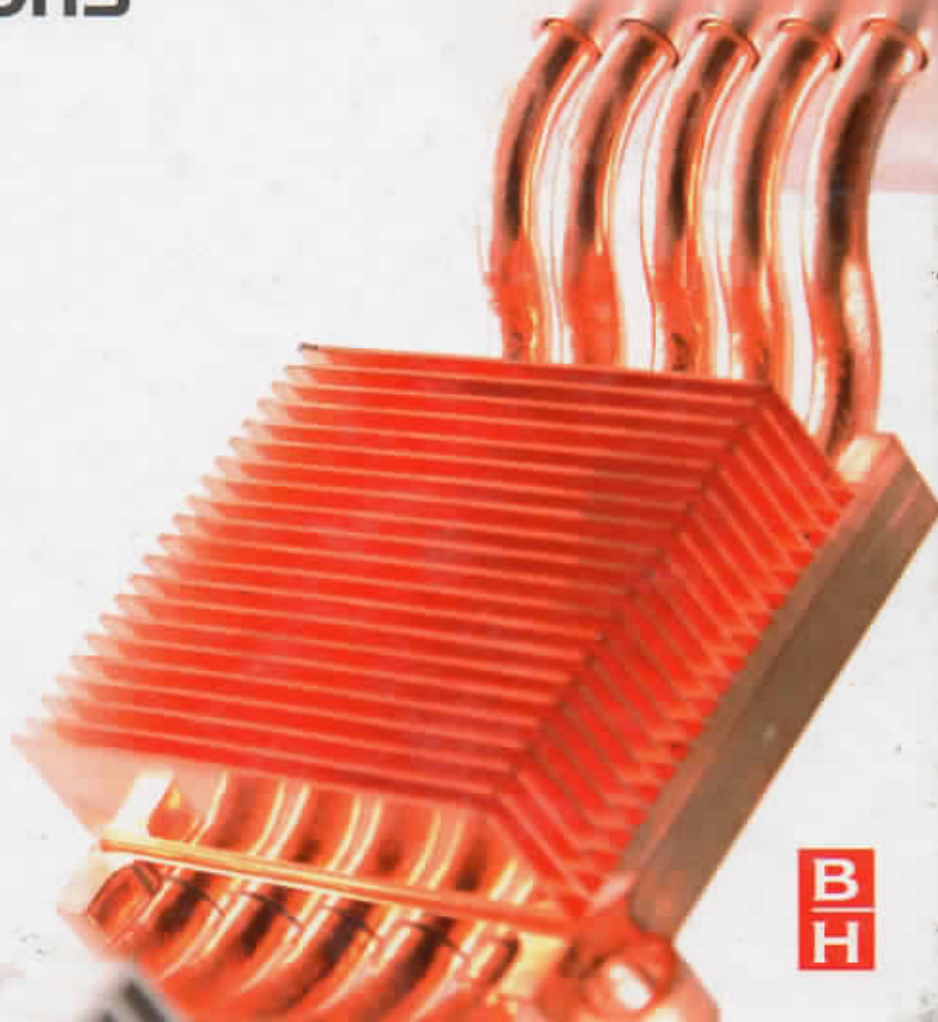


David Reay | Peter Kew | Ryan M^cGlen

Sixth Edition

Heat Pipes

Theory, Design and Applications



B
H

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



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

Butterworth-Heinemann is an imprint of Elsevier



Contents

Preface to sixth edition	ix	7. Applications of the heat pipe	175
Preface to first edition.....	xi	8. Cooling of electronic components.....	207
Acknowledgements	xiii	Appendix 1	
Nomenclature.....	xix	Working fluid properties	227
Introduction	xxi	Appendix 2	
		Thermal conductivity of heat pipe	
1. Historical development.....	1	container and wick materials	239
2. Heat transfer and fluid flow theory	15	Appendix 3	
3. Heat pipe components		A selection of heat-pipe-related	
and materials.....	65	web sites.....	241
4. Design guide.....	95	Appendix 4	
5. Heat pipe manufacture		Conversion Factors.....	243
and testing	105	Index	245
6. Special types of heat pipe	135		

Index

Note: Page numbers followed by "f" and "t" refer to figures and tables, respectively.

