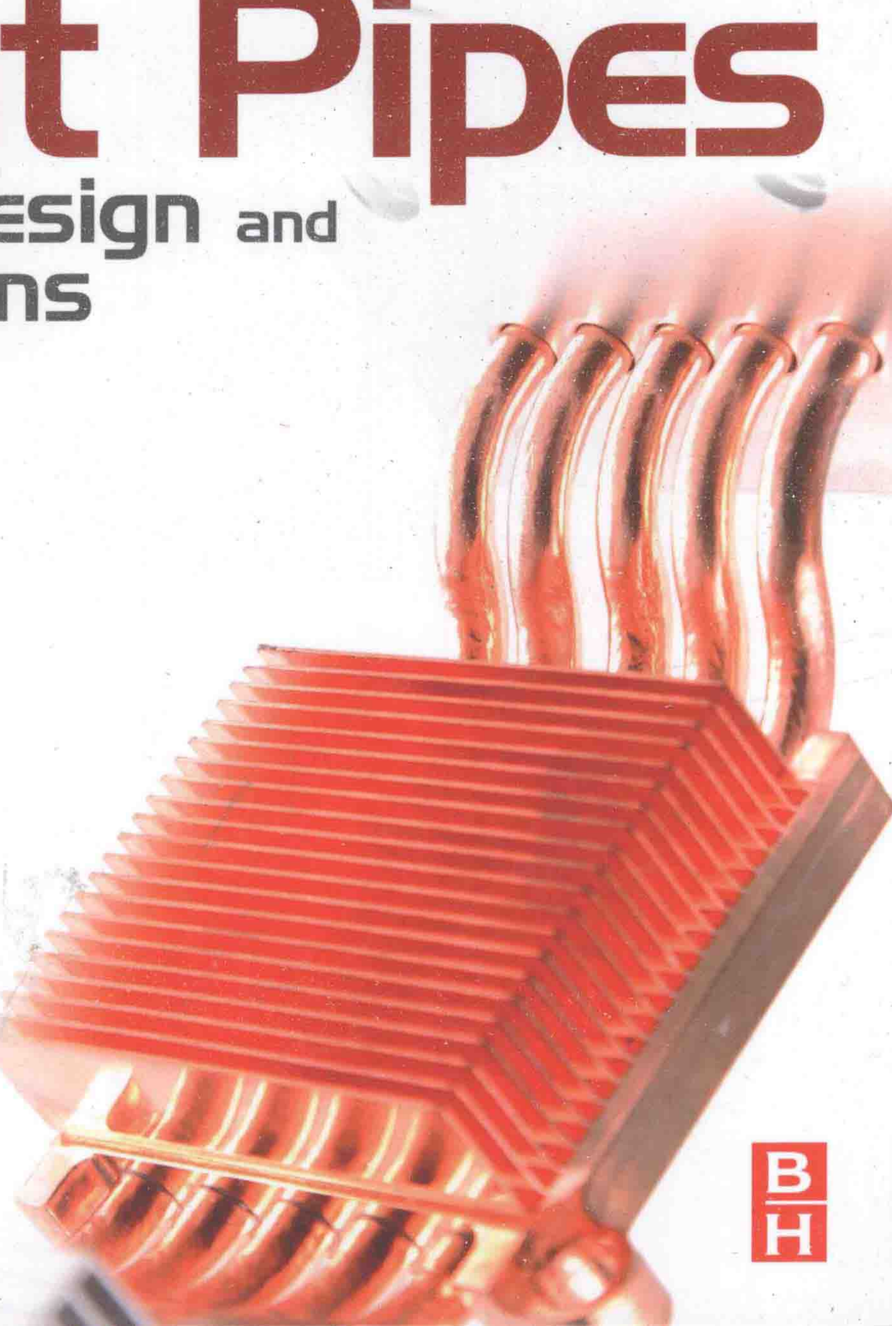
David Reay | Peter Kew | Ryan McGlen

Sixth Edition

Heat Pipes

Theory, Design and Applications



BH

Heat Pipes

Theory, Design and Applications

Sixth Edition

D.A. Reay

David Reay & Associates, Whitley Bay, UK

P.A. Kew

Heriot-Watt University, Dubai Campus, Dubai

R.J. McGlen

Thermacore Europe, Ashington, UK

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO
Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1AJ, UK
225 Wyman Street, Waltham, MA 02451, USA

