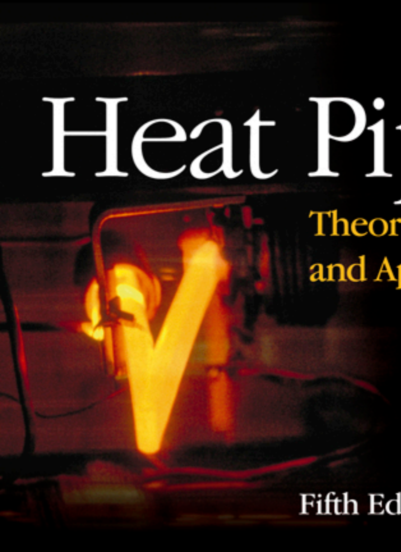
David Reay
and Peter Kew

Heat Pipes

Theory, Design and Applications



Fifth Edition

Heat Pipes

Fifth Edition

This page intentionally left blank

Heat Pipes

Fifth Edition

D.A. Reay
David Reay & Associates, Whitley Bay, UK

P.A. Kew
Heriot-Watt University, Edinburgh, UK

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

ELSEVIER

Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
Linacre House, Jordan Hill, Oxford OX2 8DP
30 Corporate Drive, Suite 400, Burlington, MA 01803, USA

Fifth edition 2006

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data
A catalogue record for this book is available from the Library of Congress

ISBN–13: 978-0-7506-6754-8
ISBN–10: 0-7506-6754-0

For information on all Butterworth-Heinemann publications visit our website at http://books.elsevier.com

Printed and bound in Great Britain
06 07 08 09 10 10 9 8 7 6 5 4 3 2 1

CONTENTS

This page intentionally left blank

DEDICATION

It is well over 30 years since the first pens were put to paper (now an old-fashioned phrase) by Professor Peter Dunn, OBE, then a Professor at Reading University, and David Reay, a research engineer at International Research & Development Company (IRD) in Newcastle upon Tyne, to start writing 'Heat Pipes'.

When a Fifth Edition was first discussed 2 or 3 years ago, Professor Dunn indicated that he would step aside as co-author, and Dr Peter Kew at Heriot-Watt University took over his role. Dr Kew had also worked on heat pipes at IRD and continues to collaborate with David Reay on heat pipe consultancy work.

Professor Dunn has now turned his hand to Appropriate Technology, where he remains active, and his illustrious career is summarised below.

Professor Dunn was trained in Civil Engineering and worked on Permanent Way Design and Manufacture first in industry and later for the LMS Railway Research Department. He then changed his career interests and moved into the design of microwave valves and particle accelerators. He was responsible for the Radio Frequency Accelerating System of the 7 GeV Accelerator Nimrod. Later, as the head of a team at AERE, Harwell, he carried out work on the direct generation of heat to electricity from nuclear reactors. One of the methods studied was thermionic diodes, and it was at this time that he first met Dr George Grover who was responsible for a similar group at the Los Alamos Laboratory in USA. Professor Dunn is a founder member of the International Conference.

Dr Grover's new work on heat pipes was exciting and highly relevant and was the start of Professor Dunn's interest in the subject. He commenced a study of liquid metal heat pipes for reactor application.

Later, Professor Dunn moved to Reading University where he set up the, then, new Department of Engineering. With his colleague Dr Graham Rice, he carried on heat pipe work.

In recent years, Professor Dunn's interests have moved to Appropriate Technology and Third World Development, he has carried out projects, particularly in renewable energy, in many countries and for some time was chairman of Gamos, a small firm concerned with development work overseas.

It is with great pleasure and thanks that we dedicate this Edition of Heat Pipes to Professor Peter Dunn.

David Reay
Peter Kew
November 2005.

This page intentionally left blank

PREFACE TO FIFTH EDITION

Recent editions of 'Heat Pipes' have appeared at intervals of approximately a decade. It is perhaps the last 10 years that have seen a transformation in heat pipe technology and application, characterised by, in the first case, loop heat pipes, and secondly, the mass production of miniature heat pipes for thermal management in the ubiquitous desktop and laptop computers. Millions of units per month are now being made, particularly in the Far East.

The other major change has been in the co-authorship of 'Heat Pipes'. As readers will see from the Dedication, Professor Dunn has relinquished his role as co-author, and this has been taken over by Dr Peter Kew, who first started research on heat pipes in the 1980s. We hope that readers will judge Dr Kew to be a worthy successor to Professor Dunn.

