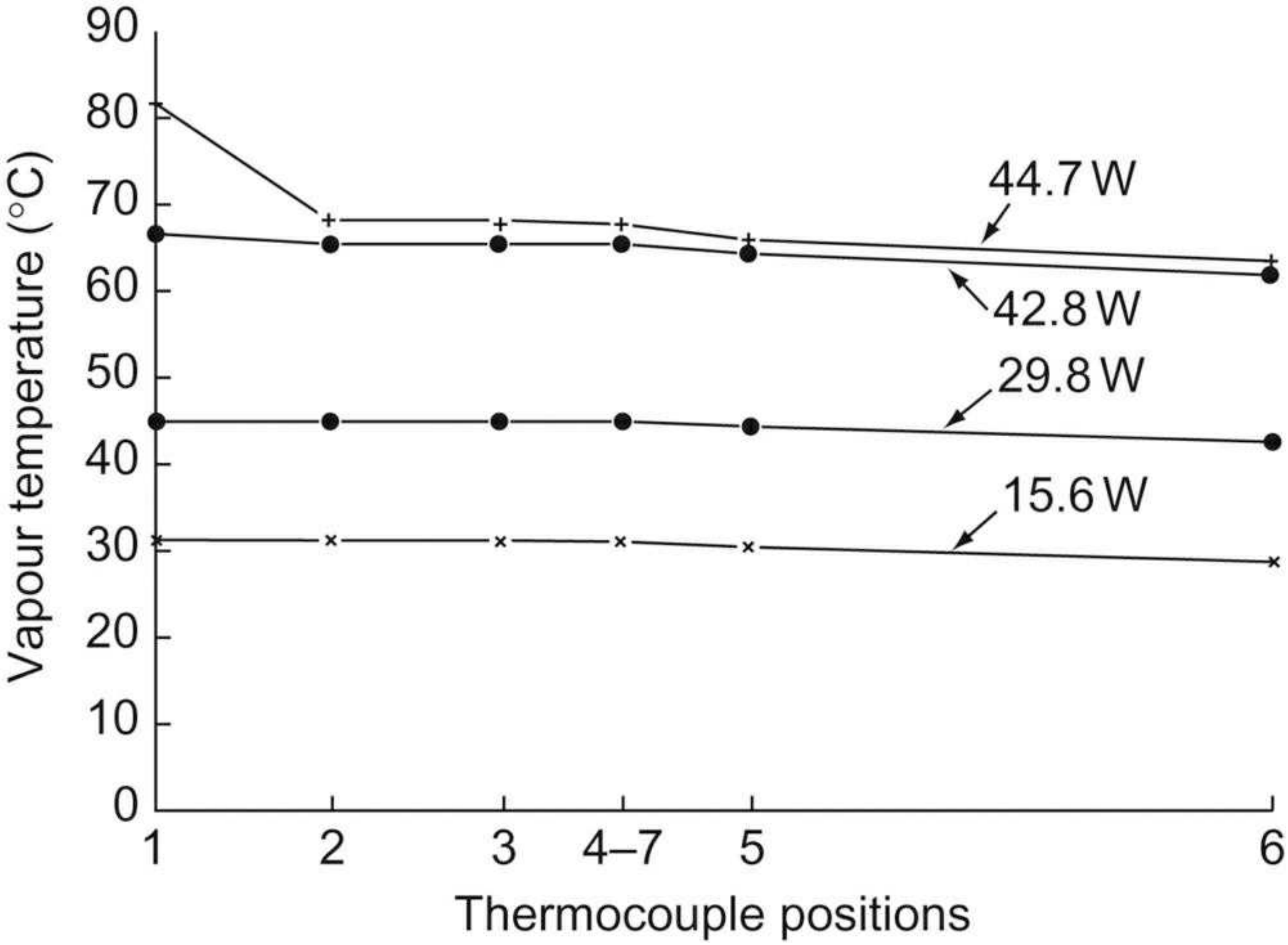


Figure 5.26: Typical temperature profiles along a heat pipe under test

The most common failure is burnout, created by excessive power input at the evaporator section. It is brought about by the inability of the wick to feed sufficient liquid to the evaporator, and is characterised by a rapid rise in evaporator temperature compared to other regions of the heat pipe. Typically, the early states of burnout are represented by the upper curve in Fig. 5.26.

