Acid Gas Injection
and Carbon Dioxide
Sequestration
Scrivener Publishing
3 Winter Street, Suite 3
Salem, MA 01970

Scrivener Publishing Collections Editors

James E. R. Couper  Richard Erdlac
Rafiq Islam        Pradip Khaladkar
Vitthal Kulkarni   Norman Lieberman
Peter Martin       W. Kent Muhlbauer
Andrew Y. C. Nee   S. A. Sherif
James G. Speight

Publishers at Scrivener
Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)
This book is dedicated to Wu Ying, my loving wife. She is the love of my life and a constant source of inspiration.
This Page Intentionally Left Blank
Contents

Preface xv
Acknowledgement xvii

Chapter 1 Introduction 1
1.1 Acid Gas 2
   1.1.1 Hydrogen Sulfide 3
   1.1.2 Carbon Dioxide 4
1.2 Anthropogenic CO₂ 5
1.3 Flue Gas 5
   1.3.1 Sulfur Oxides 7
   1.3.2 Nitrogen Oxides 8
1.4 Standard Volumes 8
   1.4.1 Gas Volumes 8
   1.4.2 Liquid Volumes 9
1.5 Sulfur Equivalent 9
1.6 Sweetening Natural Gas 11
   1.6.1 Combustion Process Gas 12
       1.6.1.1 Post-Combustion 13
       1.6.1.2 Pre-Combustion 14
1.7 Acid Gas Injection 14
1.8 Who Uses Acid Gas Injection? 16
   1.8.1 Western Canada 16
   1.8.2 United States 17
   1.8.3 Other Locations 17
   1.8.4 CO₂ Flooding 18
1.9 In Summary 18

References 18
Appendix 1A Oxides of Nitrogen 20
Appendix 1B Oxides of Sulfur 22
Chapter 2  Hydrogen Sulfide and Carbon Dioxide  23
  2.1 Properties of Carbon Dioxide  25
  2.2 Properties of Hydrogen Sulfide  27
  2.3 Estimation Techniques for Physical Properties  31
    2.3.1 Thermodynamic Properties  31
      2.3.1.1 Ideal Gas  31
      2.3.1.2 Real Gas  33
    2.3.2 Saturated Liquid and Vapor Densities  36
      2.3.2.1 Liquids  36
      2.3.2.2 Corresponding States  37
    2.3.3 Thermodynamic Properties  39
    2.3.4 Transport Properties  40
      2.3.4.1 Low Pressure Gas  40
      2.3.4.2 Gases Under Pressure  41
      2.3.4.3 Liquids  42
    2.3.5 Viscosity Charts  43
  2.4 Properties of Acid Gas Mixtures  44
    2.4.1 Thermodynamic Properties  44
      2.4.1.1 Corresponding States  45
    2.4.2 Transport Properties  47
    2.4.3 Word of Caution  48
  2.5 Effect of Hydrocarbons  50
    2.5.1 Density  50
    2.5.2 Viscosity  51
  2.6 In Summary  51

References  51
Appendix 2A  Transport Properties of Pure Hydrogen Sulfide  53
  2A.1 Viscosity  53
    2A.1.1 Liquid  53
    2A.1.2 Vapor  54
  2A.2 Thermal Conductivity  55

References  57
Appendix 2B  Viscosity of Acid Gas Mixtures  59
  2B.1.1 Correcting for High Pressure  59
  2B.1.2 Carbon Dioxide  59
  2B.1.3 Generalization  61
Chapter 3 Non-Aqueous Phase Equilibrium

3.1 Overview

3.2 Pressure-Temperature Diagrams
  3.2.1 Pure Components
  3.2.2 Mixtures
  3.2.3 Binary Critical Points
  3.2.4 Effect of Hydrocarbons
    3.2.4.1 Methane
    3.2.4.2 Ethane and Propane
    3.2.4.3 Butane and Heavier
    3.2.4.4 In Summary

3.3 Calculation of Phase Equilibrium
  3.3.1 Equations of State
  3.3.2 K-Factor Charts

3.4 In Summary

References

Appendix 3A Some Additional Phase Equilibrium Calculations
  3A.1.1 Hydrogen Sulfide + Hydrocarbons
  3A.1.2 Carbon Dioxide + Hydrocarbons
  3A.1.3 Multicomponent Mixtures

References

Appendix 3B Accuracy of Equations of State for VLE in Acid Gas Mixtures

References

Chapter 4 Fluid Phase Equilibria Involving Water

4.1 Water Content of Hydrocarbon Gas
4.2 Water Content of Acid Gas
  4.2.1 Carbon Dioxide
  4.2.2 Hydrogen Sulfide
4.2.3 Practical Representation 106
  4.2.3.1 In Summary 108