The changes in technological emphasis have allowed us to make some more radical changes to the book, rather than the 'fine-tuning' characteristic of earlier updates. To this end, we must acknowledge the referees, who assessed the contents list and made many constructive suggestions regarding the content. We hope that they find the new edition satisfies their requirements.

Particular features of the Fifth Edition are a revamped theory chapter, 'Design Guide' (Chapter 4), substantial additions to Chapter 6 'Special Types of Heat Pipe' including sections on capillary pumped loops oscillating heat pipes and electrokinetic effects, and a chapter dedicated to electronics cooling applications. The growth in use of the World Wide Web has allowed us to replace the conventional 'List of Manufacturers' with a list of useful web sites. An Appendix also covers recent papers not cited in the main text on heat pipe applications – these illustrate the breadth and depth of uses to which heat pipes have been put, or where they are the subject of feasibility studies.

Where data remain relevant, although they may be in some cases 50 years old, they are retained, as are the original data sources. Theories, wick properties, working fluids and manufacturing technologies do not change rapidly – especially where proved techniques have been successful over extended periods. We make no apologies for keeping an archive of what we believe to be useful data within one publication.

We hope that readers find the updated version as useful as earlier editions.

D.A. Reay
P.A. Kew
November 2005.

PREFACE TO FIRST EDITION

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.

This page intentionally left blank

ACKNOWLEDGEMENTS

Dr Cosimo Buffone of Thermacore Europe and Nelson J. Gernert of Thermacore, Inc. for substantial data on a range of heat pipes and case studies, in particular those related to thermal management of electronics systems.

Professor Yu. Maydanik for data on loop heat pipes and appropriate illustrations.

Professor Ali Akbarzadeh for illustrations and other data on his heat pipe turbine developments and electronics cooling concepts.

Professor Dumitru Fetcu, Transilvania University of Brasov, Romania and CTO Heat Pipe Division, iESi USA Inc., Canada, for illustration of sodium heat pipes and performance data.

Professor Leonard Vasiliev, Luikov Heat & Mass Transfer Institute, Minsk, for data and figures in Chapters 6 and 7.

Dr John Burns of Protensive Ltd, for data on spinning disc reactors.

Dr David Etheridge of Nottingham University for information on heat pipes linked to phase change materials in buildings.

Professor Graeme Maidment of London South Bank University for data on the thermal control of London Underground railway system, and supermarket chilled food cabinets (Chapter 7).

Professor Robert Critoph, University of Warwick, for data on the adsorption system that employs heat pipes (Chapter 7).

Peter C. Cologer, Director, Advanced Thermal Applications, Swales Aerospace.

Deschamps Technologies for permission to use Figure 7.21.

Dr C. James of the Food Refrigeration and Process Engineering Research Centre, University of Bristol, for data and illustrations in Section 7.8.2.

INTRODUCTION

Figure 4 reprinted from Applied Thermal Engineering, Vol. 25, Maydanik, Y.F., Loop heat pipes. Review article, pp 635–657, Copyright 2005, with permission from Elsevier.

CHAPTER 1

Figure 1.10 reprinted from Applied Thermal Engineering, Vol. 23, Swanson, T.D. and Birur, G.C. NASA thermal control technologies for robotic spacecraft, pp 1055–1066, Copyright 2003, with permission from Elsevier.

Figure 1.11 reprinted from Applied Thermal Engineering, Vol. 25, Bintoro, J.S., Akbarzadeh, A. and Mochizuki, M. A closed-loop electronics cooling by implementing single phase impinging jet and mini channels heat exchanger, pp 2740–2753, Copyright 2005, with permission from Elsevier.

CHAPTER 2

Figures 2.25 and 2.29 reprinted from Brautsch A., Heat transfer mechanisms during the evaporation process from mesh screen porous structures, Ph.D. Thesis, Copyright 2002.

Figures 2.27 and 2.28 reprinted from Proceedings of the 12th International Heat Transfer Conference, Grenoble, August 2002, Brautsch, A. and Kew, P.A. The effect of surface conditions on boiling heat transfer from mesh wicks, Copyright 2002, with permission from Elsevier.