Once burnout has occurred, the wick has to be reprimed and this is best achieved by cutting off the power input completely. When the temperature difference along the pipe drops to 1–2°C, the power may be reapplied. The wick must reprime, i.e. be rewetted and saturated with working fluid along its complete length, if operation against gravity or zero gravity is envisaged. If this is the case, the recovery after burnout must be demonstrated in the tilted condition. In other cases, the recovery may be aided by gravity assistance.

A second failure mechanism recognisable by an increased evaporator temperature, and known as overheating, occurs at elevated temperatures. As explained in Chapters 2 and 3, each working fluid has an operating temperature range characterised by the merit number, which achieves an optimum value at a particular temperature and then decreases as this temperature is exceeded. This means that the fluid is able to transport less heat. Thus, the temperature of the evaporator becomes higher than the rest of the pipe. In general, the evaporator temperature does not increase as quickly as in a burnout condition, but these two phenomena are difficult to distinguish.

Temperature changes at the condenser section can also point to failure mechanisms or a decrease in performance. A sudden drop in temperature at the end of the heat pipe downstream of the cooling jacket occurring at high powers can be attributed to the collection of working fluid in that region, insulating the wall and creating a cold spot. This has been called 'coolout' [39]. Complete failure need not necessarily occur when this happens, but the overall AT will be substantially increased and the effective heat pipe length reduced.

A similar drop in temperature downstream of the condenser jacket can occur in pipes of small diameter (<6 mm bore) when the fluid inventory is greater than that needed to completely saturate the wick. The vapour tends to push the excess fluid to the cooler end of the heat pipe, where, because of the small vapour space volume, a small excess of fluid will create a long cold region. This can occur at low powers and adjustments in fluid inventory may be made if a valve is incorporated in the heat pipe. One way is to use an excess fluid reservoir, which acts as a sponge but has pores sufficiently large to prevent it from sucking fluid out of the wick. This technique is used in heat pipes for space use and the reservoir may be located at any convenient part of the vapour space.

Failure can be brought about by incompatibilities of materials, generally in the form of the generation of non-condensable gases that collect in the condenser section. Unlike liquid accumulation, the gas volume is a function of vapour temperature and its presence is easily identified.

Unsatisfactory wick cleaning can inhibit wetting, and if partial wetting occurs the heat pipe will burnout very quickly after the application of even small amounts of power.

Recently tests are reported from the National Taiwan University to measure the viscous limits of heat pipes [40]. When considering the start-up of heat pipes and thermosyphons the viscous limit can be important as it may inhibit starting a high vapour densities/low temperatures (appropriate to the particular working fluid). Two heat pipes were tested – a short (150 mm×9 mm diameter) and long (240 mm×12 mm diameter) ones. Water was the working fluid, the wicks were grooves and the tests were in the thermosyphon mode. The test procedure was described as the 'dynamic method'. In order to study the performance during start-up, the heating temperature is controlled in a range that is only marginally above ambient temperature, being lifted by 2–3°C increments above this. Heat input to the evaporator is via circulating water in a heated bath, and heat removal is by air forced convection. The point where the condenser temperature starts to rise, as the evaporator temperature is increased in small increments, is noted, and the time taken for the condenser to start to respond is reduced as the operating temperature rises. The researchers point out that the operating temperature thus affects the 'dynamic start-up', and they define the viscous limit in the dynamic test as the 'minimum heating temperature measured to overcome the pressure drop at the corresponding ambient condition and the associated operating temperature for the heat pipe'.

For those interested in testing procedures for LHPs, the work at the Chinese Academy of Space Technology in Beijing is relevant [41]. The start-up under supercritical conditions is described for a nitrogen LHP.

5.3.3 Evaluation of a Copper Heat Pipe and Typical Performance

5.3.3.1 Capabilities

A copper heat pipe using water as the working fluid was manufactured and tested to determine the temperature profiles and the maximum capability. The design parameters of the pipe were as follows:

Length	320 mm
Outside diameter	12.75 mm
Inside diameter	10.75 mm
Material of case	Copper
Wick form	Four layers 400 mesh
Wick wire diameter	0.025 mm
Effective pore radius	0.031 mm
Calculated porosity	0.686
Wick material	Stainless steel
Locating spring length	320 mm
Pitch	7 mm
Wire diameter	1 mm
Material	Stainless steel
Working fluid	Water (10^6 Ω resistivity)
Quantity	2 ml
End fittings	Copper
Instrumentation thermocouples	7

5.3.3.2 Test Procedure

The evaporator section was fitted into the 100-mm long heater block in the test rig, and the condenser section covered by a 150-mm long water jacket. The whole system was then lagged.

