HEAT PIPES

THIRD EDITION

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Preface to Third Edition

Since the Second Edition was published in 1978, two further International Heat Pipe Conferences have been held, and significant new applications have appeared. Also, an increasing emphasis on thermosyphons has necessitated the inclusion of extra data on their performance.

Significant additions and changes have been made to Chapters 2,3,5 and 7, and some of the applications of the heat pipe described in Chapter 7, have been replaced to ensure that topical and important applications are emphasized. Thus readers of the earlier editions, as well as new readers, will find much additional data and comment. The Bibliography on Heat Pipe Applications (Appendix 6) has also been updated. New life test data is presented in Chapter 3.

We hope that this edition proves of interest and value to the reader.

May 1982

P.D. Dunn
D.A. Reay

Preface

Following the publication by G.M. Grover et al of the paper entitled "Structures of Very High Thermal Conductance" in 1964, interest in the heat pipe has grown considerably. There is now a very extensive amount of literature on the subject and the heat pipe has become recognised as an important development in heat transfer technology.

This book is intended to provide the background required by those wishing to use or to design heat pipes. The development of the heat pipe is discussed and a wide range of applications described.

The presentation emphasises the simple physical principles underlying heat pipe operation in order to provide an understanding of the processes involved. Where necessary a summary of the basic physics is included for those who may not be familiar with these particular topics.

Full design and manufacturing procedures are given and extensive data provided in Appendix form for the designer.

The book should also be of use to those intending to carry out research in the field.

The authors thank Joan Tulip for her work in typing the manuscript.

Contents

Introduction

The heat pipe is a device of very high thermal conductance. The idea of the heat pipe was first suggested by R.S. Gaugler (1) in 1942. It was not, however, until its independent invention by G.M. Grover (2,3) in the early 1960's that the remarkable properties of the heat pipe became appreciated and serious development work took place.

The heat pipe is similar in some respects to the thermosyphon and it is helpful to describe the operation of the latter before discussing the heat pipe. The thermosphon is shown in Fig.1a. A small quantity of water is placed in a tube from which the air is then evacuated and the tube sealed. The lower end of the tube is heated causing the liquid to vaporize and the vapour to move to the cold end of the tube where it is condensed. The condensate is returned to the hot end by gravity. Since the latent heat of evaporation is large, considerable quantities of heat can be transported with a very small temperature difference from end to end. Thus the structure will have a high effective thermal conductance. The thermosyphon has been used for many years and various working fluids have been employed. (The history of the thermosyphon, in particular the version known as the Perkins Tube, is reviewed in Chapter 1). One limitation of the basic thermosyphon is that in order for the condensate to be returned to the evaporator region by gravitational force, the latter must be situated at the lowest point.

The heat pipe is similar in construction to the thermosyphon but in this case a wick, constructed for example from a few layers of fine gauze, is fixed to the inside surface and capillary forces return the condensate to the evaporator. (See Fig.1b). In the heat pipe the evaporator position is not restricted and it may be used in any orientation. If, of course, the heat pipe evaporator happens to be in the lowest position gravitational forces will assist the capillary forces. The term 'heat pipe' is also used to describe high thermal conductance devices in which the condensate return is achieved by other means, for example centripetal force, osmosis, or electrohydrodynamics.

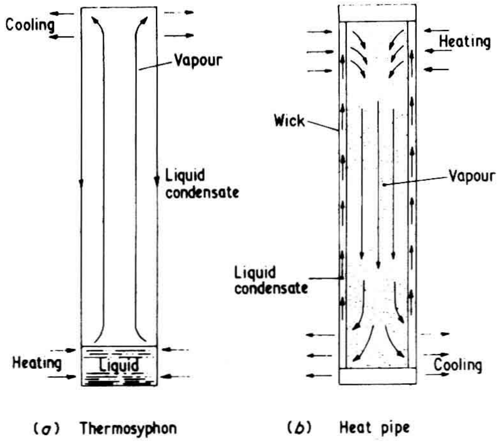

Fig.1 The heat pipe and thermosyphon.