Fifth edition 2006
Sixth edition 2014

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

Library of Congress Cataloging-in-Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-098266-3

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

Typeset by MPS Limited, Chennai, India
www.adi-mps.com

Printed and bound in Singapore by Markono Print Media Pte Ltd

Dedication

It is approaching 40 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 some 10 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 then 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 United States. 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 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.

His current technical activities relate to writing a book on *The British Steam Locomotive*, and we look forward to seeing that in print.

It is with great pleasure and thanks that we dedicate this edition of *Heat Pipes* to Professor Peter Dunn, as we did the fifth edition.

David Reay
Peter Kew
Ryan McGlen
April 2013

Preface

to sixth edition

Recent editions of 'Heat Pipes' have appeared at intervals of approximately a decade, the fifth edition appearing in 2006. It was perhaps the period 1995–2005 that saw 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 continue to be made, mainly in China, where there are substantial production cost benefits. Heat pipe research and application remains vigorous, but the challenges are great. Miniaturisation of electronics systems, in particular portable equipment, challenges thermal engineers as well as the broader packaging concepts employed. Getting more power out of ever-smaller devices can take us beyond heat pipes in some instances.

The other major change, starting with the fifth edition, and involving a further change for this edition, has been in the co-authorship of 'Heat Pipes'. As readers will see from the Dedication, Professor Dunn relinquished his role as co-author after the fourth edition, and this was taken over by Dr Peter Kew, who first started research on heat pipes in the 1980s. Peter's activity continues in the sixth edition, and we are pleased to welcome on board Dr. Ryan McGlen, a Senior Scientist at Thermacore Europe, the major heat pipe and thermal engineering company. He has made a major contribution to Chapter 8 and helped elsewhere in the book.

The changes in technological emphasis allowed us to make several changes to the fifth edition. In this new edition we have carried out 'fine-tuning' but also added new data on thermosyphons, applications and manufacturing methods. The innovative designer will find comments on 3D printing of heat pipes interesting, we hope!

Particular features of the sixth edition are additions to the theory (Chapter 2), in particular a section on nanofluids, substantial additions to Chapter 6 'Special types of heat pipe', and a rewriting of the chapter dedicated to electronics cooling applications. Applications discussed in Chapter 7 have been reassessed as appropriate. The list of useful web sites has been updated. We have deleted the bibliography. Easy electronic access to resources, in particular journal papers, make such bibliographies less useful, and of course they quickly become dated.

Where data remain relevant, although they may be in some cases over 50 years old, they are retained, as are the original data sources (although where these have not been converted into electronic format, access may be difficult, except through *National Archives*). 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.

April 2013

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.

Acknowledgements

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

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

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

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

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

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

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

P. C. Cologer, Director, Advanced Thermal Applications, Swales Aerospace, in particular, for data and illustrations used in Chapter 7.

Deschamps Technologies for permission to use Figure 7.28.

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 I.4 reprinted from Y.F. Maydanik, Loop heat pipes, Appl. Therm. Eng. 25 (review article) (2005) 635–657, Copyright 2005, with permission from Elsevier.

CHAPTER 1

Figure 1.10 reprinted from T.D. Swanson, G.C. Birur, NASA thermal control technologies for robotic spacecraft, Appl. Therm. Eng. 23 (2003) 1055–1066, Copyright 2003, with permission from Elsevier.