4.3 Estimation Techniques 108
  4.3.1 Simple Methods 109
    4.3.1.1 Ideal Model 109
    4.3.1.2 McKetta-Wehe Chart 109
    4.3.1.3 Maddox Correction 110
    4.3.1.4 Wichert Correction 110
    4.3.1.5 Alami et al. 111
  4.3.2 Advanced Methods 111
    4.3.2.1 AQUAlibrium 111
    4.3.2.2 Other Software 112

4.4 Acid Gas Solubility 113
  4.4.1 Henry’s Law 113
  4.4.2 Solubility in Brine 115
    4.4.2.1 Carbon Dioxide in NaCl 116
    4.4.2.2 Hydrogen Sulfide in NaCl 116
    4.4.2.3 Mixtures of Gases 119
    4.4.2.4 Effect of pH 119

4.5 In Summary 119

References 120

Appendix 4A Compilation of the Experimental Data for the Water Content of Acid Gas 122

References 124

Appendix 4B Comments on the Work of Selleck et al. 127

Appendix 4C Density of Brine (NaCl) Solutions 129

Chapter 5 Hydrates 131
  5.1 Introduction to Hydrates 131
  5.2 Hydrates of Acid Gases 132
  5.3 Estimation of Hydrate Forming Conditions 135
    5.3.1Shortcut Methods 135
    5.3.2 Rigorous Methods 136
  5.4 Mitigation of Hydrate Formation 136
    5.4.1 Inhibition with Methanol 136
    5.4.2 Water-Reduced Cases 138
      5.4.2.1 Carbon Dioxide 139
      5.4.2.2 Dehydration 140
Chapter 6 Compression

6.1 Overview 145
6.2 Theoretical Considerations 148
6.3 Compressor Design and Operation 148
6.4 Design Calculations 149
   6.4.1 Compression Ratio 150
   6.4.2 Ideal Gas 151
   6.4.3 Efficiency 157
   6.4.4 Ratio of the Heat Capacities 158
6.5 Interstage Coolers 159
   6.5.1 Design 160
   6.5.2 Pressure Drop 164
   6.5.3 Phase Equilibrium 164
6.6 Compression and Water Knockout 167
   6.6.1 Additional Cooling 171
6.7 Materials of construction 172
6.8 Advanced design 172
   6.8.1 Cascade 172
   6.8.2 CO₂ Slip 173
6.9 Case studies 174
   6.9.1 Wayne-Rosedale 174
   6.9.2 Acheson 175
   6.9.3 West Pembina 175
6.10 In Summary 175

References 176

Appendix 6A Additional Calculations 177
Chapter 7  Dehydration of Acid Gas  183

7.1 Glycol Dehydration  184
   7.1.1 Acid Gas Solubility  185
   7.1.2 Desiccant  187

7.2 Molecular Sieves  189
   7.2.1 Acid Gas Adsorption  191

7.3 Refrigeration  192
   7.3.1 Selection of Inhibitor  193

7.4 Case Studies  194
   7.4.1 CO₂ Dehydration  194
   7.4.2 Acid Gas Dehydration  195
      7.4.2.1 Wayne-Rosedale  195
      7.4.2.2 Acheson  195

7.5 In Summary  196

References  196

Chapter 8  Pipeline  199

8.1 Pressure Drop  199
   8.1.1 Single Phase Flow  199
      8.1.1.1 Friction Factor  202
      8.1.1.2 Additional Comments  204
   8.1.2 Two-Phase Flow  205
   8.1.3 Transitional Flow  205

8.2 Temperature Loss  206
   8.2.1 Carroll's Method  206

8.3 Guidelines  207

8.4 Metering  208

8.5 Other Considerations  209

8.6 In Summary  210

References  210

Appendix 8A  Sample Pipeline Temperature Loss Calculation  211

8A.1 AQUAlibrium 3.0  212
   8A.1.1 Acid Gas Properties  212
      8A.1.1.1 Conditions  212
      8A.1.1.2 Component Fractions  212
      8A.1.1.3 Phase properties  212
      8A.1.1.4 Warnings  212
Chapter 9 Injection Profiles

9.1 Calculation of Injection Profiles
9.1.1 Gases
9.1.1.1 Ideal Gas
9.1.1.2 Real Gas
9.1.2 Liquids
9.1.3 Supercritical Fluids
9.1.4 Friction
9.1.5 AGIProfile
9.2 Effect of Hydrocarbons
9.3 Case Studies
9.3.1 Chevron Injection Wells
9.3.1.1 West Pembina
9.3.1.2 Acheson
9.3.2 Anderson Puskwaskau
9.4 Other Software
9.5 In Summary