First tests were carried out with the heat pipe operating vertically with gravity assistance. The power was applied and on achievement of a steady state condition the thermocouple readings and temperature rise through the water jacket were noted, as was the flow rate.

Power to the heaters was increased incrementally and the steady state readings noted until dryout was seen to occur. (This was characterised by a sudden increase in the potential of the thermocouple at the evaporator section relative to the readings of the other thermocouples.)

The above procedure was performed for various vapour temperatures and heat pipe orientations with respect to gravity.

5.3.3.3 Test Results

Typical results obtained are shown in Fig. 5.26, showing the vapour temperature profile along the pipe when operating with the evaporator 10 mm above the condenser.

The table below gives power capabilities for a 9.5-mm-outside diameter copper heat pipe of length 30 cm, with a composite wick of 100 and 400 mesh, operating at an elevation (evaporator above condenser) of 18 cm.

Vapour Temperature (°C)	Power Out (W)
84	17
121	30.5
162.5	54
197	89

The working fluid was again water, and a capability of 165 W was measured with horizontal operation (290 W with gravity assistance).

5.3.4 Tests on Thermosyphons to Compare Working Fluids

The tests on several thermosyphons are described here. The work was carried out at Heriot-Watt University in Edinburgh, UK, as part of a post-graduate short research project directed at looking at fluids that could replace R134a, which is a rather strong global warming gas [42].

The thermosyphons in an air–air heat exchanger application currently use R134a as the working fluid for the target temperature ranges of −10 to –50°C on the cold side and 60–80°C on the hot side. Storage temperatures can be as low as −30°C. While performance is adequate with R134a, there are compelling reasons to investigate a replacement:

- At the upper end of the operating temperature range, the vapour pressure reaches about 30 bar.
- R134a is one of the replacement refrigerants for the CFCs but it has a large GWP.
- Fluids such as R1234ze [43] have been proposed as replacements for HFCs. (These fluids and other HFOs are currently proposed for refrigeration, air conditioning and heat pump systems.)
- Theory suggests other fluids could perform better.

The final choice of fluids was:

- Water – Expected to give the best performance.
- Methanol – has a high merit number.
- Water–5% ethylene glycol – could potentially combine the performance of water and avoid problems associated with freezing.
- Two R134a pipes – one as a control for all the experiments and one for calibration of the test rig.

A full selection of fluids that might be considered for thermosyphons at the temperatures of interest is given, with properties and comments, in the Table in Appendix 1.

Using the facility described in Ref. [42] experiments were conducted keeping the cooling water at about 30°C, and heating the evaporator, from about 35 to 65°C. As T_e increased, and thus ΔT, the duty increased. Fig. 5.27 shows typical results. All the pipes appeared to reach a limit in performance. For R134a, it occurred at a lower ΔT, about 12°C. The methanol pipe had a limit close to ΔT of 25°C. The water and water–5% ethylene glycol pipes appeared to reach a limit at the upper end of the ΔT at which the rig could operate. Like the methanol pipe, there was audible pinging, which is a sign that the flooding limit has been reached. This is also likely to be the limit for the R134a pipe, but it was silent. The vapour pressure is much higher in the R134a pipe than the others, and this may be responsible for this difference.