Figure 1.11 reprinted from J.S. Bintoro, A. Akbarzadeh, M. Mochizuki, A closed-loop electronics cooling by implementing single phase impinging jet and mini channels heat exchanger, Appl. Therm. Eng. 25 (2005) 2740–2753, Copyright 2005, with permission from Elsevier.

CHAPTER 2

Figures 2.25 and 2.29 reprinted from A. Brautsch, 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 A. Brautsch, P.A. Kew, The effect of surface conditions on boiling heat transfer from mesh wicks, in: Proceedings of the Twelfth International Heat Transfer Conference, Grenoble, August 2002, Copyright 2002, with permission from Elsevier.

Figure 2.44 reprinted from T. Payakaruk, P. Terdtoon, S. Ritthidech, Correlations to predict heat transfer characteristics of an inclined closed two-phase thermosyphon at normal operating conditions, Appl. Therm. Eng. 20 (1999) 781–790, Copyright 1999, with permission from Elsevier.

Table 2.13 reprinted from I. Golobic, B. Gaspersic, Corresponding states correlation for maximum heat flux in two-phase closed thermosyphon, Int. J. Refrig. 20 (1997) 402–410, Copyright 1997, with permission from Elsevier.

Table 2.14 reprinted from Z.-H. Liu, L.Y.-Y. Li, A new frontier of nanofluid research – Application of nanofluids in heat pipes, Int. J. Heat Mass Transfer 55 (2012) 6786–6797, with permission from Elsevier.

Figures 2.45 and 2.46 and Table 2.15 reprinted from N. Putra, W.N. Septiadi, H. Rahman, I. Irwansyah, Thermal performance of screen mesh wick heat pipes with nanofluids, Exp. Therm. Fluid Sci. 40 (2012) 10–17, with permission from Elsevier.

CHAPTER 3

Figure 3.2 reprinted from A. Brusly Solomon, K. Ramachandran, B.C. Pillai, Thermal performance of a heat pipe with nanoparticles coated wick, Appl. Therm. Eng. 36 (2012) 106–112, with permission from Elsevier.

Figure 3.3 reprinted from K.Y. Leong, R. Saidur, T.M.I. Mahlia, Y.H. Yau, Performance investigation of nanofluids as working fluid in a thermosyphon air preheater, Int. Commun. Heat Mass Transfer 39 (2012) 523–529, with permission from Elsevier.

Figure 3.5 reprinted from C. Byon, S.J. Kim, Capillary performance of bi-porous sintered metal wicks, Int. J. Heat Mass Transfer 55 (2012) 4096–4103, with permission from Elsevier.

Figure 3.8 reprinted from P.H.D. Santos, E. Bazzo, A.A.M. Oliveira, Thermal performance and capillary limit of a ceramic wick applied to LHP and CPL. Applied Thermal Engineering 41 (2012) 91–103 with permission from Elsevier.

CHAPTER 4

Figure 4.6 reprinted from M.S. El-Genk, H.H. Saber, Determination of operation envelopes for closed two-phase thermosyphons, Int. J. Heat Mass Transfer 42 (1999) 889–903, Copyright 1999, with permission from Elsevier.

CHAPTER 5

Figure 5.6 reprinted from C. Byon, S.J. Kim. Effects of geometrical parameters on the boiling limit of bi-porous wicks, Int. J. Heat Mass Transfer 55 (2012) 7884–7891, with permission from Elsevier.

Figure 5.9 reprinted from S. Launay, V. Sartre, M. Lallemand, Experimental study on silicon micro-heat pipe arrays, Appl. Therm. Eng. 24 (2004) 233–243, Copyright 2004, with permission from Elsevier.

Figures 5.21 and 5.22 reprinted from M. Ameli, B. Agnew, P. Leung, B. Ng, C.J. Sutcliffe, J. Singh, et al., A novel method for manufacturing sintered aluminium heat pipes (SAHP), Appl. Therm. Eng.52 (5) (2013) 498–504, with permission from Elsevier.