A

- A. Reyrolle Switchgear Company, 209
- Absolute viscosity, 20
- Acetone, 66t, 97
 - compatibility, 87t
 - cracking, 86
 - merit no., 98f
 - versus temperature, 164f
 - thermosyphons, 52t
 - preparation, 113
 - priming factor, 98f
 - properties, 97t
 - sonic limit, 97
 - superheat, 98
- Advanced Cooling Technologies, Inc., 69
- Aerospatiale, 8
- Air-conditioning units, 7, 177, 181-183
- Aircraft and spacecraft, 187-192
 - aircraft avionics thermal control, 191-192
 - component cooling, temperature control and radiator design, 188-191
 - spacecraft temperature equalisation, 188
- Alcatel Space, 8, 190
- Aluminium, 106
 - compatibility, 82t, 87t
 - water, 90
 - outgassing, 112
 - wire mesh, 107
- Alyeska Pipeline Service Company, 196
- Ames Heat Pipe Experiment, 189
- Ammonia, 66t, 73t, 84, 97
 - compatibility, 87t
 - gas bubbles
 - half life, 117t
 - venting time, 117t
 - heat transfer coefficient, 80
 - interfacial heat flux, 43t
 - merit no., 67f, 98f
 - thermosyphons, 52t
 - preparation, 113
 - priming factor, 98f
 - properties, 34t, 97t
 - sonic limit, 97
 - superheat, 98
 - thermal resistance, 80
- Amporcop, 74t
- Ampornik, 74t
- Applications, 175
 - aircraft and spacecraft, 187-192
 - Apollo, 189
 - component cooling, temperature control and radiator design, 188-191
 - International Space Station, 189
 - qualification plan, 125-126
 - Space Shuttle, 8, 8f, 188-189
 - temperature equalisation, 188
 - chemical reactors, 184-187
 - adsorption reactions, 184-185
 - Fischer-Tropsch-type, 185
 - operation curves, 186
 - solar-powered dehydrogenation reactor, 187f
 - stirred pot type, 184
 - tube wall type, 184
 - electronics cooling
 - cooling of concentrated heat source, 218
 - flexible heat pipes, 217-218
 - multi-kilowatt heat pipe assembly, 218, 218f
 - energy conservation and renewable energy, 193-196
 - heat pipe turbine, 195-196
 - solar energy, 196
 - energy storage systems, 176-184
 - food industry, 199-203
 - chilled food display cabinets, 200-201
 - cooking, cooling and defrosting meat, 201-203
 - Perkins tube, 1-2
 - permafrost preservation, 197
 - temperature control, 175-176, 188-191
- Arcton 11
 - merit no., 98f
 - priming factor, 98f
- Arcton 21, 163-164
 - merit no. versus temperature, 164f
 - merit no. versus temperature, 164f
- Arcton 113, 163-164
 - merit no., 98f
 - priming factor, 98f
- Arrhenius model, 124
- Arterial diameter, 99
- Arterial wicks, 6f, 23f, 77-78, 100
 - gas bubbles in, 116-117
- Astrium, 8, 77
- Atherm, 108-109
- Automated Transfer Vehicle (ATV), 191
- Axial dry-out, 49
- Axial Reynolds number, 24, 101
- Axial rotating heat pipes, 166
- Axial vapour mass flux, 52
- Azimuthal dry-out, 49

B

- Baking ovens, use of Perkins tube in, 3-4
- Base fluid, 53-55
- Bearings, cooling of, 203