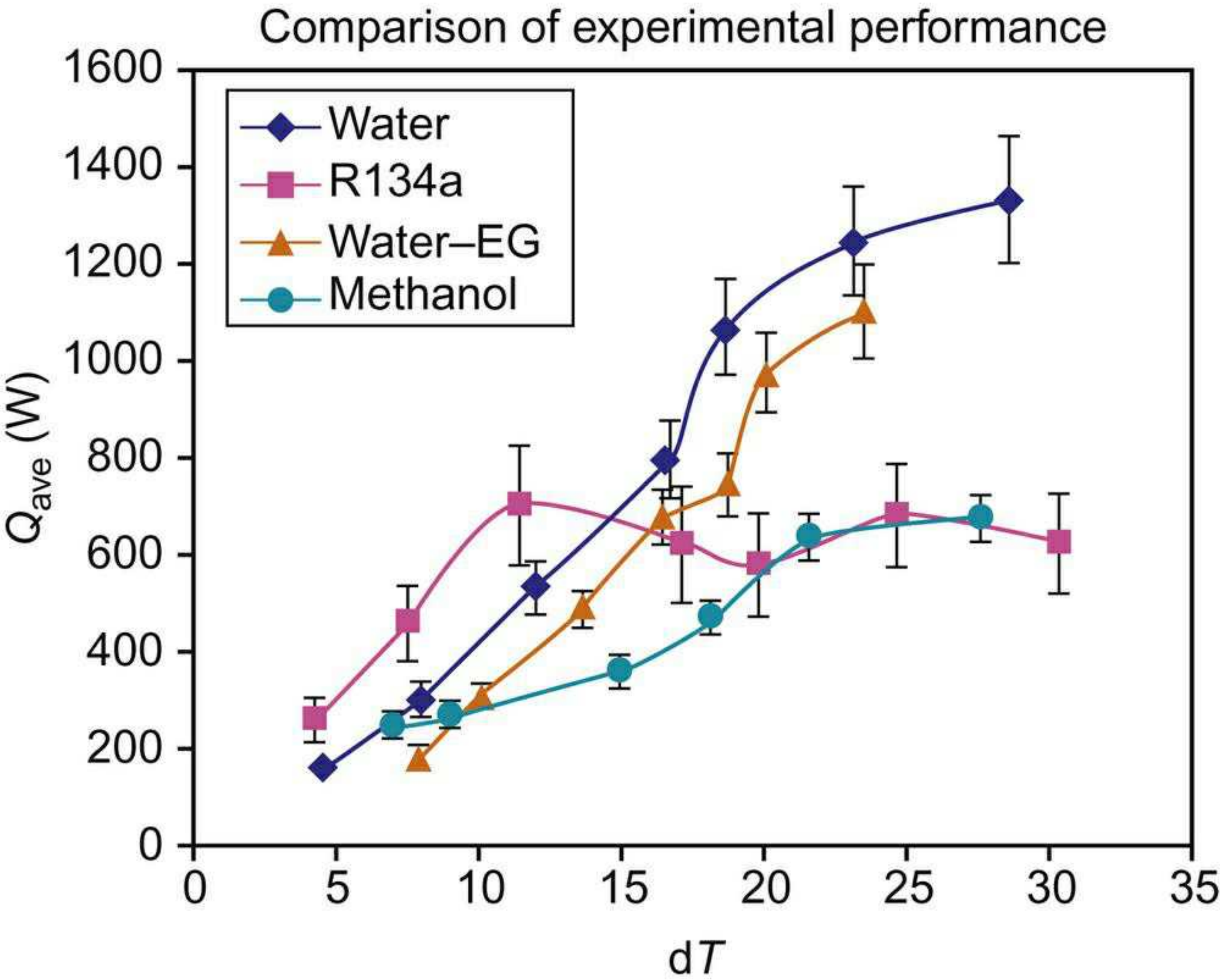


Figure 5.27: Experimental results for heating the evaporator while keeping the condenser at a constant 30°C

Water gave the highest duty, reaching over 1300 W. The addition of 5% ethylene glycol in the water–5% ethylene glycol pipe lowered performance by a small amount, the highest duty being over 1200 W. Methanol had a maximum duty of about 750 W, compared to 700 W for R134a.

R134a has the best duty at lower values of Δ*T*, up to approximately Δ*T* of 14°C when water becomes the best choice. Water–5% ethylene glycol becomes better than R134a above a Δ*T* of approximately 16°C. Methanol has a similar duty to R134a above a Δ*T* of 20°C, and significantly less at lower Δ*T*s. Water–5% ethylene glycol followed a similar pattern to that of water, but the curve was displaced to a duty of 100–150 W less.

The performance predicted by the ESDU equations is shown in Fig. 5.28, for the same conditions as in Fig. 5.27. It shows similar trends to the experimental results for water and water–5% ethylene glycol, but different trends for methanol, and especially R134a.

