

Verein Deutscher Ingenieure
VDI-Gesellschaft Verfahrenstechnik und Chemieingenieurwesen (GVC)
Editor

VDI Heat Atlas

Second Edition

With 1011 Figures and 539 Tables

Table of Contents

| | |
|---|------|
| List of Contributors | xvii |
| A Symbols, Units and Dimensionless Numbers | |
| A1 Symbols and Units | 3 |
| <i>Matthias Kind · Holger Martin</i> | |
| A2 Dimensionless Numbers | 11 |
| <i>Holger Martin</i> | |
| B Fundamentals of Heat Transfer | |
| B1 Fundamentals of Heat Transfer | 17 |
| <i>Peter Stephan</i> | |
| C Fundamentals of Heat Exchanger Design | |
| C1 Thermal Design of Heat Exchangers | 33 |
| <i>Wilfried Roetzel · Bernhard Spang</i> | |
| C2 Overall Heat Transfer | 67 |
| <i>Wilfried Roetzel · Bernhard Spang</i> | |
| C3 Typical Values of Overall Heat Transfer Coefficients | 75 |
| <i>Wilfried Roetzel · Bernhard Spang</i> | |
| C4 Fouling of Heat Exchanger Surfaces | 79 |
| <i>Hans Müller-Steinhagen</i> | |
| C5 Heat Exchanger Networks | 105 |
| <i>Xing Luo · Wilfried Roetzel</i> | |
| C6 Costs and Economy of Heat Exchangers | 115 |
| <i>Bernhard Spang · Wilfried Roetzel</i> | |
| D Thermophysical Properties | |
| D1 Calculation Methods for Thermophysical Properties | 121 |
| <i>Michael Kleiber · Ralph Joh</i> | |
| D2 Properties of Selected Important Pure Substances | 153 |
| D2.1 Properties of Water and Steam | 153 |
| <i>Wolfgang Wagner · Hans-Joachim Kretzschmar</i> | |
| D2.2 Properties of Dry Air | 172 |
| <i>Roland Span</i> | |

| | | |
|------|--|-----|
| D2.3 | Properties of Nitrogen | 192 |
| | <i>Roland Span · Rolf Krauss</i> | |
| D2.4 | Properties of Carbon Dioxide | 213 |
| | <i>Roland Span · Rolf Krauss</i> | |
| D2.5 | Properties of Oxygen | 235 |
| | <i>Roland Span · Rolf Krauss</i> | |
| D2.6 | Properties of Ammonia | 257 |
| | <i>Roland Span · Rolf Krauss</i> | |
| D2.7 | Properties of R134a (1,1,1,2-tetrafluoromethane) | 278 |
| | <i>Roland Span · Rolf Krauss</i> | |
| D3 | Properties of Pure Fluid Substances | 301 |
| D3.1 | Liquids and Gases | 301 |
| | <i>Michael Kleiber · Ralph Joh</i> | |
| D3.2 | Properties at Saturation | 394 |
| | <i>Roland Span</i> | |
| D4 | Properties of Industrial Heat Transfer Media | 419 |
| D4.1 | Refrigerants: Regulations | 419 |
| | <i>Ewald Preisegger · Felix Flohr</i> | |
| D4.2 | Cryostatic Bath Fluids, Aqueous Solutions, and Glycols | 435 |
| | <i>Gernot Krakat</i> | |
| D4.3 | Oil-based and Synthetic Heat Transfer Media | 458 |
| | <i>Andreas Glück · Dietmar Hunold</i> | |
| D5 | Properties of Multicomponent Fluid Mixtures | 513 |
| D5.1 | Calculation of Vapor–Liquid Equilibria | 513 |
| | <i>Andreas Pfennig</i> | |
| D5.2 | Polymer Solutions: Vapor–Liquid Equilibrium and Diffusion Coefficients | 527 |
| | <i>Wilhelm Schabel</i> | |
| D5.3 | Vapor Pressures of Aqueous Salt Solutions | 534 |
| | <i>Hartwig Wolf</i> | |
| D6 | Properties of Solids and Solid Materials | 551 |
| D6.1 | Thermodynamic Properties of Pure Metals and Metal Alloys | 551 |
| | <i>Matthias Neubronner · Thomas Bodmer</i> | |
| D6.2 | Polymers | 566 |
| | <i>Christof Hübner · Paul Bernd Kempa</i> | |
| D6.3 | Thermal Conductivity of Packed Beds | 570 |
| | <i>Evangelos Tsotsas</i> | |
| D6.4 | Industrial Refractories | 581 |
| | <i>Axel Eschner</i> | |
| D6.5 | Insulations Materials | 591 |
| | <i>Günther Kasperek</i> | |