- Beijing University School of
Aeronautical Science and
Engineering, 191
- Bellows control, 136–137
- Bent and flattened heat pipes, 211
- Benzene, 83
- Biological heat pipes, 157
- Bi-porous wicks, 77, 77f, 109
- Bismuth, compatibility, 85f
- Blake–Kozeny equation, 23, 99
- Blasius equation, 22, 102
- Boiling
nucleate, 33, 35–36
from plane surfaces, 32–36
from wicked surfaces, 36–41
- Boltzmann constant, 124
- Bond number, 52, 52f, 144
- British Aircraft Corporation, 7
- Brown Boveri, 7, 109
- Bubble nucleation, 33–34
- Buffalo River heated bridge, 199
- Building Product Design Ltd,
183, 184
- Burnout, 45–48
correlations, 17, 36
test, 126
- C**
- Cadmium, merit no., 67f
- Caesium, 66f
compatibility, 85f
merit no., 67f
- Caesium, properties of, 19f
- Capillary (wicking) limit, 45, 97–98
- Capillary heat loops, 156
- Capillary paths, 10f
- Capillary pressure, 20, 102
- Capillary pumped loops, 16, 77,
149–156
compensation chamber, 150–151
dimensions of, 154f
geometric characteristics, 154f
performance, 155f
- Capillary structures. *See* Wicks
- Car passenger compartment heating,
203
- Carbon fibre wicks, 76
- Carbon steel, compatibility, 87f
- Central processors, cooling of, 9
- Ceramic wicks, 80–81
- Chemical heat pipes, 187
- Chemical reactors, 184–187
adsorption reactions, 184–185
Fischer–Tropsch-type, 185
operation curves, 186
solar-powered dehydrogenation
reactor, 187f
- stirred pot type, 184
tube wall type, 184
- Chilled food display cabinets, 200–201
- Chlorofluorocarbons (CFCs), 10–11
- Choked flow, 29
- Circumferential liquid distribution,
99–100
- Clapeyron equation, 17, 42–43, 50
- Cleaning, 111
liquid metal heat pipes, 118–120
wicks, 111
- Closed end oscillating heat pipes,
144–146
- Closed loop pulsating heat pipes,
143–146
- Coefficient of performance, 196
- Cold reservoir VCHPs, 136
- Cold welding, 115, 115f
- Combined pulsating and capillary
transport system, 217
- Compatibility, 81–90. *See also*
individual working fluids
historical data, 82–86
testing, 69f, 124
water and steel, 86–90
- Compensation chamber, 149–151,
150f
- Component cooling, spacecraft,
188–191
- Components and materials, 65
- Composite wicks, 22, 24, 109
- Compressible flow, 28–30
- Computational fluid dynamics, 30
- Concentric annulus, 80
- Concentric tube boiler, 1–2
- Condensate return, 3
- Condensation, 43
- Condensers, heat transfer in, 43
- Containers
cleaning, 111
materials, 81. *See also individual*
materials
manufacture and testing, 106
- Coolout, 129
- Coopers correlation, 38, 156
- Copper, 74f, 106
compatibility, 82f, 87f
foam, 74f
powder, 74f
wicks, 157f
sintered, 153f
- Corona wind cooling, 162
- Corrugated screen wicks, 23f
- Cotter's micro-heat pipe, 158f
- Counter-current flow limit, 11
- CP-32, 84
- CP-34, 84
- Crimping, 115, 115f, 116f
- Critchley–Norris car radiator, 4, 4f
- Critical heat flux, 33, 38
- Cryo-anchors, 197
- Cryogenic fluids, 72
- Cryogenic heat pipes, 121, 128
- Curved surfaces
change in vapour at, 18
pressure difference across, 17–18
- D**
- Darcy's law, 23
- David Reay & Associates, 184
- Density ratio, 30
- Design, 95
heat pipes, 95–96
arterial diameter, 99
arterial wick, 100
circumferential liquid distribution
and temperature difference,
99–100
entrainment limit, 97
fluid inventory, 95
materials and working fluid,
96–99
prediction of performance,
100–102
priming, 95–96
radial heat flux, 98
sonic limit, 97
specification, 96
wall thickness, 98
wicking limit, 97–98
wick priming, 98
wick selection, 99
thermosyphons, 103–104
entrainment limit, 104
fluid inventory, 103
- Diecasting, thermal control, 203
- Diphenyl, 68, 69f
- Diphenyl oxide, 69f
- Direct contact systems, 215–216
- Disc heat pipe, 165–166
- Distillation, 119
- Dornier, 8
- Dow Chemical Company, 68, 82
- Dowtherm A., 86, 161
compatibility, 87f
- Drills, cooling, 203
- Dry-out, 49
- Dynatherm Corporation, 7, 185
- Dynamic viscosity, 20
- E**
- E911 emergency location detection
service, 218–219
- Earth, as heat sink, 178