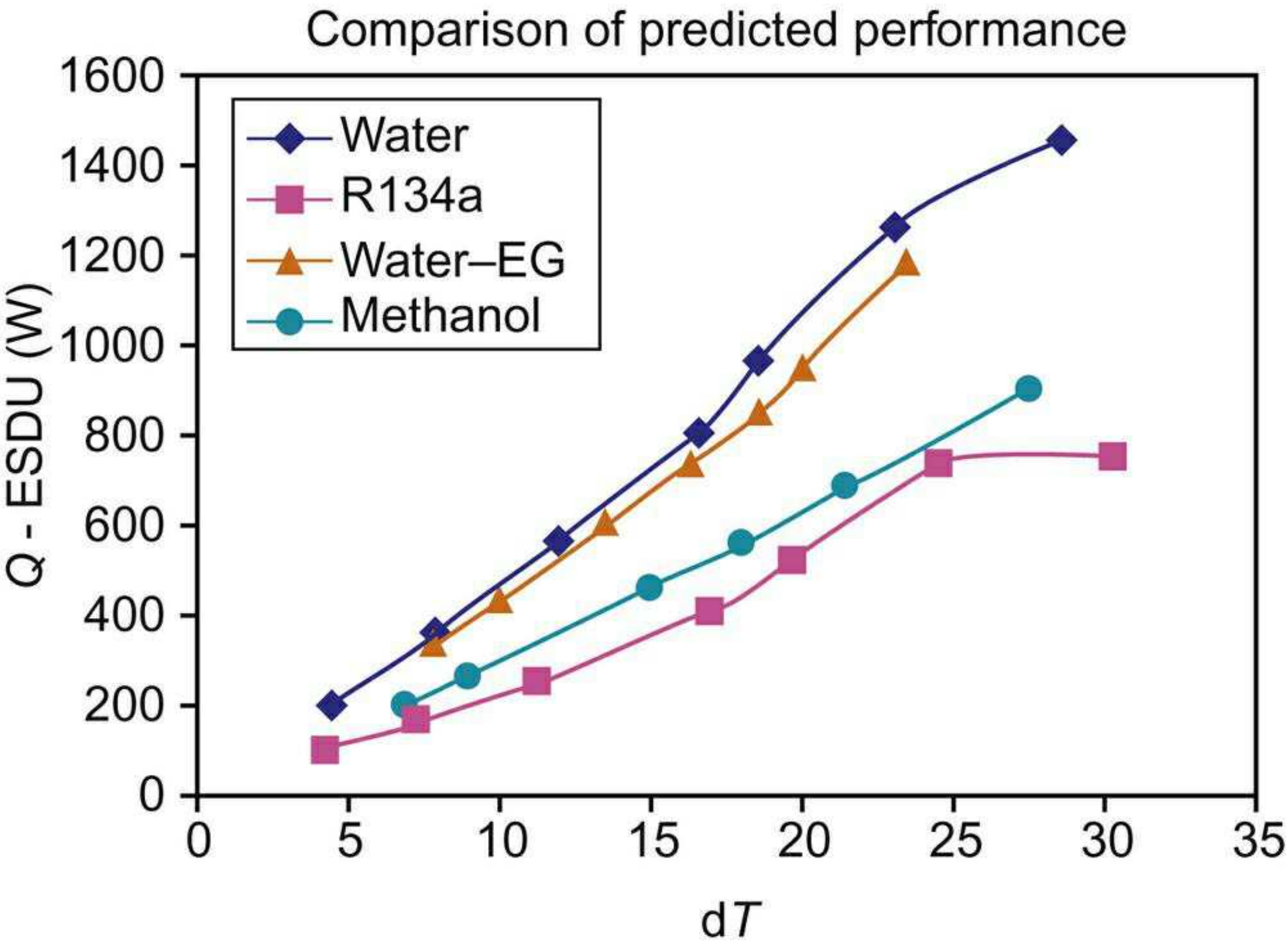


Figure 5.28: Predicted results for the same Δ*T*s for each fluid as the results in Fig. 5.26

In all cases the first predicted limit encountered was the flooding limit. Water–5% ethylene glycol has a higher flooding limit than pure water. This does not agree with the experiment, since it appeared that the flooding limit had been reached for both fluids, with water giving a higher duty. Methanol has a much higher predicted limit than was found in practice. Fig. 5.29 shows the predicted limits graphically.