| | | |
|----------|--|-----|
| D6.6 | Thermal Conductivity of Insulation Materials Depending on Moisture Content and Temperature . . . | 595 |
| | <i>Fabian Ochs · Hans Müller-Steinhagen</i> | |
| D6.7 | Thermal Conductivity of Building Materials | 601 |
| | <i>Hans Werner · Martin H. Spitzner</i> | |
| E | Heat Conduction | |
| E1 | Steady-State Heat Conduction | 617 |
| | <i>Erich Hahne</i> | |
| E2 | Transient Conduction in Stagnant Media | 637 |
| | <i>Holger Martin</i> | |
| F | Free Convection | |
| F1 | Heat Transfer by Free Convection: Fundamentals | 663 |
| | <i>André Thess</i> | |
| F2 | Heat Transfer by Free Convection: External Flows | 667 |
| | <i>Werner Kast · Herbert Klan · (Revised by André Thess)</i> | |
| F3 | Heat Transfer by Free Convection: Internal Flows | 673 |
| | <i>André Thess</i> | |
| F4 | Heat Transfer by Free Convection: Special Cases | 681 |
| | <i>Werner Kast · Herbert Klan · (Revised by André Thess)</i> | |
| F5 | Thermal Output of Heating Appliances Operating with Hot Water | 685 |
| | <i>Werner Kast · Herbert Klan · (Revised by André Thess)</i> | |
| G | Forced Convection | |
| G1 | Heat Transfer in Pipe Flow | 693 |
| | <i>Volker Gnielinski</i> | |
| G2 | Heat Transfer in Concentric Annular and Parallel Plate Ducts | 701 |
| | <i>Volker Gnielinski</i> | |
| G3 | Heat Transfer in Helically Coiled Tubes | 709 |
| | <i>Volker Gnielinski</i> | |
| G4 | Heat Transfer in Flow Past a Plane Wall | 713 |
| | <i>Volker Gnielinski</i> | |
| G5 | Heat Transfer to Single Cylinders, Wires, and Fibers in Longitudinal Flow | 717 |
| | <i>Holger Martin · Bernhard Gampert</i> | |
| G6 | Heat Transfer in Cross-flow Around Single Tubes, Wires, and Profiled Cylinders | 723 |
| | <i>Volker Gnielinski</i> | |
| G7 | Heat Transfer in Cross-flow Around Single Rows of Tubes and Through Tube Bundles | 725 |
| | <i>Volker Gnielinski</i> | |
| G8 | Shell-Side Heat Transfer in Baffled Shell-and-Tube Heat Exchangers | 731 |
| | <i>Edward S. Gaddis · Volker Gnielinski</i> | |