- Effective pore radius, 18, 19f
 Electric batteries, thermal control, 203
 Electrical feedback control, 137–138
 Electrically isolated heat pipes, 209–210
 Electrohydrodynamics, 160–163
 Electrokinetic forces, 160–163
 Electrokinetics, 10, 160
 Electron beam welding, 112
 Electronics cooling, 207
 applications
 cooling of concentrated heat source, 218
 flexible heat pipes, 217–218
 multi-kilowatt heat pipe assembly, 218, 218f
 bent and flattened heat pipes, 211
 direct contact systems, 215–216
 electrically isolated heat pipes, 209–210
 embedded heat pipes, 210
 emerging/future heat pipe technologies, 221–224
 heat pipe integrated into PCB, 222–224
 integrated high power thermal management, 222
 thermal ground plane, 221–222
 flat plate heat pipes, 210–211
 loop heat pipes, 212–214
 microheat pipes and arrays, 211–212
 pulsating heat pipes, 214
 sheet heat pipes, 216–217
 tubular heat pipes, 209–210
 vapour chamber heat pipe, 211
 Electro-osmosis, 10, 160
 Embedded heat pipes, 210
 Emerging/future heat pipe technologies, 221–224
 heat pipe integrated into PCB, 222–224
 integrated high power thermal management, 222
 thermal ground plane, 221–222
 End caps, 106
 fitting, 112
 Energy conservation and renewable energy, 193–196
 heat pipe turbine, 195–196
 solar energy, 196
 Energy storage systems, 176–184
 nuclear reactors and storage facilities, 178–180
 phase change stores, 181–184
 reasons for using heat pipes, 177
 sensible heat storage devices, 177–178
 tunnel structures and earth as heat sink, 178
 Engineering Sciences Data Unit, 80
 Entrainment limit, 44
 heat pipes, 30–31, 97
 thermosyphons, 16, 52
 Entrainment limited axial flux, 31
 Environmental Process Systems Ltd, 184
 Eötvös–Ramsay–Shields equation, 19
 Ethanol, 66t, 73t
 interfacial heat flux, 43t
 merit no., 67f
 versus temperature, 164f
 properties of, 34t
 European Space Agency, 8, 122, 188
 heat pipe qualification plan, 125–126
 European Space Organisation, 77
 Eutectic mixtures, 68
 Evaporator length, 144
 'Ever full' water boiler, 1
- F**
 Faculty of Engineering and Environment of Northumbria University, Newcastle, 121
 Fanning equation, 22, 26
 Fanning friction factor, 22
 Feedback control, 137–140
 comparison of systems, 139–140
 electrical, 137–138
 mechanical, 138–139
 Felt metal wicks, 74t
 Felts, 72, 110–111
 Filling, 113–115
 liquid metal heat pipes, 118–119
 procedure, 114–115
 Filling rig, 114
 Filling tube, 106
 Flat plate heat pipes, 108, 210–211
 Flexible heat pipes, 217–218
 Flooding limit, 45, 52. *See also* Entrainment limit
 Flow
 choked, 28–29
 laminar, 20–22
 turbulent, 20–22
 in wicks, 22–24
 Fluid inventory
 heat pipes, 95–96
 rotating heat pipes, 165
 thermosyphons, 103
 Fluids and materials, 10–11
 Flutec PP2, 66t
 Flutec PP9, 66t
 FM1308, 40, 41t
 Foams, 72, 110–111
 Food industry, 199–203
 chilled food display cabinets, 200–201
 cooking, cooling and defrosting meat, 201–203
 Food Refrigeration and Process Engineering Centre, Bristol University, 201
 Foster Wheeler, US Patent 4315893, 185
 Freeze-degassing, 113, 115
 Freon
 heat transfer coefficient, 80
 thermal resistance, 80
 Freon 11, 6–7, 97
 properties, 97t
 sonic limit, 97
 superheat, 98
 Freon 113, 97
 heat transfer coefficient, 80
 properties, 97t
 sonic limit, 97
 superheat, 98
 thermal resistance, 80
 Furukawa Company, 158–159
 Furukawa Electric, 216
 Fuzzy Incremental Control (FIC) strategy, 191
- G**
 Gas bubbles, 116–117
 half lives, 117t
 venting time, 117t
 Gas turbine blades, cooling of, 203
 Gas–gas heat pipe exchanger, 193
 Gaugler, R.S., 4–5
 Gay, F.W., 3
 GE Global Research Centre, 78
 General Electric, 187
 General Motors Corporation, US Patent 2350348, 4–5
 GEOS-B satellite, 6–7
 Gettering, 120
 Glass fibre wicks, 74t
 Glauber's salt, 182
 Goddard Space Flight Center, 9
 Gravitational head, 16
 Gravitational pressure drop, 102
 Gravity-assisted heat pipes, 48–50
 Grenoble Nuclear Research Centre, 7
 Grooved wicks, 79–80
 manufacture, 109–110
 Grumman Aerospace, 189

H

- Hagen-Poiseuille equation, 21–23, 25–26, 101
- Hairpin thermosyphons, 197
- Heat flux, 122
- critical, 33, 38
- effect of, 124
- interfacial, 43t
- maximum, 52–53
- radial, 46t, 73t, 98
- transformation, 176, 198–199
- variation in, 46f
- Heat pipe cooking pin, 200
- Heat pipe heat exchangers
- gas–gas, 193
- spray bar, 194f
- Heat pipe turbine, 195–196
- Heat pipes, 4–9, 56t. *See also various types*
- applications. *See Applications components and materials*, 65
- filling, 113–115
- loop. *See Loop heat pipes*
- magnetic fluid, 169
- manufacture and testing.
- See Manufacture and testing microheat pipes. See Microheat pipes nanofluids*, 70–72
- operation, 15–16
- polymer, 106
- pulsating (oscillating). *See Pulsating (oscillating) heat pipes*
- rotating. *See Rotating heat pipes*
- sealing, 115
- sorption, 168–169
- switches, 142
- thermal diodes, 140–142, 176
- variable conductance. *See Variable conductance heat pipes*
- wall, 123
- Heat spreading, 210
- Heat storage units, 177–178
- Heat transfer, 31–32
- boiling
- from plane surfaces, 32–36
- from wicked surfaces, 36–41
- condenser, 43
- evaporator region, 32
- liquid–vapour interface temperature drop, 42–43
- rotating heat pipes, 164–165
- wick thermal conductivity, 43
- Heat transfer coefficients, 41t, 80
- Heat transport limitations, 16f
- Heat-pipe-cooled dipstick, 203
- Helium, 66t, 73t
- Heptane, 66t