Figures 5.27–5.29 reprinted from R.W. MacGregor, P.A. Kew, D.A. Reay, Investigation of low global warming potential working fluids for a closed two-phase thermosyphons, Appl. Therm. Eng. 51 (2013) 917–925, with permission from Elsevier.

CHAPTER 6

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

Figure 6.9 reprinted from A. Chernenko, V. Kostenko, V. Loznikov, N. Semena, S. Konev, B. Rybkin, et al., Optimal cooling of HPGe spectrometers for space-born experiments, Nucl. Instrum. Methods Phys. Res. A, 442 (2000) 404–407, Copyright 2000, with permission from Elsevier.

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

Figures 6.13 and 6.14(a) reprinted from P. Charoensawan, S. Khandekar, M. Groll, P. Terdtoon, Closed loop pulsating heat pipes, Part A: parametric experimental investigations, Appl. Therm. Eng. 23 (2003) 2009–2020, Copyright 2003, with permission from Elsevier.

Figure 6.14(b) reprinted from M. Vogel, G. Xu, Low profile heat sink cooling technologies for next generation CPU thermal designs, Electronics Cooling, Figure 4, Electron. Cooling 11 (1) (2005) 16, Copyright 2005, with permission from Electronics Cooling.

Figures 6.15 and 6.16 reprinted from S. Khandekar, P. Charoensawan, M. Groll, P. Terdtoon, Closed loop pulsating heat pipes. Part B: visualization and semi-empirical modeling, Appl. Therm. Eng. 23 (2003) 2021–2033, Copyright 2003, with permission from Elsevier.

Figure 6.17 reprinted from S. Khandekar, N. Dollinger, M. Groll, Understanding operational regimes of closed loop pulsating heat pipes: an experimental study, Appl. Therm. Eng. 23 (2003) 707–719, Copyright 2003, with permission from Elsevier.

Figure 6.18 reprinted from P. Sakulchangsatjatai, P. Terdtoon, T. Wongratanaphisan, P. Kamonpet, M. Murakami, Operation modeling of closed-end and closed-loop oscillating heat pipes at normal operating condition, Appl. Therm. Eng. 24 (2004) 995–1008, Copyright 2004, with permission from Elsevier.

Figure 6.19 reprinted from T. Katpradit, T. Wongratanaphisan, P. Terdtoon, P. Kamonpet, A. Polchai, A. Akbarzadeh, Correlation to predict heat transfer characteristics of a closed end oscillating heat pipe at critical state, Appl. Therm. Eng. 25 (2004) 2138–2151, Copyright 2004, with permission from Elsevier.

Figures 6.25 and 6.26 reprinted from Y.F. Maydanik, Loop heat pipes, Appl. Therm. Eng. 25 (2005) 635–657, Copyright 2005, with permission from Elsevier.

Figures 6.21–6.23 reprinted from H. Yang, S. Kandekhar, M. Groll, Operational limit of closed loop pulsating heat pipes, Appl. Therm. Eng. 28 (2008) 49–59, with permission from Elsevier.

Figure 6.24 reprinted from J. Clement, X. Wang, Experimental investigation of pulsating heat pipe performance with regard to fuel cell cooling application, Appl. Therm. Eng. 50 (2013) 268–274, with permission from Elsevier.

Figures 6.29–6.31 reprinted from E. Bazzo, R.R. Riehl, Operation characteristics of a small-scale capillary pumped loop, Appl. Therm. Eng. 23 (2003) 687–705, Copyright 2003, with permission from Elsevier.

Figure 6.32 reprinted from Y. Chen, M. Groll, R. Merz, Y.F. Maydanik, S.V. Vershinin, Steady state and transient performance of a miniature loop heat pipe, Int. J. Therm. Sci. 45 (2006) 1084–1090, with permission from Elsevier.

