HEAT PIPES

P. Dunn

Department of Engineering and Cybernetics
University of Reading, England

and

D. A. Reay

International Research and Development Co. Ltd.,
Newcastle-Upon-Tyne, England

PERGAMON PRESS

OXFORD · NEW YORK · TORONTO · SYDNEY
PARIS · BRAUNSCHWEIG

U. K.	Pergamon Press Ltd., Headington Hill Hall, Oxford OX3 0BW, England
U. S. A.	Pergamon Press Inc., Maxwell House, Fairview Park, Elmsford, New York 10523, U.S.A.
CANADA	Pergamon of Canada, Ltd., 207 Queen's Quay West, Toronto 1, Canada
AUSTRALIA	Pergamon Press (Aust.) Pty. Ltd., 19a Boundary Street, Rushcutters Bay, N.S.W. 2011, Australia
FRANCE	Pergamon Press SARL, 24 rue des Ecoles, 75240 Paris, Cedex 05, France
WEST GERMANY	Pergamon Press GMbH, 3300 Braunschweig, Postfach 2923, Burgplatz 1, West Germany

First edition 1976

Library of Congress Catalog Card No. 75-21727

In order to make this volume available as economically and rapidly as possible the authors' typescript has been reproduced in its original form. This method unfortunately has its typographical limitations but it is hoped that they in no way distract the reader.

Printed in Great Britain by A. Wheaton & Co. Exeter
ISBN 0 08 019854 6

Preface

Following the publication by G.M. Grover et al of the paper entitled "Structure 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 wish to thank those who assisted in providing material for this book. They are especially grateful to Pru Leach for typing the major part of the manuscript and for making many valuable suggestions concerning presentation of the data.

Contents

Introduction

The Heat Pipe and the Thermal Syphon

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 1960s 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 thermal syphon and it is helpful to describe the operation of the latter before discussing the heat pipe. The thermal syphon 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 thermal syphon has been used for many years and various working fluids have been employed. One limitation of the basic thermal syphon 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 thermal syphon 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.

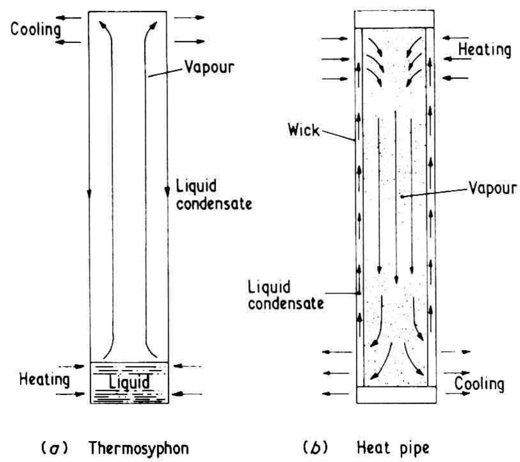

Fig. 1 The heat pipe and thermal syphon.

Several methods of condensate return are listed in Table 1.

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

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.

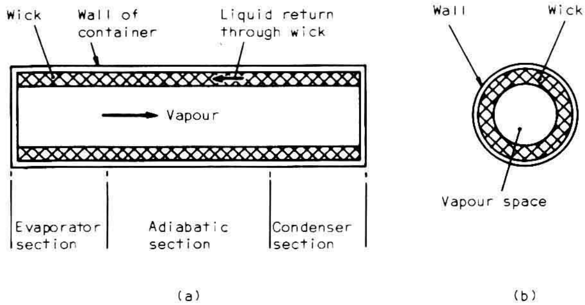

Fig. 2 The main regions of the heat pipe.

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°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°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 4°K to 2300°K.

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.

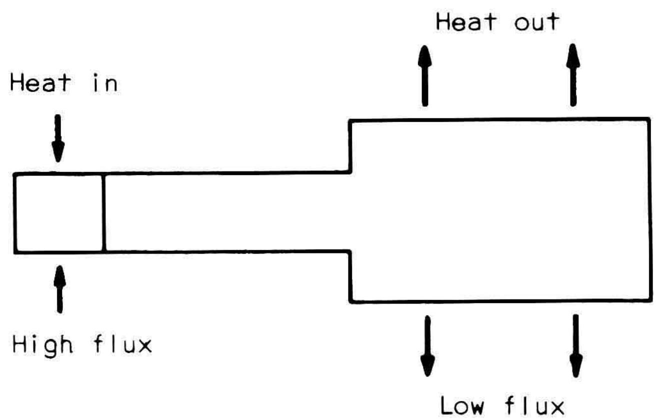

Fig. 3 The heat pipe as a thermal flux transformer.

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^{o}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.

(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 (4) in 1965. The manner in which heat pipe work expanded is seen from the growth in number of publications, following Grover's first paper in 1964. In 1968 Cheung (5) lists 80 references; in 1970 Chisholm in his book (6) cites 149 references, and the recent NEL Heat Pipe bibliography (7) has 544 references. Most recently an International Heat Pipe Conference has been held in Stuttgart in Oct., 1973: with this the heat pipe can truly be said to have arrived.

Applications of the heat pipe range from the cooling of cryogenic targets in nuclear accelerators, cooling of electronic equipment, building air conditioning, furnaces, engine heating and cooling, to cooling of space vehicles. The applications are discussed in more detail in Chapter 7 .

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 operation; this is now broadly understood though some areas exist where further work is necessary, notably in the prediction of burn-out characteristics. 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 reference purposes.