References
Appendix 9A Additional Examples

Chapter 10 Selection of Disposal Zone

10.1 Containment
10.1.1 Reservoir Capacity
10.1.2 Caprock
10.1.3 Other Wells
10.2 Injectivity
10.2.1 Liquid Phase
10.2.2 Gas Injection
10.2.3 Fracturing
10.2.4 Horizontal Wells
10.3 Interactions With Acid Gas
10.4 In Summary

References

Chapter 11 Health, Safety and The Environment

11.1 Hydrogen Sulfide
11.1.1 Physiological Properties
11.1.2 Regulations
11.1.3 Other Considerations
## Chapter 11: Carbon Dioxide

11.2 Carbon Dioxide
   11.2.1 Physiological Properties 249
   11.2.2 Climate Change 250
   11.2.3 Other Considerations 250

11.3 Emergency Planning 250
   11.3.1 Accidental Releases 250
   11.3.2 Planning Zones 251
   11.3.3 Other Considerations 255
      11.3.3.1 Sour vs. Acid Gas 255
      11.3.3.2 Wind 256
      11.3.3.3 Carbon Dioxide 256
      11.3.3.4 Sensitive Areas 256

## Chapter 12: Capital Costs

12.1 Compression 257
   12.1.1 Reciprocating Compressor 258
   12.1.2 Centrifugal 259

12.2 Pipeline 259

12.3 Wells 260

12.4 In Summary 261

## Chapter 13: Additional Topics

13.1 Rules of Thumb 263
   13.1.1 Physical Properties 263
   13.1.2 Water Content 264
   13.1.3 Hydrates 264
   13.1.4 Compression 264
   13.1.5 Pipelines 265
   13.1.6 Reservoir 266

13.2 Graphical Summary 266
   13.2.1 Pressure-Temperature 266
   13.2.2 Water Content 268
   13.2.3 Operation 269
   13.2.4 Summary 270

13.3 The Three Types of Gas 270
   13.3.1 Example Gases 270

Index 275
Acid gas injection (AGI) has become a mature technology for disposing of acid gas, a mixture of CO$_2$ and H$_2$S. AGI is particularly useful for small producers who have few options for dealing with the H$_2$S. Larger producers, however, have seen the value in AGI as well and the industry has discovered that AGI is an environmentally friendly solution to a difficult problem.

This book presents the art, the science, and the engineering aspects of AGI, and to present it in a manner that is accessible to the average engineer. It begins with a discussion of the basic data and models for designing an injection scheme. In particular it is important that those working in the field have a good understanding of the phase equilibria involved. Most of the operational problems are related to the formation of an unwanted phase. Admittedly, some of these concepts are a little complicated, and it is a challenge to present them in a form that is comprehensible to a wide audience.

Next the engineering aspects are presented. These include the design of the compressor and pipeline and in particular what makes them different from standard designs. Finally, some of the subsurface aspects are reviewed. Admittedly, the focus of this book is the surface aspects of AGI, but the subsurface aspects cannot be overlooked, even by the process engineer.

Hopefully, those involved in the emerging field of CO$_2$ sequestration will note the similarities and take the information presented here and apply it to their projects. Lessons learned in AGI can be exported to the technology of carbon sequestration.
This Page Intentionally Left Blank
Acknowledgements

There are many people to thank when one writes a book. The first, and certainly the most important, is my employer Gas Liquids Engineering, and in particular the company principals Doug MacKenzie and Jim Maddocks but also my colleague Peter Griffin. They provided me the opportunity to present the course and much of the time to write the manuscript.

In addition, through my job at Gas Liquids Engineering, I have had the chance to work on many acid gas injection projects throughout the world. Some of these were just studies that have not yet come to fruition, but others have been operating for many years. Much of what is presented in this book has come from lessons learned from working on those projects.

Alan Mather has been my long time friend and mentor. He is an important source of information, often from obscure sources. Plus his lab is the source of much of the useful information in this field. The research studies of his group are vital to the advancement of many fields in the gas processing.

This book is based on a course on acid gas injection that I have presented throughout the world. Feedback from the attendees over the years has greatly improved the quality and content of both the course and this book. The acid gas injection course has also been presented in Chinese and Polish. I have received excellent feedback from Eugene Grynia, my Polish translator, and Ying Wu, my Chinese translator.
This Page Intentionally Left Blank