Figure 6.33 reprinted from W. Deng, Z. Xie, Y. Tang, R. Zhou, Experimental investigation on anti-gravity loop heat pipe based on bubbling mode, Exp. Therm. Fluid Sci. 41 (2012) 4–11, with permission from Elsevier.

Figure 6.34 reprinted from R. Khodabandeh, Thermal performance of a closed advanced two-phase thermosyphon loop for cooling of radio base stations at different operating conditions, Appl. Therm. Eng. 24 (2004) 2643–2655, Copyright 2004, with permission from Elsevier.

Figure 6.40 reprinted from S. Qian, H.H. Bau, Magneto-hydrodynamic stirrer for stationary and moving fluids, Sens. Actuators B 106 (2005) 859–870, Copyright 2005, with permission from Elsevier.

Figures 6.53 and 6.54 reprinted from L. Vasiliev, L. Vasiliev, Jr. Sorption heat pipe – a new thermal control device for space and ground application, Int. J. Heat Mass Transfer 48 (2005) 2464–2472, Copyright 2005, with permission from Elsevier.

CHAPTER 7

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

Figures 7.4 and 7.5 reprinted from F. Ampofo, G. Maidment, J. Missenden, Underground railway environment in the UK. Part 3: methods of delivering cooling, Appl. Therm. Eng. 24 (2004) 647–659, Copyright 2004, with permission from Elsevier.

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

Figure 7.7 reprinted from P. Sabharwall, M. Patterson, V. Utgikar, F. Gunnerson, Phase change heat transfer device for process heat applications, Nucl. Eng. Des. 240 (2010) 2409–2414, with permission from Elsevier.

Figure 7.8 reprinted from C.W. Robak, T.L. Bergman, A. Faghri, Enhancement of latent heat energy storage using embedded heat pipes, Int. J. Heat Mass Transfer 54 (2011) 3476–3484, with permission from Elsevier.

Figures 7.10–7.12 reprinted from R.E. Critoph, Multiple bed regenerative adsorption cycle using the monolithic carbon–ammonia pair, Appl. Therm. Eng. 22 (2002) 667–677, Copyright 2002, with permission from Elsevier.

Figure 7.13 reprinted from H. Zhang, J. Zhuang, Research, development and industrial application of heat pipe technology, Appl. Therm. Eng. 23, in: Proceedings of the Twelfth International Heat Pipe Conference, Moscow, 2002, pp. 1067–1083, Copyright 2003, with permission from Elsevier.

Figure 7.14 reprinted from F. Aghbalou, et al., A parabolic solar collector heat pipe heat exchanger reactor assembly for cyclohexane's dehydrogenation: a simulation study, Renew. Energy 14 (1998) 61–67, Copyright 1998, with permission from Elsevier.

Figure 7.16 is reprinted from H. Loewe, R.D. Axinte, D. Breuch, C. Hofmann, Heat pipe controlled syntheses of ionic liquids in microstructured reactors, Chem. Eng. J. 155 (2009) 548–550, with permission from Elsevier.

Figure 7.22 is reprinted from S.-J. Dong, Y.-Z. Li, J. Wang, J. Wang, Fuzzy incremental control algorithm of loop heat pipe cooling system for spacecraft applications, Comput. Math. Appl. 64 (2012) 877–886, with permission from Elsevier.

Figures 7.23–7.25 are reprinted from C. Sarno, C. Tantolin, R. Hodot, Yu. Maydanik, S. Vershinin, Loop thermosyphon thermal management of the avionics of an in-flight entertainment system, Appl. Therm. Eng. 51 (2013) 764–769, with permission from Elsevier.

Figures 7.33 and 7.34 are reprinted from M. Zhang, Y. Lai, J. Zhang, Z. Sun, Numerical study on cooling characteristics of two-phase closed thermosyphon embankment in permafrost regions, Cold Reg. Sci. Technol. 65 (2011) 203–210, with permission from Elsevier.