Several methods of condensate return are listed in Table 1. A review of techniques is given by Roberts (Ref.4).

TABLE 1 METHODS OF CONDENSATE RETURN.

Gravity	Thermal syphon
Capillary force	Standard heat pipe
Centripetal force	Rotating heat pipe
Electrostatic volume forces	Electrohydrodynamic heat pipe
Magnetic volume forces	Magnetohydrodynamic heat pipe
Osmotic forces	Osmotic heat pipe
Bubble pump	Inverse thermal syphon

The Heat Pipe. Construction, Performance and Properties

The main regions of the heat pipe are shown in Fig.2. In the longitudinal direction (see Fig.2a), the heat pipe is made up of an evaporator section and a condenser section. Should external geometrical requirements make this necessary a further, adiabatic, section can be included to separate the evaporator and condenser. The cross-section of the heat pipe, Fig.2b, consists of the container wall, the wick structure and the vapour space.

The performance of a heat pipe is often expressed in terms of 'equivalent thermal conductivity'. A tubular heat pipe of the type illustrated in Fig.2, using water as the working fluid and operated at 150^{o}C would have a thermal conductivity several hundred times that of copper. The power handling capability of a heat pipe can be very high- pipes using lithium as the working fluid at a temperature of 1500^{o}C will carry an axial flux of 10-20 kW/cm^2. By suitable choice of working fluid and container materials it is possible to construct heat pipes for use at temperatures ranging from 4K to in excess of 2300 K.

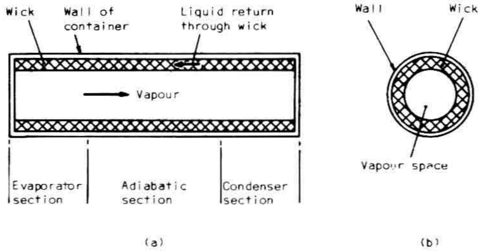

Fig.2 The main regions of the heat pipe.

For many applications the cylindrical geometry heat pipe is suitable but other geometries can be adopted to meet special requirements.

The high thermal conductance of the heat pipe has already been mentioned; this is not the sole characteristic of the heat pipe.

The heat pipe is characterised by:

(i) Very high effective thermal conductance.

(ii) The ability to act as a thermal flux transformer. This is illustrated in Fig.3.

(iii) An isothermal surface of low thermal impedance. The condenser surface of a heat pipe will tend to operate at uniform temperature. If a local heat load is applied, more vapour will condense at this point, tending to maintain the temperature at the original level.

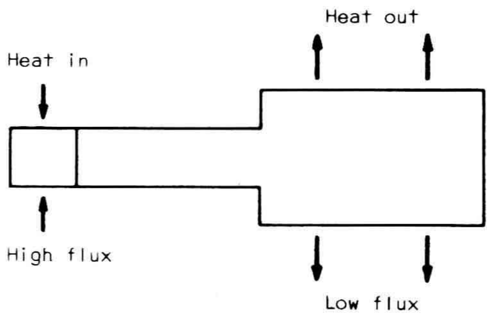

Fig.3 The heat pipe as a thermal flux transformer.

Special forms of heat pipe can be designed having the following characteristics:

(iv) Variable thermal impedance or VCHP.
A form of the heat pipe, known as the gas buffered heat pipe, will maintain the heat source temperature at an almost constant level over a wide range of heat input. This may be achieved by maintaining a constant pressure in the heat pipe but at the same time varying the condensing area in accordance with the

change in thermal input. A convenient method of achieving this variation of condensing area is that of 'gas buffering'. The heat pipe is connected to a reservoir having a volume much larger than that of the heat pipe. The reservoir is filled with an inert gas which is arranged to have a pressure corresponding to the saturation vapour pressure of the fluid in the heat pipe. In normal operation a heat pipe vapour will tend to pump the inert gas back into the reservoir and the gas-vapour interface will be situated at some point along the condenser surface. The operation of the gas buffer is as follows.

