Table of Contents

Disclaimer IV

Preface by the editors XLIII

Introduction by ATMOsphere XLV

Abbreviations and units LIII

1 Introduction 1

1.1 Ammonia 3

1.2 Carbon Dioxide 4

1.3 Hydrocarbons 6

1.4 Water as a refrigerant 7

1.5 Literature 8

2 Thermodynamic properties of natural refrigerants 9

3 Comparisons of natural refrigerants 15

3.1 Literature 18

4 Ammonia as a refrigerant 19

4.1 Introduction 19
4.1.1 General characteristics and manufacture of ammonia 19
4.1.2 Use of ammonia 21
4.1.3 Use and economic importance in refrigeration 22

4.2 Thermodynamics 22
4.2.1 Main features 22
4.2.2 Impact on the components of the refrigeration system 31

4.3 Plant engineering aspects 39
4.3.1 Plant systems and types 39
4.3.2 Components 44
4.3.3 Leakage monitoring 54
4.3.4 Contamination by water and inert gases 54
4.3.5 Risks from hydraulic pressure surges in refrigerant piping system 56
4.3.6 Direct and indirect systems 57

4.4 Safety precautions when handling ammonia 59
4.4.1 Ammonia in the atmosphere 60
4.4.2 Flammability 60
4.4.3 Effects on food 61
4.4.4 Effects on humans 61
4.4.5 Accidents 62

4.4.6 Technical safety equipment . . . 64
4.4.7 Personal protective equipment . . . 65
4.4.8 Work in plant room . . . 66

4.5 Design criteria for ammonia plants . . . 70
4.5.1 General basics . . . 70
4.5.2 Materials . . . 70
4.5.3 Joining techniques . . . 71

4.6 Applications of ammonia as refrigerant . . . 74
4.6.1 Refrigerated warehouses . . . 74
4.6.2 Supermarkets . . . 76
4.6.3 Commercial kitchens . . . 78
4.6.4 Ice rinks . . . 79
4.6.5 Air conditioners . . . 80
4.6.6 Heat pumps / heat recovery . . . 80
4.6.7 Chillers for process cooling . . . 82
4.6.8 CO_2 and NH_3 cascade systems . . . 82
4.6.9 Small capacity installations . . . 84
4.6.10 Container solutions . . . 84

4.7 Standards and regulations . . . 85
4.7.1 European regulations . . . 85
4.7.2 Safety training of employees . . . 86

4.8 Summary of the advantages and disadvantages of ammonia . . . 87

4.9 Outlook . . . 88

4.10 System examples . . . 89
4.10.1 Refrigeration supply for a fruit-and-vegetable wholesaler . . . 89
4.10.2 Cooling provision for a commercial kitchen of an automobile manufacturer . . . 91
4.10.3 Liquid chiller for air conditioning office and server rooms . . . 92
4.10.4 Cooling supply for a company restaurant . . . 94

4.11 Literature . . . 96

5 Carbon dioxide as refrigerant . . . 97

5.1 History of the refrigerant CO_2 . . . 97

5.2 CO_2 effects on health, system reliability, and the environment . . . 98

5.3 R744 refrigeration system characteristics and their effect on design and operation . . . 101
5.3.1 Introduction and definitions . . . 101
5.3.2 Importance of the relatively low critical temperature . . . 102
5.3.3 Significance of high pressure at the triple point . . . 105
5.3.4 Significance of a generally high-pressure level . . . 106
5.3.5 Importance of good heat transfer properties . . . 111
5.3.6 Provision for the high coefficient of thermal expansion of the liquid . . . 112

5.4 Transcritical refrigeration / heat pump process . . . 113
5.4.1 The process on the pressure-enthalpy diagram . . . 113
5.4.2 Temperature curve in the gas cooler . . . 115
5.4.3 Significance of the gas cooler pressure on cooling capacity . . . 119
5.4.4 The importance of gas cooler pressure for the coefficient of performance . . . 121
5.4.5 Optimal high-pressure control of CO_2 processes . . . 121

5.5 Technical solutions with CO_2 . . . 124
5.5.1 CO_2 as an evaporating coolant . . . 124
5.5.2 CO_2 in the conventional refrigeration process – cascade system . . . 126
5.5.3 The transcritical process – basic solutions . . . 129

5.6 Process improvement methods . . . 135
5.6.1 Intercooling in two-stage systems . . . 135
5.6.2 Parallel compression . . . 136
5.6.3 Cooling of the supercritical gas after the gas cooler . . . 137
5.6.4 Expansion work recovery . . . 138

5.7 Heat recovery with CO_2 installations . . . 142
5.7.1 Heat recovery at one temperature level: a simple solution . . . 143
5.7.2 Heat recovery at different temperature levels . . . 144

5.8 CO_2 heat pumps . . . 147
5.8.1 General . . . 147
5.8.2 Production of industrial hot water . . . 148
5.8.3 Combined space heating and hot water preparation . . . 151