Figure 2.44 reprinted from Applied Thermal Engineering, Vol. 20, Payakaruk, T. Terdtoon, P., Ritthidech, S. Correlations to predict heat transfer characteristics of an inclined closed two-phase thermosyphon at normal operating conditions, pp 781–790, Copyright 1999, with permission from Elsevier.

Table 2.13 reprinted from International Journal of Refrigeration, Vol. 20, Golobic, I. and Gaspersic, B. Corresponding states correlation for maximum heat flux in two-phase closed thermosyphon, pp 402–410, Copyright 1997, with permission from Elsevier.

CHAPTER 4

Figure 4.6 reprinted from International Journal of Heat and Mass Transfer, Vol. 42, El-Genk, M.S. and Saber, H.H. Determination of operation envelopes for closed two-phase thermosyphons. pp 889–903, Copyright 1999, with permission from Elsevier.

CHAPTER 5

Figure 5.8 reprinted from Applied Thermal Engineering, Vol. 24, Launay, S., Sartre, V. and Lallemand, M. Experimental study on silicon micro-heat pipe arrays, pp 233–243, Copyright 2004, with permission from Elsevier.

CHAPTER 6

Figure 6.7 reprinted from Applied Thermal Engineering, Vol. 23, Marcarino, P. and Merlone, A. Gas-controlled heat-pipes for accurate temperature measurements. Paper presented at 12th International Heat Pipe Conference, Moscow, pp 1145–1152, Copyright 2003, with permission from Elsevier.

Figure 6.9 reprinted from Nuclear Instruments and Methods in Physics Research A, Vol. 442, Chernenko, A., Kostenko, V., Loznikov, V., Semena, N., Konev, S., Rybkin, B., Paschin, A. and Prokopenko, I. Optimal cooling of HPGe spectrometers for space-born experiments, pp 404–407, Copyright 2000, with permission from Elsevier.

Figure 6.10 reprinted from Energy and Buildings, Vol. 34, Varga, S., Oliveira, A.C. and Afonso, C.F. Characterisation of thermal diode panels for use in the cooling season in buildings, pp 227–235, Copyright 2002, with permission from Elsevier.

Figures 6.13 and 6.14a reprinted from Applied Thermal Engineering, Vol. 23, Charoensawan, P., Khandekar, S., Groll, M. and Terdtoon, P. Closed loop pulsating heat pipes, Part A: parametric experimental investigations, pp 2009–2020, Copyright 2003, with permission from Elsevier.

Figure 6.14b reprinted from Electronics Cooling, Vogel, M. and Xu, G., 'Low Profile Heat Sink Cooling Technologies for Next Generation CPU Thermal Designs,' Figure 4, Electronics Cooling, Vol. 11, No. 1, February 2005, p. 16. Copyright 2005, with permission from Electronics Cooling.

Figures 6.15 and 6.16 reprinted from Applied Thermal Engineering, Vol. 23, Khandekar, S., Charoensawan, P., Groll, M. and Terdtoon, P. Closed loop pulsating heat pipes. Part B: visualization and semi-empirical modeling, pp 2021–2033, Copyright 2003, with permission from Elsevier.

Figure 6.17 reprinted from Applied Thermal Engineering, Vol. 23, Khandekar, S., Dollinger, N. and Groll, M. Understanding operational regimes of closed loop pulsating heat pipes: an experimental study, pp 707–719, Copyright 2003, with permission from Elsevier.

Figure 6.18 reprinted from Applied Thermal Engineering, Vol. 24, Sakulchangsatjatai, P., Terdtoon, P., Wongratanaphisan, T., Kamonpet, P. and Murakami, M. Operation modeling of closed-end and closed-loop oscillating heat pipes at normal operating condition, pp 995–1008, Copyright 2004, with permission from Elsevier.

Figure 6.19 reprinted from Applied Thermal Engineering, Vol. 25, Katpradit, T., Wongratanaphisan, T., Terdtoon, P., Kamonpet, P., Polchai, A. and Akbarzadeh, A. Correlation to predict heat transfer characteristics of a closed end oscillating heat pipe at critical state, pp 2138–2151, Copyright 2004, with permission from Elsevier.

Figures 6.20 and 6.22 reprinted from Applied Thermal Engineering, Vol. 25, Maydanik, Y.F. Loop heat pipes, pp 635–657, Copyright 2005, with permission from Elsevier.