Assume that the heat pipe is initially operating under steady state conditions. Now let the heat input increase by a small increment. The saturation vapour temperature will increase and with it the vapour pressure. Vapour pressure increases very rapidly for very small increases in temperature, for example the vapour pressure of sodium at 800°C varies as the tenth power of the temperature. The small increase in vapour pressure will cause the inert gas interface to recede, thus exposing more condensing surface. Since the reservoir volume has been arranged to be large compared to the heat pipe volume, a small change in pressure will give a significant movement of the gas interface. Gas buffering is not limited to small changes in heat flux but can accommodate considerable heat flux changes.

It should be appreciated that the temperature which is controlled in the more simple gas buffered heat pipes, as in other heat pipes, is that of the vapour in the pipe. Normal thermal drops will occur when heat passes through the wall of the evaporating surface and also through the wall of the condensing surface.

A further improvement is the use of an active feedback loop. The gas pressure in the reservoir is varied by means of an electrical heater which is controlled by a temperature sensing element placed in the heat source. Other sophisticated control systems have been introduced, and these are reviewed in Chapter 6.

(v) Thermal diodes and switches.

The former permit heat to flow in one direction only, whilst thermal switches enable the pipe to be switched off and on.

The Development of the Heat Pipe

Initially Grover was interested in the development of high temperature heat pipes, employing liquid metal working fluids, and suitable for supplying heat to the emitters of thermionic electrical generators and of removing heat from the collectors of these devices. This application is described in more detail in Chapter 7. Shortly after Grover's publication (3), work was started on liquid metal heat pipes by Dunn at Harwell and Neu and Busse at Ispra where both establishments were developing nuclear powered thermionic generators. Interest in the heat pipe concept developed rapidly both for space and terrestrial applications. Work was carried out on many working fluids including metals, water, ammonia, acetone, alcohol, nitrogen and helium.

At the same time the theory of the heat pipe became better understood; the most important contribution to this theoretical understanding was the paper by Cotter (5) in 1965. The manner in which heat pipe work expanded is seen from the growth in the number of publications, following Grover's first paper in 1964. In 1969 Cheung (6) lists 80 references; in 1970 Chisholm in his book (7) cites 149 references, and by 1972 the NEL Heat Pipe Bibliography (8) contained 544 references. By the end of 1976, in excess of 1000 references to the topic were available and two International Heat Pipe Conferences had been held.

The III International Heat Pipe Conference, held in 1978 in Palo Alto, California, was sponsored by the American Institute of Aeronautics and Astronautics. Sixty five papers were included in the proceedings (Ref.9), and it was noticeable that the term 'gravity assisted heat pipe' was becoming popular as a description of units operating with the evaporator located below the condenser, while retaining some form of wick structure. Many so-called heat pipes are strictly thermosyphons, as they do not possess capillary or other means for transporting liquid internally.

Following the trend of approximately 3 year intervals, the IV International Heat Pipe Conference was held in 1981 in London. The proceedings (10) contain almost 70 papers, and of particular note is the contribution made to heat pipe technology during the past 3-4 years by Japan, particularly in applications technology in electronics and energy conservation, (see Chapter 7).

In the first edition of this book, we stated that, with the staging of the first International Heat Pipe Conference in Stuttgart in 1973, the heat pipe had truely arrived. By 1977 it had become established as a most useful device in many mundane applications, as well as retaining its more glamorous status in spacecraft temperature control (11). Five years later, it is gradually consolidating its position.

The most obvious pointer to the success of the heat pipe is the wide range of applications where its unique properties have proved beneficial. Some of these applications are discussed in some detail in Chapter 7, but they include the following: electronics cooling, diecasting and injection moulding, heat recovery and other energy conserving uses, de-icing duties, cooking, cooling of batteries, control of manufacturing process temperatures, and as a means of transferring heat from fluidized beds.