- Heriot-Watt University, UK, 130
- Hermetic tube boiler, 1–2
- Hiroshima Machine Tool Works, 167
- Historical development, 1
- Hoke bellows valves, 113
- Homogeneous wicks, 23, 72–77
- Hot-reservoir VCHPs, 137
- Hubble Space Telescope, 8, 190
- Hughes Aircraft Co., 86
- compatibility recommendations, 87t
- US Patent 4673030, 181
- Hydrofluorocarbons (HFCs),
- Hydrogen generation, 88

I

- Ice 'island' drilling platforms, preservation of, 203
- Impinging water jet cooling system, 9f
- Incompressible flow, 24–26
- one-dimensional, 26
- two-dimensional, 28
- Inconel 600, 118
- compatibility, 87t
- Inert gases, 116–117
- diffusion at vapour/gas interface, 116
- gas bubbles in arterial wicks, 116–117
- In-flight entertainment systems (IFEs), 191–192
- Inhibitors, 89–90
- Injection moulding, thermal control, 203
- Institut für Kernenergetic, Stuttgart, 7, 68, 83
- Integrated high power thermal management, 222
- Intel Corporation, 217
- International Heat Pipe Conferences, 11
- International Space Station, 189
- Intrachip/Interchip Enhanced Cooling (ICECool) research programme, 207
- Inverse thermosyphon, 8–9
- Inverted meniscus hybrid wicks, 47f
- Isothermalisation, 175, 176f
- Itoh's micro-heat pipe, 158, 158f

J

- Jacob number, 143–144
- Jäger's method for surface tension measurement, 19f
- Jet Propulsion Laboratory, 9, 124
- Joint Nuclear Research Centre, Ispra, 5, 7, 70

K

- Karlsruhe Nuclear Research Centre, 7
- Karman number, 143–144
- Kinetic energy, 22
- Kisha Seizo Kaisha Company, 7
- Kutateladze number, 52, 54t, 144–146
- Kyushu Institute of Technology, 9

L

- Laminar flow, 20–21
- Hagen-Poiseuille equation, 21–22
- Lampore 7.4, 40t
- Latent heat of vaporisation, 16–17, 67
- Lavochkin Association, 190
- Leaching, 76
- Lead
- compatibility, 85t
- Leak detection, 112–113
- Leidenfrost Point, 33
- Lewis Research Centre, 149
- Life test procedures, 122–126
- compatibility, 124
- effect of heat flux, 124
- effect of temperature, 124
- heat pipe wall, 123
- performance prediction, 124–125
- variables, 122–123
- wick, 123
- working fluid, 122
- Life test programme, 125
- Liquid blockage diodes, 140, 140f
- Liquid metal heat pipes, 118
- cleaning and filling, 118–119
- gettering, 120
- operation, 119–120
- safety, 120
- sealing, 119
- temperature range 500–1000°C, 118–120
- temperature range >1200°C, 120
- Liquid metals, 48, 70
- Liquid trap diodes, 140, 140f
- Liquid–vapour interface, temperature drop, 42–43
- Lithium, 66t, 73t, 120
- compatibility, 85t
- interfacial heat flux, 43t
- merit no., 67–68, 67f
- properties of, 19t, 34t
- Lockhart–Martinelli correlation, 155
- Lockheed Martin Space Systems, 117
- London South Bank University, 178, 200–201
- London underground, 178
- Longitudinal groove wicks, 24
- Loop heat pipes, 16, 149–156