REFERENCES

1. Gaugler, R.S. US Patent Application. Dec. 21, 1942. Published US Patent No. 2350348. June 6, 1944.
2. Grover, G.M. US Patent 3229759. Filed 1963.
3. Grover, G.M., Cotter, T.P., Erickson, G.F. Structures of very high thermal conductance. J. App. Phys. Vol. 35, p 1990, 1964.
4. Cotter, T.P. Theory of heat pipes. Los Alamos Sci. Lab. Report No. LA-3246-MS, 1965.
5. Cheung, H. A critical review of heat pipe theory and application UCRL - 50453. July 15, 1968.
6. Chisholm, D. The heat pipe. M & B Technical Library. TL/ME/2. Pub. Mills and Boon Ltd., London 1971.
7. McKechnie, J. The heat pipe: a list of pertinent references. National Engineering Laboratory, East Kilbride. Applied Heat SR. BIB. 2 - 72, 1972.

Historical Development

As mentioned in the Introduction, the heat pipe concept was first put forward by R.S. Gaugler of the General Motors Corporation, Ohio, USA. In a patent application dated December 21st, 1942, and published (1.1) as US Patent No. 2350348 on June 6th, 1944, the heat pipe is described as applied to a refrigeration system.

According to Gaugler, the object of the invention was to "... cause absorption of heat, or in other words, the evaporation of the liquid to a point above the place where the condensation or the giving off of heat takes place without expending upon the liquid any additional work to lift the liquid to an elevation above the point at which condensation takes place." A capillary structure was proposed as the means for returning the liquid from the condenser to the evaporator, and Gaugler suggested that one form this structure might take would be a sintered iron wick. The wick geometries proposed by Gaugler are shown in Fig. 1.1. It is interesting to note the comparatively small proportion of the tube cross-section allocated to vapour flow in all three of his designs.

Fig. 1.1 Gaugler's proposed heat pipe wick geometries.

One form of refrigeration unit suggested by Gaugler is shown in Fig. 1.2. The heat pipe is employed to transfer heat from the interior compartment of the refrigerator to a pan below the compartment containing crushed ice. In order to improve heat transfer from the heat pipe into the ice, a tubular vapour chamber with external fins is provided, into which the heat pipe is fitted. This also acts as a reservoir for the heat pipe working fluid.

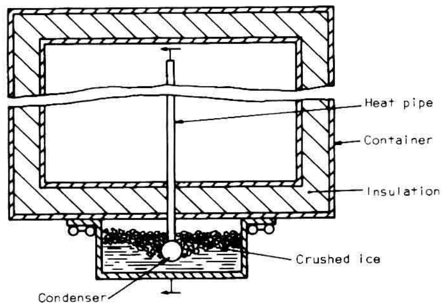

Fig. 1.2 The refrigeration unit suggested by Gaugler in his patent published in 1944.

The heat pipe as proposed by Gaugler was not developed beyond the patent stage, as other technology currently available at that time was applied to solve the particular thermal problem at General Motors Corporation.

Grover's patent (1.2), filed on behalf of the United States Atomic Energy Commission in 1963, coins the name 'heat pipe' to describe devices essentially identical to that in the Gaugler patent. Grover, however includes a limited theoretical analysis and presents results of experiments carried out on stainless steel heat pipes incorporating a wire mesh wick and sodium as the working fluid. Lithium and silver are also mentioned as working fluids.

An extensive programme was conducted on heat pipes at Los Alamos Laboratory, New Mexico, under Grover, and preliminary results were reported in the first publication on heat pipes (1.3). Following this the United Kingdom Atomic Energy Laboratory at Harwell started similar work on sodium and other heat pipes (1.4). The Harwell interest was primarily the application to nuclear thermionic diode converters, a similar programme commenced at the Joint Nuclear Research Centre, Ispra, in Italy under Neu and Busse. The work at Ispra built up rapidly and the laboratory became the most active centre for heat pipe research outside the US, (1.5, 1.6).

The work at Ispra was concerned with heat pipes for carrying heat to emitters

Interest in the USSR in heat pipes was evident from an article published in the Russian journal 'High Temperature' (1.21) although much of the information described a summary of work published elsewhere.

1969 saw reports of further work on variable conductance heat pipes, the principle contributions being made by Turner (1.22) at RCA and Bienert (1.23) at Dynatherm Corporation. Theoretical analyses were carried out on VCHP's to determine parameters such as reservoir size, and practical aspects of reservoir construction and susceptibility to external thermal effects were considered.

A new type of heat pipe, in which the wick is omitted, was developed at this time by NASA (1.24). The rotating heat pipe utilises centrifugal acceleration to transfer liquid from the condenser to the evaporator, and can be used for cooling motor rotors and turbine blade rotors. Gray (1.24) also proposed an air conditioning unit based on the rotating heat pipe, and this is illustrated in Fig. 1.6. (The rotating heat pipe is described fully in Chapter 5.) The rotating heat pipe does not of course suffer from the capillary pumping limitations which occur in conventional heat pipes, and its transport capability can be greatly superior to that of wicked pipes.

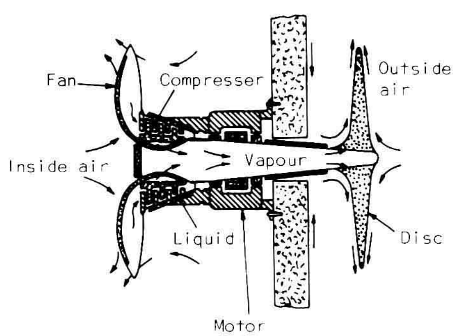

Fig. 1.6 A compact air conditioning unit based on the wickless rotating heat pipe. (Courtesy NASA)

The application of heat pipes to electronics cooling in areas other than satellites was beginning to receive attention. Pipes of rectangular section were proposed by Sheppard (1.25) for cooling integrated circuit packages, and the design, development and fabrication of a heat pipe to cool a high-power