The Contents of This Book

Chapter 1 describes the development of the heat pipe in more detail. Chapter 2 gives an account of the theoretical basis of heat pipe operations; this is now broadly understood though some areas exist where further data is needed. Chapter 3 is concerned with the application of the theory in Chapter 2, together with other practical considerations, to the overall design of heat pipes, and includes a number of design examples. Chapter 4 deals with the selection of materials, compatibility considerations including life tests and the problems of fabrication, filling and sealing. Chapter 5 describes special types of heat pipe. Chapter 6 discusses Variable Conductance Heat Pipes and Chapter 7 describes typical applications.

A considerable amount of data is collected together in Appendices for references purposes.

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CHAPTER 1

Historical Development

The heat pipe, as will be seen later from the patent claims made, differs from the thermosyphon by virtue of its ability to transport heat against gravity by an evaporation-condensation cycle. It is, however, important to realize that many heat pipe applications do not need to rely on this feature, and the Perkins Tube, which predates the heat pipe by several decades and is basically a form of thermosyphon, is still used in heat transfer equipment. The Perkins Tube must therefore be regarded as an essential part of the history of the heat pipe.

The Perkins Tube

Angier March Perkins was born in Massachusetts, USA, at the end of the eighteenth century, the son of Jacob Perkins, also an engineer (1.1). In 1827 A.M. Perkins came to England, where he subsequently carried out much of his development work on boilers and other heat distribution systems. The work on the Perkins Tube, which is a two-phase flow device, is attributed in the form of a patent to Ludlow Patton Perkins, the son of A.M. Perkins, but the main initiative for the device appears to lie with A.M. Perkins in the mid 19th century. A.M. Perkins, however, also worked on single phase heat distribution systems, with some considerable success, and although the chronological development has been somewhat difficult to follow from the papers available, the single phase systems preceded the Perkins Tube, and some historical notes on both systems seem appropriate.

The catalogue describing the products of A.M. Perkins and Sons Ltd., published in 1898, states that in 1831 A.M. Perkins took out his first patent for what is known as 'Perkins' system of heating by small bore wrought iron pipes. This system is basically a hermetic tube boiler in which water is circulated in tubes (in single phase and at high pressure) between the furnace and the steam drum, providing an indirect heating system. The boiler using hermetic tubes, described in UK Patent No. 6146, was produced for over 100 years on a commercial scale. The specification describes this closed cycle hot water heater as adapted for sugar making and refining for evaporators, for steam boilers, and also for various processes requiring molten metals for alloying or working of other metals at high temperatures, suggesting that the tubes in the Perkins system operate with high pressure hot water (HPHW) at temperatures well in excess of 150°C.

The principle of the 'ever full' water boiler, as devised in the United States by Jacob Perkins to prevent the formation of a film of bubbles on the inner wall of the heat input section of the tubes is applied as described in the above patent:

"As water expands about one-twentieth of its bulk before being converted into steam, I provide about double that extra space in the 'expansion tube' which is fitted with a removable air plug to allow the escape of air when the boiler is being filled. With this space for the expansion of the heated water the boiler is completely filled, and will at all times be kept in constant contact with the metal, however high the degree of heat such apparatus may be submitted to; and at the same time there will be no danger of bursting the apparatus with the provision of the sufficient space as named for the expansion of the water."

In 1839 most of the well-known forms of A.M. Perkins hot water hermetic heating tubes were patented in UK Patent No. 8311, and in that year a new invention, a concentric tube boiler, was revealed. The hot water closed circuit heating tubes in the concentric tube system were fork-ended, and dipped into two or more steam generation tubes. These resembled superheater elements as applied on steam locomotives, and a large boiler operating on this principle would consist of many large firetubes, all sealed off at one end and traversed by the inner hot water tubes, connected up externally by U bends. This proved to be the most rapid producer of superheated steam manufactured by the Perkins Company, and was even used as the basis for a steam actuated rapid firing machine gun, offered to the US Federal Government at the time of the Civil War. Although not used, they were "guaranteed to equal the efficiency of the best Minie rifles of that day, but at a much lower cost for coal than for gun powder." The system was, however, used in marine engines,"..... it gives a surprising economy of fuel and a rapid generation, with lightness and compactness of form; and a uniform pressure of from 200 lbs to 800 lbs per sq.in., may be obtained by its use.