| | | |
|------------|--|------------|
| G9 | Fluid-Particle Heat Transfer in Flow Through Packed Beds of Solids | 743 |
| | <i>Volker Gnielinski</i> | |
| G10 | Impinging Jet Flow Heat Transfer | 745 |
| | <i>Wilhelm Schabel · Holger Martin</i> | |
| H | Boiling | |
| H1 | Fundamentals of Bubble Formation | 755 |
| | <i>Karl Stephan</i> | |
| H2 | Pool Boiling | 757 |
| | <i>Dieter Gorenflo · David Kenning</i> | |
| H3 | Flow Boiling – An Introduction | 793 |
| | <i>Matthias Kind</i> | |
| | H3.1 Flow Patterns in Evaporator Tubes | 796 |
| | <i>Dieter Steiner · Matthias Kind</i> | |
| | H3.2 Pressure Drop in Evaporator Tubes | 801 |
| | <i>Jogindar Mohan Chawla · Matthias Kind</i> | |
| | H3.3 Subcooled Boiling | 804 |
| | <i>Matthias Kind · Jens-Jürgen Schröder</i> | |
| | H3.4 Saturated Flow Boiling | 813 |
| | <i>Matthias Kind · Yasushi Saito</i> | |
| | H3.5 Critical Boiling States in Flowing Liquids | 832 |
| | <i>Hein Auracher · Oliver Herbst</i> | |
| | H3.6 Postdryout Heat Transfer in Flow Boiling | 870 |
| | <i>Anastassios Katsaounis · Matthias Kind</i> | |
| | H3.7 Flow Boiling of Mixtures | 887 |
| | <i>Dieter Steiner · Matthias Kind · Yasushi Saito</i> | |
| | H3.8 Special Symbols and References Used and Cited in Subchaps. H3.1–H3.7 | 892 |
| | <i>Matthias Kind</i> | |
| J | Condensation | |
| J1 | Filmwise Condensation of Pure Vapors | 905 |
| | <i>Reiner Numrich · Jürgen Müller</i> | |
| J2 | Film Condensation of Binary Mixtures with and without Inert Gas | 919 |
| | <i>Ernst-Ulrich Schlünder</i> | |
| J3 | Dropwise Condensation | 933 |
| | <i>Alfred Leipertz</i> | |
| J4 | Mixing and Spray Condensation | 939 |
| | <i>Ulrich Hochberg</i> | |

K Radiation

| | | |
|-----------|--|-------------|
| K1 | Radiation of Surfaces | 947 |
| | <i>Stephan Kabelac · Dieter Vortmeyer</i> | |
| K2 | View Factors | 961 |
| | <i>Dieter Vortmeyer · Stephan Kabelac</i> | |
| K3 | Gas Radiation: Radiation from Gas Mixtures | 979 |
| | <i>Dieter Vortmeyer · Stephan Kabelac</i> | |
| K4 | Thermal Radiation of Gas-Solids-Dispersions | 989 |
| | <i>Hans-Gerd Brummel</i> | |
| K5 | Heat Radiation in Furnaces | 1001 |
| | <i>Wolfgang Richter · Klaus Görner</i> | |
| K6 | Superinsulations | 1013 |
| | <i>Harald Reiss</i> | |

L Fluid Dynamics and Pressure Drop

| | | |
|-------------|--|-------------|
| L1 | Pressure Drop in Single Phase Flow | 1055 |
| L1.1 | Pressure Drop in Single Phase Flow in Pipes | 1055 |
| | <i>Werner Kast · (Revised by Hermann Nirschl)</i> | |
| L1.2 | Pressure Drop in Flow Through Pipes | 1057 |
| | <i>Werner Kast · (Revised by Hermann Nirschl)</i> | |
| L1.3 | Pressure Drop in Flow Through Pipes of Changing Cross-section | 1065 |
| | <i>Werner Kast · (Revised by Hermann Nirschl)</i> | |
| L1.4 | Pressure Drop of Tube Bundles in Cross Flow | 1076 |
| | <i>Edward S. Gaddis</i> | |
| L1.5 | Pressure Drop in the Outer Shell of Heat Exchangers | 1092 |
| | <i>Edward S. Gaddis</i> | |
| L1.6 | Pressure Drop in Fixed Beds | 1106 |
| | <i>Karl-Ernst Wirth</i> | |
| L1.7 | Pressure Drop in Orifices and Column Trays | 1111 |
| | <i>Johann Stichlmair</i> | |
| L2 | Two-Phase Gas-Liquid Flow | 1117 |
| L2.1 | Prediction of Void Fraction | 1117 |
| | <i>Holger Schmidt</i> | |
| L2.2 | Pressure Drop in Tubes, Valves, and Fittings | 1125 |
| | <i>Anton Wellenhofer · Sebastian Muschelknautz</i> | |
| L2.3 | Sizing of Safety Devices for Heat Exchangers | 1137 |
| | <i>Jürgen Schmidt</i> | |