- classification, 152
 compensation chamber, 149–151, 150f
 electronics cooling, 212–214
 evaporator, 149
 thermodynamic cycle, 150–151
 Loop thermosyphon, 212–213
 Los Alamos Laboratory, 5, 84
 Luikov Heat and Mass Transfer Institute, 177
- M**
- Mach number, 24, 30
 Magnesium, 70
 merit no., 67f
 Magnetic fluid heat pipes, 169
 Manufacture and testing, 105
 cleaning of container and wick, 111
 container materials, 106
 felts and foams, 110–111
 grooves, 109–110
 microlithography, 109
 quality control, 105
 sintering, 107–109
 vapour deposition, 109
 wick materials and form, 106–111
 wire mesh, 107
 Marconi, 8
 Maximum heat flux, 52–53
 Maxwell's equation, 79
 McDonnell Douglas Astronautics Company, 8
 McDonnell Douglas Corporation, 196
 Meat, cooking, cooling and defrosting, 201–203
 Mechanical feedback control, 138–139
 Mercury, 66t, 70, 73t
 merit no., 67f
 properties of, 19t
 wetting, 70
 Merit no.,
 versus temperature, 164f
 thermosyphons, 52t
 Meshes, 78–79
 Metal halides, 68
 Methanol, 66t, 73t
 compatibility, 87t
 gas bubbles
 half life, 117t
 venting time, 117t
 merit no., 67f
 versus temperature, 164f
 thermosyphons, 52t
 Micro-electro mechanical system (MEMS), 191
 Microfluidic pumps, 10
 Microheat pipes, 156–160, 208
 Cotter's, 158
 electronics cooling, 212
 Itoh's, 158, 158f
 tapered, 159f
 Microlithography, 109
 Microscale technology, 10–11
 Mini-heat pipes, 157
 Mitsubishi Electric Corporation, 198
 Modular high temperature reactors, 178
 Monel beads, 74t
 Monogroove heat pipe, 78, 78f, 189
 Multiple wicks, 189
- N**
- Nanjing University of Technology, 185
 Nanofluids, 11, 53–59
 Nanoparticles, 11
 Naphthalene, 68, 69t
 NASA, 9
 Glenn Research Centre, 68–69
 National Engineering Laboratory (TUV-NEL), 7
 National Space Observatory, 188
 Navier–Stokes equation, 26
n-butane, 84
 New York City Transit Authority, 178
n-Heptane, 83
 Nickel, 74t
 cleaning, 111
 compatibility, 82t, 87t
 felt, 74t
 fibre, 74t
 foam, 74t
 powder, 74t
 wicks, 157t
 sintered, 153t
 Nitrogen, 66t, 73t
N-Octane, 69t
 Noren Products, 8
n-Pentane, 83
 Nuclear reactors, 178–180
 Nucleate boiling, 33, 35–36
 Nusselt number, 162, 162f
 Nusselt theory, 43
- O**
- Open channel wick, 23f
 Operating limits
 capillary (wicking), 45
 entrainment, 44
 sonic, 44
 viscous/vapour pressure, 44
 Optomicrofluidics, 163
 Oregon Institute of Technology, 198
 Oscillating heat pipes, 146–147
 Ostwald coefficient, 117
 Outgassing, 111–112
- P**
- Parachor, 19
 Particle accelerators, cooling of targets, 203
 Passivation of mild steel, 88
 Patents, 2–3
 Pentane, 66t
 Performance
 capillary pumped loops, 155f
 coefficient of, 196
 prediction of, 100–102, 124–125
 Performance tests, 126–131
 copper heat pipe, 129–130
 test procedures, 128–129
 test rig, 127–128
 on thermosyphons, 130–131
 Perkins, Angier March, 1
 Perkins, Jacob, 1
 Perkins tube, 1–2
 applications, 2
 baking ovens, 3–4
 patents, 2–3
 Permafrost preservation, 197
 Phase change materials, 177
 Phase change stores, 181–184
 air-conditioning systems, 181–183
 field trials, 183
 system advantages, 183–184
 Phosphor/bronze, 74t
 Pirani head, 114
 Pitzer acentric factor, 53
 Plastic, 82
 Plug sealing, 119, 119f
 Pole-mounted telecom server heat pipe assembly, 219–221
 Polyethylene terephthalate (PET) plastic film, 106
 Polymers, 77, 106
 Pore size of wicks, 74t
 Potassium, 66t, 73t
 burnout, 42f
 compatibility, 85t, 87t
 critical flux, 40f
 heat transfer coefficients, 41t
 merit no., 67f
 properties of, 19t, 34t
 Prandtl number, 143–144
 Pressure difference
 across curved surfaces, 17–18
 due to friction, 20–22
 in liquid phase, 22–23
 Pressure recovery, 26–28
 Priming, 95–96
 Printed circuit boards (PCBs), 207