CHAPTER 8

Figures 8.6–8.8 reprinted from S.H. Moon, G. Hwang, H.G. Yun, T.G. Choy, Y. Kang II, Improving thermal performance of miniature heat pipe for notebook PC cooling, Microelectron. Reliab. 44 (2002) 135–140, Copyright 2002, with permission from Elsevier.

Figure 8.9 reprinted from S. Murer, P. Lybaert, L. Gleton, A. Sturbois. Experimental and numerical analysis of the transient response of a miniature heat pipe, Appl. Therm. Eng. 25 (2005) 2566–2577, Copyright 2005, with permission from Elsevier.

Figure 8.10 reprinted from Y.F. Maydanik, Loop heat pipes, Appl. Therm. Eng. 25 (2005) 635–657, Copyright 2005, with permission from Elsevier.

Figures 8.37 and 8.38 reprinted from W.W. Wits, F.J.A.M. van Houten, Improving system performance through an integrated design approach, CIRP Ann. Manufact. Technol. 60 (2011) 187–190, with permission from Elsevier.

Nomenclature

A_c	circumferential flow area
A_w	Wick cross-sectional area
C_p	specific heat of vapour, constant pressure
C_v	specific heat of vapour, constant volume
D	sphere density in Blake–Kozeny equation
H	constant in the Ramsey–Shields–Eotvös equation
J	4.18 J/g mechanical equivalent of heat
K	Wick permeability
L	enthalpy of vaporisation or latent heat of vaporisation
M	molecular weight
M	Mach number
M	figure of merit
N	number of grooves or channels
Nu	Nusselt number
Pr	Prandtl number
P	pressure
ΔP	pressure difference
$\Delta P_{c\ max}$	maximum capillary head
ΔP_1	pressure drop in the liquid
ΔP_v	pressure drop in the vapour
ΔP_g	pressure drop due to gravity
Q	quantity of heat
R	radius of curvature of liquid surface
R_o	universal gas constant = 8.3×10^3 J/K kg mol
Re	Reynolds number
Re_r	radial Reynolds number
Re_b	a bubble Reynolds number
S	volume flow per second
T	absolute temperature
T_c	critical temperature
T_v	vapour temperature
ΔT_s	superheat temperature
T_w	heated surface temperature
V	volume
V_c	volume of condenser
V_R	volume of gas reservoir
We	Weber number
a	groove width
a	radius of tube
b	constant in the Hagen–Poiseuille equation
c	velocity of sound

Nomenclature

d_a	artery diameter
d_w	wire diameter
f	force
g	acceleration due to gravity
g	heat flux
g_c	Rohsenhow correlation
h	capillary height, artery height, coefficient of heat transfer
k	Boltzmanns constant $= 1.38 \times 10^{-23}$ J/K
k_w	Wick thermal conductivity – k_s solid phase, k_l liquid phase
l	length of heat pipe section defined by subscripts, Section 2.3.4
l_{eff}	effective length of heat pipe
m	mass
m	mass of molecule
m	mass flow
n	number of molecules per unit volume
r	radius
r	radial co-ordinate
r_e	radius in the evaporator section
r_c	radius in the condensing section
r_H	hydraulic radius
r_v	radius of vapour space
r_w	Wick radius
u	radial velocity
v	axial velocity
y	co-ordinate
z	co-ordinate
α	heat transfer coefficient
β	defined as $(1 + k_s/k_l)/(1 - k_s/k_l)$
δ	constant in Hsu formula – thermal layer thickness
ε	fractional voidage
θ	contact angle
ϕ	inclination of heat pipe
ϕ_c	function of channel aspect ratio
λ	characteristic dimension of liquid–vapour interface
μ	viscosity
μ_l	dynamic viscosity of liquid
μ_v	dynamic viscosity of vapour
γ	ratio of specific heats
ρ	density
ρ_l	density of liquid
ρ_v	density of vapour
σ	σ_{LV} used for surface energy where there is no ambiguity
σ_{SL}	surface energy between solid and liquid
σ_{LV}	surface energy between liquid and vapour
σ_{SV}	surface energy between solid and vapour

Other notations are as defined in the text.