| | | | |
|-----------|-------------|--|-------------|
| | L2.4 | Calculating Critical Mass Flux | 1150 |
| | | <i>Florian Schmidt</i> | |
| | L2.5 | Flooding and Pressure Drop of Counter Current Gas-Liquid Flow in Vertical Pipes | 1164 |
| | | <i>Dieter Mewes</i> | |
| | L2.6 | Pressure Drop and Flooding in Packed Towers | 1169 |
| | | <i>Alfons Mersmann</i> | |
| | L2.7 | Pressure Drop and Operating Limits of Trays | 1178 |
| | | <i>Johann Stichlmair</i> | |
| L3 | | Two-Phase Gas-Solid Flow | 1181 |
| | L3.1 | Particle Motion in Fluids | 1181 |
| | | <i>Martin Sommerfeld</i> | |
| | L3.2 | Flow Patterns and Pressure Drop in Fluidized Beds | 1197 |
| | | <i>Karl-Ernst Wirth</i> | |
| | L3.3 | Pressure Drop in Pneumatic Conveying Systems | 1207 |
| | | <i>Ulrich Muschelknautz</i> | |
| | L3.4 | Cyclones for the Precipitation of Solid Particles | 1226 |
| | | <i>Ulrich Muschelknautz</i> | |
| L4 | | Bubble and Drops in Technical Equipment | 1239 |
| | L4.1 | Formation and Movement of Bubbles and Drops | 1239 |
| | | <i>Norbert Rübiger · Michael Schlüter</i> | |
| | L4.2 | Production and Mechanical Destruction of Foams | 1254 |
| | | <i>Alfons Mersmann</i> | |
| | L4.3 | Droplet Separation | 1264 |
| | | <i>Hans Detlef Dahl</i> | |
| M | | Specific Heat Transfer Problems | |
| | M1 | Heat Transfer to Finned Tubes | 1273 |
| | | <i>Klaus Gerhard Schmidt</i> | |
| | M2 | Heat Transfer to Walls with Welded Coils | 1279 |
| | | <i>Wolfgang Heidemann</i> | |
| | M3 | Heat Transfer to Falling Films at Vertical Surfaces | 1287 |
| | | <i>Günter Schnabel</i> | |
| | M4 | Heat Transfer to Non-Newtonian Fluids | 1295 |
| | | <i>Manfred H. Wagner</i> | |
| | M5 | Heat Transfer in Fluidized Beds | 1301 |
| | | <i>Holger Martin</i> | |
| | M6 | Heat Transfer from a Wall to Stagnant and Mechanically Agitated Beds | 1311 |
| | | <i>Evangelos Tsotsas</i> | |
| | M7 | Heat and Mass Transfer in Packed Beds with Fluid Flow | 1327 |
| | | <i>Evangelos Tsotsas</i> | |

| | | |
|------------|---|-------------|
| M8 | Humidifying and Drying of Air | 1343 |
| | <i>Manfred Zeller · Ulrich Busweiler</i> | |
| M9 | Convective Heat Transfer at High Velocities | 1363 |
| | <i>Bernhard Weigand · Nimai-Kumar Mitra</i> | |
| M10 | Heat Transfer and Momentum Flux in Rarefied Gases | 1375 |
| | <i>Arnold Frohn · Norbert Roth · Klaus Anders</i> | |
| M11 | Spontaneous Condensation and Cavitation | 1391 |
| | <i>Karlheinz Schaber · Günter H. Schnerr</i> | |
| N | Specific Heat Transfer Devices | |
| N1 | Heat Transfer in Regenerators | 1423 |
| | <i>Helmuth Hausen · (Revised by Wolfgang Bender)</i> | |
| N2 | Combined Heat and Mass Transfer in Rotating Regenerators | 1435 |
| | <i>Gerd Gaiser</i> | |
| N3 | Heat Transfer and Power Consumption in Stirred Vessels | 1451 |
| | <i>Edward S. Gaddis</i> | |
| N4 | Cooling Towers | 1485 |
| | <i>Paul J. Erens</i> | |
| N5 | Heat Pipes | 1503 |
| | <i>Peter Stephan</i> | |
| N6 | Pressure Drop and Heat Transfer in Plate Heat Exchangers | 1515 |
| | <i>Holger Martin</i> | |
| O | Construction of Heat Exchangers | |
| O1 | Hints on the Construction of Heat Exchangers | 1525 |
| | <i>Günther Kirchner</i> | |
| O2 | Vibration of Tube Bundles in Heat Exchangers | 1553 |
| | <i>Horst Gelbe · Samir Ziada</i> | |