5.9 Safety when using CO_2 . . . 152
5.9.1 Pressure and temperature – safety conditions . . . 152
5.9.2 Dry ice – safety and operating conditions . . . 153

5.10 Examples for CO_2 refrigeration system applications . . . 154
5.10.1 Cascade refrigeration installations using CO_2 as a refrigerant . . . 154
5.10.2 Transcritical systems . . . 158

5.11 Literature . . . 176

6 Hydrocarbons as refrigerant . . . 179

6.1 Introduction . . . 179
6.1.1 Ecological characteristics . . . 180

6.2 Thermodynamic aspects . . . 182
6.2.1 Evaporation latent heat . . . 183
6.2.2 Evaporation temperature and pressure . . . 185
6.2.3 Isentropic expansion exponent κ . . . 186
6.2.4 Coefficient of Performance / Energy Efficiency Ratio . . . 187
6.2.5 Compression or pressure ratio . . . 188
6.2.6 Volumetric cooling capacity . . . 190
6.2.7 Discharge temperature . . . 190

6.2.8	Density	192
6.2.9	Viscosity	193
6.2.10	Material compatibility	193
6.3	Refrigeration system components	194
6.3.1	Compressor	194
6.3.2	Piping and fittings	194
6.3.3	Heat exchangers	195
6.3.4	Throttle device	195
6.3.5	Receivers	195
6.3.6	Multi-stage systems	195
6.4	Safety of refrigeration systems with hydrocarbons	196
6.4.7	System tightness	197
6.4.8	Charge minimisation	198
6.4.9	Determination of limited refrigerant charge	198
6.4.10	Mechanical ventilation	201
6.4.11	Ventilated enclosures	202
6.4.12	Machinery room ventilation	203
6.4.13	Gas/leak detection	204
6.4.14	Safety devices	204
6.4.15	Ignition sources	204
6.5	Safe handling of flammable refrigerants	206
6.6	Smaller systems	207
6.7	Larger systems	212
6.7.16	Application examples	214
6.8	Outlook	220
6.8.1	Differences between purpose of systems	221
6.8.2	Assumed leak rates	222
6.8.3	Improved tightness systems	224
6.8.4	Use of integral airflow to disperse leaks	225
6.8.5	Releasable charge	226
6.8.6	Equipment enclosures or housing to disperse leaks	227
6.8.7	Black box assessment	227
6.9	Literature	228
7	**Water as a refrigerant**	231
7.1	Introduction	231
7.2	Properties and area of application	231
7.2.1	Thermodynamic properties and comparison to common refrigerants	231
7.2.2	Use as a refrigerant	235
7.2.3	Use in vapour compression refrigeration machines	236

7.3 Functionality of compression refrigeration systems with the refrigerant water 237

7.4 Application in the low power range . . . 239
7.4.1 Compact water chillers . . . 239
7.4.2 Practical examples . . . 240

7.5 Generation of temperatures below freezing . . . 241
7.5.1 Description of the systems . . . 241
7.5.2 Possible applications . . . 242

7.6 Conclusion . . . 243

7.7 Literature . . . 243

8 Refrigeration systems for temperatures below –50 °C (–58 °F) . . . 245

8.1 Hydrocarbons and mixtures with CO_2 . . . 245

8.2 Nitrous oxide and mixtures with CO_2 . . . 245

8.3 Air . . . 246

8.4 Literature . . . 249

9 Lubricants for natural refrigerants . . . 251

9.1 Lubricants for ammonia (NH_3 – R717) . . . 251

9.2 Lubricants for hydrocarbons (propane – R290, propene – R1270, isobutane – R600a etc.) . . . 252

9.3 Lubricants for carbon dioxide (CO_2 – R744) . . . 254
9.3.1 Miscibility properties with liquid CO_2 . . . 254
9.3.2 Thermal stability . . . 255
9.3.3 Lubrication properties . . . 256
9.3.4 Water content . . . 257
9.3.5 Areas of application for CO_2 refrigeration oils . . . 257

9.4 Selection table – Refrigeration oil type for natural refrigerants . . . 258

9.5 Literature . . . 258

10 Coolants . . . 259

10.1 Requirements for coolants . . . 261

10.2 Types of heat transfer fluids (HTF) . . . 261

10.3 Liquid coolants for medium- and low-temperature applications . . . 264
10.3.1 Cooling of foodstuffs . . . 264
10.3.2 Deep freezing food . . . 266

10.4 HTF with phase change . . . 269
10.4.1 Evaporating carbon dioxide . . . 270
10.4.2 Ice Slurry . . . 270

10.5 Corrosion protection 271
10.6 Case study: Propane – CO_2 cascade ice slurry installation. 272
10.7 Integral system for cooling goods, air conditioning and heating in supermarkets 274
10.8 Literature 279

Appendix 281