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. I.1(a). 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 vaporise 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. I.1(b)). 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 I.1. A review of techniques is given by Roberts [4], and others are discussed by Reay [5], Jeyadeven et al. [6] and Maydanik [7].

I.1 THE HEAT PIPE – CONSTRUCTION, PERFORMANCE AND PROPERTIES

The main regions of the standard heat pipe are shown in Fig. I.2. In the longitudinal direction (see Fig. I.2(a)), 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 the condenser. The cross section of the heat pipe, Fig. I.2(b), 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. I.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

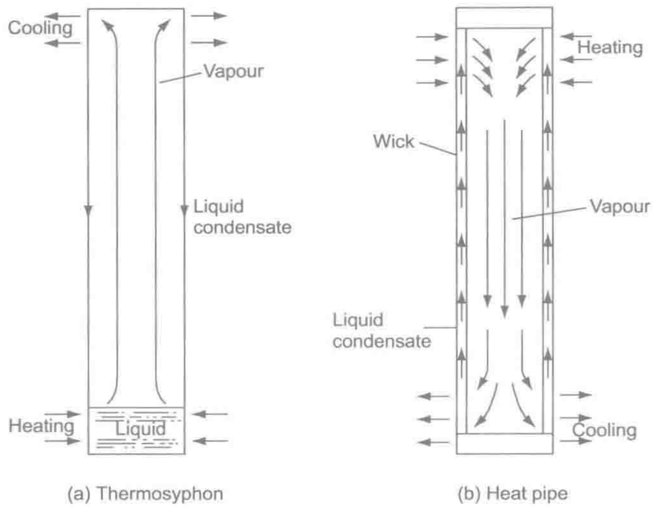


Figure I.1 The heat pipe and thermosyphon.

Table I.1

Methods of Condensate Return

Gravity	Thermal syphon
Capillary force	Standard heat pipe LHP
Centripetal force	Rotating heat pipe
Electrokinetic forces	Electrohydrodynamic heat pipe Electro-osmotic heat pipe
Magnetic forces	Magnetohydrodynamic heat pipe Magnetic fluid heat pipe
Osmotic forces	Osmotic heat pipe
Bubble pump	Inverse thermal syphon

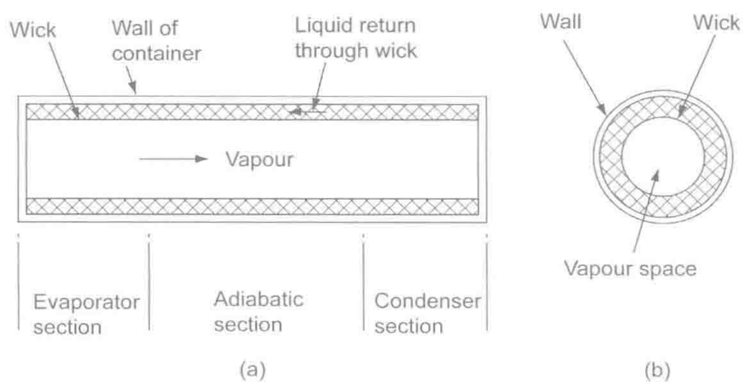


Figure I.2 The main regions of the heat pipe.