Returning to the Perkins hermetic tube single phase water circulating boiler, as illustrated in Fig.1.1, some catalogues describe these units as operating at pressures up to 4000 psi, and being pressure-tested in excess of 11,000 psi. Operators were quick to praise the cleanliness, both inside and outside, of the hermetic tubes after prolonged use.

The first use of the Perkins Tube, i.e., one containing only a small quantity of water and operating on a two-phase cycle, is described in a patent by Jacob Perkins (UK Patent No. 7059, April 1936). The general description is as follows, (1.2).

One end of each tube projects downwards into the fire or flue and the other part extends up into the water of the boiler; each tube is hermetically closed to prevent escape of steam. There will be no incrustation of the interior of the tubes and the heat from the furnace will be quickly transmitted upwards. The interior surfaces of the tubes will not be liable to scaleage or oxidation, which will, of course, tend much to preserve the boiler so constructed. The specification says:- "These tubes are each one to have a small quantity of water depending upon the degree of pressure required by the engine; and I recommend that the density of the steam in the tubes should be somewhat more than that intended to be produced in the boiler, and, for steam and other boilers under the atmospheric pressure,

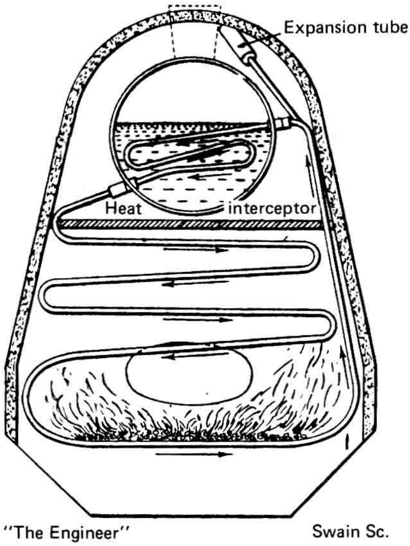

Fig. 1.1. Perkins Boiler.

that the quantity of water to be applied in each tube is to be about 1:1800 part of the capacity of the tube; for a pressure of 2 atm to be two 1:1800 parts; for 3 atm,three 1:1800 parts, and so on, for greater or less degrees of pressure, and by which means the tubes of the boiler when at work will be pervaded with steam, and any additional heat applied thereto will quickly rise to the upper parts of the tubes and be given off to the surrounding water contained in the boiler- for steam already saturated with heat requires no more (longer) to keep the atoms of water in their expanded state, consequently becomes a most useful means of transmitting heat from the furnace to the water of the boiler."

The earliest applications for this type of tube were in locomotive boilers and in locomotive fire-box superheaters (in France in 1863). Again, as with the single phase sealed system, the cleanliness of the tubes was given prominant treatment in many papers on the subject. At the Institution of Civil Engineers in February 1837 Perkins stated that following a 7 month life test on such a boiler tube under representative operating conditions, there was no leakage or incrustation, no deposit of any kind occurring within the tube.

Patents

Reference has already been made to several patents taken out by A.M. Perkins and J. Perkins on hermetic single phase and two phase heating tubes, normally for boiler applications. The most interesting patent, however, which relates to improvements in the basic Perkins Tube, is UK Patent 22272, dated 1892, and granted to L.P. Perkins and W.E. Buck: "Improvements in Devices for the Diffusion or Transference of Heat", (1.3).

The basic claim, with a considerable number of modifications and details referring to fluid inventory and application, is for a closed tube