- Printed circuit boards (PCBs)
(Continued)
 heat pipe integrated into, 222–224
- Printed circuit boards, 207
- Protective layer, 88
- Pulsating (oscillating) heat pipes,
 142–149, 214
 closed, 143
 evaporator length, 144
 filling ratio, 144
 internal diameter, 144
 maximum heat flux, 144–146, 146f
 operating zones, 144f
 working fluid, 144
- Q**
- Quality control, 105
- R**
- R134a, 130–131
- Radial heat flux, 73r
 heat pipes, 98
 wicks, 46t
- Radial Reynolds number, 24, 25f,
 26–28
- Radial rotating heat pipe, 168
- Radioactive waste, 178
- Raney catalyst, 184
- Rayleigh's equation, 78–79
- RCA, 5, 8
- Reaction activation energy, 124
- Rectangular heat pipes, 7
- Refrasil, 74t, 110
 compatibility, 82r
 sleeving, 74r
- Refrigeration units, 4–5, 5f
- Remote weather station equipment,
 passive cooling, 203
- Reynolds number, 20–21
- Rhenium, 120
- Rocol HS, 112
- Rohsenow correlation, 35–36
- Roll-bond panels, 203
- Rotating heat pipes, 7, 163–168
 applications, 165–167
 heat transfer capacity, 164–165
 microrotating, 167–168
- Royal Aircraft Establishment, 7
- Rubidium, merit no., 67f
- Rutherford High Energy Laboratory,
 7–8
- S**
- SABCA, 8
- Safety, 120–121
- Satellites, 6–7. *See also* Spacecraft
 isothermalisation, 175, 176f
- Screen wick, 23f
- Sealing, 115
 liquid metal heat pipes, 119
- Selective Laser Sintering/Melting
 (SLS/SLM), 121
- Semi-automatic welding equipment,
 cooling of, 203
- Sensible heat storage devices,
 177–178
- Sest Inc., 84–86
- Shear stress, 20
- Sheet heat pipes, 216–217
- Silica, compatibility, 87r
- Silver, 66t, 73t, 120
 compatibility, 85t
- Sintered metal fibres, 80
- Sintered powders, 76
- Sintered wicks, 79, 153t
- Sintering, 107–109
- Snow melting and deicing, 198–199
- Sodium, 66t, 73t, 84–86, 118
 compatibility, 85t, 87r
 critical flux, 38–39
 interfacial heat flux, 43t
 merit no., 67f
 properties of, 19t, 34r
- Soil thermal conductivity, 178, 179f
- Solar collectors, 177
- Solar energy, 196
- Solar-powered dehydrogenation reactor,
 187f
- Soldering iron bit, cooling of, 203
- Sonic limit, 44, 97
- Sony Corporation, 8
- Sorption heat pipe, 168–169
- Source–sink separation, 176
- Space Shuttle, 8, 8f, 188–189
- Spacecraft, 187–192
 Apollo, 189
 component cooling, temperature
 control and radiator design,
 188–191
 International Space Station, 189
 qualification plan, 125–126
 Space Shuttle, 8, 8f, 188–189
 temperature equalisation, 188
- Spinning disc reactor, 165–166, 167f
- Stainless steel, 82, 106
 cleaning, 111
 compatibility, 82t, 87r
 water, 86–90
 wire mesh, 107
- Start-up procedures, 90–91
- STENTOR, 8
- Stirling Converter, 84–86
- Stirling coolers, 140–141
- Surface tension, 16–20, 67–68
 measurement of, 18–19
 metals, 19, 19r
 pressure difference across curved
 surface, 17–18
 temperature dependence, 19
- Swales Aerospace, 190, 190f, 191f
- Sweat glands, 156–157, 157f
- Switches, 142
- T**
- Tapered micro-heat pipe, 159f
- Temperature control, 176
 aircraft and spacecraft, 187–192
- Temperature difference, 31–43,
 99–100. *See also* Heat transfer
 liquid–vapour interface, 42–43
 total temperature drop, 50–51
- Temperature effect, 124
- Temperature flattening, 210
- Thales Avionics, 191–192
- Therma-Base, 108
- Thermacore Europe, 184
- Therma-core heat spreader, 108f
- Thermacore Inc., 84–86, 121,
 207–208, 217–221
- Thermal conductivity, 67, 175–176
 of soil, 178
 wicks, 43, 79
- Thermal diodes, 140–142, 176
 liquid blockage, 140, 140f
 liquid trap, 140, 140f
 wall panels, 141f
- Thermal ground plane, 221–222
- Thermal resistance, 50t, 51t, 52–53
- Thermal switches, 142
- Thermex, 66r
- Thermoelectric generators, thermal
 control, 203
- Thermo-Electron, 8
- Thermosyphon heat exchanger, 3f
- Thermosyphon loop, 153–156
- Thermosyphon Rankine engine.
 See Heat pipe turbine
- Thermosyphons, 1, 16, 52–53, 197
 closed two-phase, 96
 design, 103–104
 entrainment limit, 104
 fluid inventory, 103
 entrainment limit, 52
 hairpin, 197
 inverse, 8–9
 nanofluids in, 71–72
 thermal resistance and maximum
 heat flux, 52–53
 working fluid section, 52
- 3D printed heat pipes, 121–122