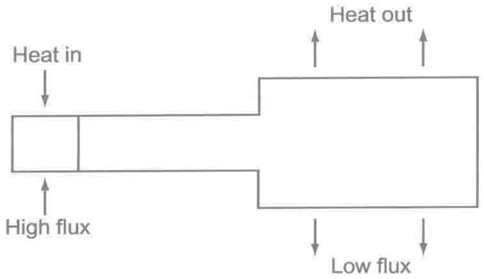


Figure I.3 The heat pipe as a thermal flux transformer.

fluid and container materials, it is possible to construct heat pipes for use at temperatures ranging from 4 K to in excess of 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 the following:

i. Very high effective thermal conductance
ii. The ability to act as a thermal flux transformer. This is illustrated in Fig. I.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

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

iv. Variable thermal impedance

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 that is arranged to have a pressure corresponding to the saturation vapour pressure of the fluid in the heat pipe. In normal operation, the 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. The vapour pressure increases very rapidly for very small increases in temperature, for example the vapour pressure of sodium at 800°C varies as the 10th 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 a temperature-sensing element placed in the heat source:

v. Loop heat pipes

The loop heat pipe (LHP), illustrated in Fig. I.4, comprises an evaporator and a condenser, as in conventional heat pipes, but differs in having separate vapour and liquid lines, rather like the layout of the single-phase heat exchanger system used in buildings for heat recovery,

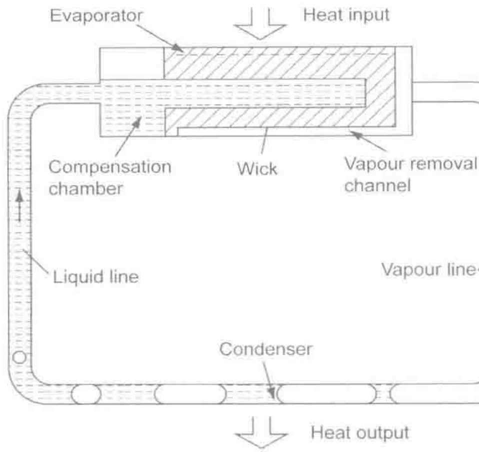


Figure I.4 LHP [7].

the run-around coil. Those who recall the technical efforts made to overcome liquid–vapour entrainment in heat pipes and, more importantly, in thermosyphons will know that isolation of the liquid path from the vapour flow (normally counter-current) is beneficial. In the LHP, these flows are co-current in different parts of the tubing.

A unique feature of the LHP is the use of a compensation chamber. This two-phase reservoir helps to establish the LHP pressure and temperature, as well as maintain the inventory of the working fluid within the operating system. The LHP, described fully in Chapter 6, can achieve very high pumping powers, allowing heat to be transported over distances of several metres. This overcomes some of the limitations of other 'active' pumped systems that require external power sources.

vi. Thermal diodes and switches

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

vii. Pulsating or oscillating heat pipes

The pulsating heat pipe (PHP, sometimes called the oscillating heat pipe (OHP)), discussed in Chapter 6, is like the LHP, a relative newcomer to the heat pipe field, but one that is receiving substantial attention because of its lack of reliance on capillary action. The PHP consists of a long, small diameter, tube that is 'concertined' into a number of U-turns. There is no capillary structure within the tube, and the liquid distributes itself in the form of slugs between vapour sections, as shown in Fig. I.5. Heat transfer is via the movement (oscillation) of the liquid slugs and vapour plugs between the evaporator and the condenser.

The oscillation of the slug, in this case in a single tube at different times, is shown. The time step between two frames is equal to 20 ms. The authors [8] state: 'Advancing and receding menisci refer to the liquid plug motion: advancing corresponds to the leading edge and receding to the tail of the liquid plug. Enlargements (a), (b) and (c) show a strong dissymmetry of left and right interfaces: the curvature radius of advancing menisci (right interface in (a) and left interface in (c)) is smaller than that of receding menisci. This dissymmetry is a view of the pressure difference between both sides of the liquid slug. In case (b), the interface velocity is equal to zero and the liquid slug is then symmetric.'

Increasingly in the literature, one notes the addition of nanoparticles, to create nanofluids, in an attempt to improve the performance of most of the above types of heat pipe or thermosyphon. Some examples are given elsewhere in the text, but the word 'nano' does not in our opinion warrant its use in a new category of heat pipe. A nano-sized heat pipe would be a different kettle of fish, however (as would a carbon nanotube heat pipe).