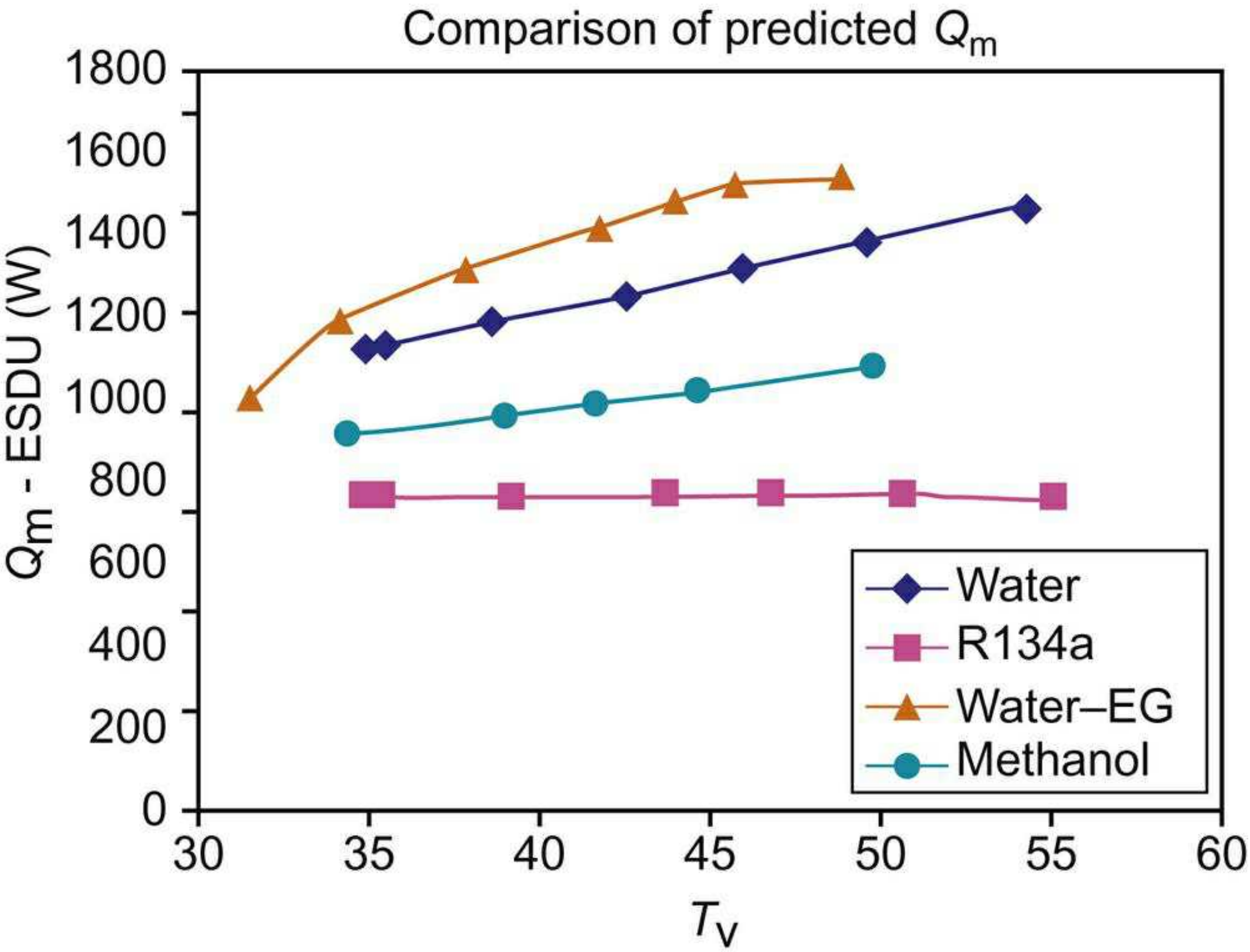


Figure 5.29: Predicted limiting duty for each fluid at each T_v corresponding to the results in Fig. 5.27

It was concluded that it is possible to recommend using water–5% ethylene glycol in thermosyphons for use in a range of ambient conditions representative of most regions of the world. Tests to confirm the behaviour at low storage temperatures should be undertaken, which would be relevant to the application conditions of the user of these thermosyphons. Water–5% ethylene glycol meets the environmental criteria and is suitable for the operating and storage conditions, subject to experimental confirmation of the latter aspect. Water–5% ethylene glycol does not outperform R134a at all operating conditions, so this should be borne in mind when designing the heat exchangers. It can offer significantly better duty, but only with a ΔT above 16°C between the evaporator and condenser.

The prediction model was found to work best for water, for which it gives values mostly within the experimental error. For water–5% ethylene glycol, it gives reasonable agreement and underestimates for most cases when it is outside the experimental range. For methanol the agreement was not so good, and there was a limit reached by the test pipe which was not predicted by the model. For R134a the model did not match the results well at all. The magnitude of the maximum heat flux was correct, but it occurred for different conditions than it did in the experiments. It remains unclear as to why it does not work well for R134a.

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