Figures 6.24, 6.25 and 6.26 reprinted from Applied Thermal Engineering, Vol. 23, Bazzo, E. and Riehl, R.R. Operation characteristics of a small-scale capillary pumped loop, pp 687–705, Copyright 2003, with permission from Elsevier.

Figure 6.27 reprinted from Applied Thermal Engineering, Vol. 24, Khodabandeh, R. Thermal performance of a closed advanced two-phase thermo-syphon loop for cooling of radio base stations at different operating conditions, pp 2643–2655, Copyright 2004, with permission from Elsevier.

Figure 6.33 reprinted from Sensors and Actuators B, Vol. 106, Qian, S. and Bau, H.H. Magneto-hydrodynamic stirrer for stationary and moving fluids, pp 859–870, Copyright 2005, with permission from Elsevier.

Figures 6.46 and 6.47 reprinted from International Journal of Heat & Mass Transfer, Vol. 48, Vasiliev, L. and Vasiliev, L. Jr. Sorption heat pipe – a new thermal control device for space and ground application, pp 2464–2472, Copyright 2005, with permission from Elsevier.

CHAPTER 7

Figure 7.3 reprinted from Heat Recovery Systems & CHP, Vol. 12, Valisiev, L.L., Boldak, I.M., Domorod, L.S., Rabetsky, M.I. and Schirokov, E.I. Experimental device for the residential heating with heat pipe and electric heat storage blocks, pp 81–85, Copyright 1992, with permission from Elsevier.

Figures 7.4 and 7.5 reprinted from Applied Thermal Engineering, Vol. 24, Ampofo, F., Maidment, G. and Missenden, J. Underground railway environment in the UK. Part 3: methods of delivering cooling, pp 647–659, Copyright 2004, with permission from Elsevier.

Figure 7.6 reprinted from Progress in Nuclear Energy, Vol. 32, Ohashi, K., Hayakawa, H., Yamada, M., Hayashi, T. and Ishii, T. Preliminary study on the application of the heat pipe to the passive decay heat removal system of the modular HTR, pp 587–594, Copyright 1998, with permission from Elsevier.

Figures 7.8, 7.9 and 7.10 reprinted from Applied Thermal Engineering, Vol. 22, Critoph, R.E. Multiple bed regenerative adsorption cycle using the monolithic carbon–ammonia pair, pp 667–677, Copyright 2002, with permission from Elsevier.

Figure 7.11 reprinted from Applied Thermal Engineering, Vol. 23, Zhang, H and Zhuang, J. Research, development and industrial application of heat pipe technology. Proceedings of the 12th International Heat Pipe Conference, Moscow, 2002, pp 1067–1083, Copyright 2003, with permission from Elsevier.

Figure 7.12 reprinted from Renewable Energy, Vol. 14, Aghbalou, F. et al. A parabolic solar collector heat pipe heat exchanger reactor assembly for cyclohexane's dehydrogenation: a simulation study, pp 61–67, Copyright 1998, with permission from Elsevier.

CHAPTER 8

Figures 8.6, 8.7 and 8.8 reprinted from Microelectronics Reliability, Vol. 44, Moon, S.H. et al. Improving thermal performance of miniature heat pipe for notebook PC cooling, pp 135–140, Copyright 2002, with permission from Elsevier.

Figure 8.9 reprinted from Applied Thermal Engineering, Vol. 25, Murer, S. et al. Experimental and numerical analysis of the transient response of a miniature heat pipe, pp 2566–2577, Copyright 2005, with permission from Elsevier.

Figure 8.10 reprinted from Applied Thermal Engineering, Vol. 25, Maydanik, Y.F. Loop heat pipes, pp 635–657, Copyright 2005, with permission from Elsevier.

This page intentionally left blank

INTRODUCTION

The heat pipe is a device of very high thermal conductance. The idea of the heat pipe was first suggested by Gaugler [1] in 1942. It was not, however, until its independent invention by 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 thermosyphon and it is helpful to describe the operation of the latter before discussing the heat pipe. The thermosyphon 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 vapourise 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 also 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 basic heat pipe differs from the thermosyphon in that 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.

Several methods of condensate return are listed in Table 1. A review of techniques is given by Roberts [4], and others are discussed by Reay [13], Jeyadeven et al. [14] and Maydanik [15].