- Titanium, 74t
 compatibility, 87t
 wicks, 157t
 sintered, 153t
- Tokyo Electric Power Company, 139
- Toluene, 66t, 69t, 83–84
 merit no., thermosyphons, 52t
- Total temperature drop, 50–51
- Trans-Alaska pipeline, 196
- Transitional load, 102
- Travelling wave tubes, 188–189
- Tubular heat pipes, 209–210
- Tungsten, 120
- Tunnel heat sink effect, 178
- Tunnels, 178
- Turbulent flow, 20–21
 Fanning equation, 22
- U**
- UK Atomic Energy Authority, 68
- UK Atomic Energy Laboratory, 5
- Ultrasonic cleaning bath, 111
- Unidirectional heat pipe, 189
- University of Houston, 185
- University of Liverpool, UK, 121
- University of Nottingham, EcoHouse,
 183, 183f
- Ural Polytechnic Institute, 149
- US Air Force Research Laboratory, 208
- US Atomic Energy Commission, 5
- V**
- Vacuum rigs, 113
- Vapour chamber heat pipe, 211
- Vapour deposition, 109
- Vapour phase pressure difference,
 24–30
 compressible flow, 28–30
 incompressible flow, 24–26
 one-dimensional, 26
 two-dimensional, 28
 pressure recovery, 26–28
- Vapour plating, 109
- Vapour pressure, 15, 18, 67
 change at curved surface, 18
- Vapour temperature, 101–102
- Vapour/gas interface, 116
- Variable conductance heat pipes, 7–8,
 117, 135–140, 191
 applications
 aircraft and spacecraft, 187–192
 nuclear reactors, 178–180
 temperature control, 175–176,
 184, 189
 cold reservoir, 136
 feedback control, 137–140
 comparison of systems, 139–140
 electrical, 137–138
 mechanical, 138–139
 hot reservoir, 137
 passive control using bellows,
 136–137
- VCHPs. *See* Variable conductance
 heat pipes
- Viscosity number, 31
- Viscous/vapour pressure limit, 44
- W**
- Wall superheat, 33
- Wall thickness, 98
- Warwick University, 184–185, 185f, 186f
- Water, 66t, 73t, 84
 burnout, 42f
 compatibility, 87t
 aluminium, 90
 steel, 86–90
 gas bubbles
 half life, 117t
 venting time, 117t
 interfacial heat flux, 43t
 merit no., 67f
 versus temperature, 164f
 thermosyphons, 52t
 properties of, 34t
- Weber number, 31
- Wetting, 17, 17f, 67
- Wicked heat pipes, 15–16, 43–51
 burnout, 45–48
 gravity-assisted, 48–50
 merit number, 43–44
 operating limits, 44–45
- Wicked surfaces, boiling from, 36–41
- Wicking limit, 45, 97–98
- Wickless heat pipe, 7f
- Wicks, 4–5, 72
 arterial, 6f, 23f, 77–78, 100
 gas bubbles in, 116–117
 bi-porous, 77, 77f, 109
 carbon fibre, 76
 ceramic, 80–81
 characteristics, 157t
 cleaning, 111
 composite, 24, 109
 corrugated screen, 23f
 design of, 100
 dry-out, 49
 fitting, 112
 flow in, 22–24
 forms, 76f, 106–111
 open channel, 23f
 screen, 23f
 grooved, 79–80
 manufacture, 109–110
 homogeneous, 23, 72–77
 inverted meniscus hybrid, 47, 47f
 longitudinal groove, 24
 materials, 40t, 74t, 106–111
 FM1308, 40, 41t
 Lamipore 7.4, 40
 multiple, 189
 nonhomogeneous, 24
 permeability, 72, 74t
 pore size, 74t
 priming, 98
 radial heat fluxes, 46t
 selection, 99
 sintered, 79, 153t
 spot welding, 107
 testing, 123
 thermal conductivity, 43, 79
 thermal resistance, 78–81
 thickness, 72
- Wire mesh, 107
- Working fluids,
 compatibility tests, 69t, 124
 gas bubbles
 half life, 116–117
 venting time, 117t
 heat flux, 122
 merit number, 67–68
 nanofluids, 70–72
 preparation, 113
 pulsating (oscillating) heat pipes,
 144
 purity, 122
 requirements for, 66
 selection of, 84
 surface tension, 66–72
 temperature, 122
 testing, 122
 thermal degradation, 67
 thermosyphons, 52
 vapour pressure, 67
- Z**
- Zinc
 interfacial heat flux, 43t
 merit no., 67f