

# FUNDAMENTALS OF GAS LIFT ENGINEERING

**Well Design and Troubleshooting**

Ali Hernández



# Fundamentals of Gas Lift Engineering

## Well Design and Troubleshooting

**Ali Hernández**



AMSTERDAM • BOSTON • HEIDELBERG • LONDON  
NEW YORK • OXFORD • PARIS • SAN DIEGO  
SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO  
Gulf Professional Publishing is an imprint of Elsevier



Gulf Professional Publishing is an imprint of Elsevier  
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, USA  
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Copyright © 2016 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

#### **Notices**

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

#### **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: 978-0-12-804133-8

For information on all Gulf Professional Publishing  
visit our website at <http://store.elsevier.com/>



Working together  
to grow libraries in  
developing countries

[www.elsevier.com](http://www.elsevier.com) • [www.bookaid.org](http://www.bookaid.org)

# **Fundamentals of Gas Lift Engineering**

Well Design and Troubleshooting



*Dedicated with love and gratitude to Carmen and Mauricio for their continuous support and understanding*

*And*

*In memory of my friend and mentor Walter George Zimmerman, a very practical engineer who always based his technical decisions on sound engineering judgment.*



# Acknowledgments

The author wishes to recognize the collaboration given by the following persons:

*Herald W. Winkler, John Martinez, Gary Milam, Cleon Dunham, and the late Jack Blann* for their valuable advice on so many gas lift theoretical subjects and practical field applications; *Ken Decker* and *Juan Faustinelli Jr* for their guidance on the dynamic modeling of gas lift valves; *Wim der Kinderen* for his important contribution on gas lift design stability; *Dr Jesus Enrique Chacin* for his development of mechanistic models for intermittent gas lift; Wireline Expert *Hector Rivas* and Team Leader *Francisco Corrales* for their outstanding work in many of the gas lift field-scale research projects performed by the author; *Juan Carlos Iglesias* for his contribution during the research on the dynamic behavior of gas lift valves carried out by the author; *Balmiro Villalobos* for his collaboration in the implementation of wellhead intermitters and many other field applications; and *Crisanto Acevedo Caceres* and *Cesar A. Perez Montaner* for their contributions in the development of Accumulation Chambers and Insert Accumulators.





# Contents

Acknowledgments.....	xiii
<b>CHAPTER 1 Gas Properties .....</b>	<b>1</b>
1.1 Equation of State.....	2
1.2 Gas Viscosity .....	13
1.3 Solubility of Natural Gas in Water.....	14
1.4 Solubility of Water Vapor in Natural Gas .....	16
1.5 Hydrates.....	18
1.6 Specific Heat Ratio .....	22
References .....	23
<b>CHAPTER 2 Single-Phase Flow .....</b>	<b>25</b>
2.1 Single-Phase Gas Flow .....	25
2.1.1 Static Gas Gradients in Vertical Pipes and Annuli.....	26
2.1.2 Gas Pressure Gradients in Vertical Pipes Considering Frictional Pressure Drop .....	33
2.1.3 Gas Flow in Horizontal Pipes .....	42
2.2 Single-Phase Liquid Flow.....	62
2.2.1 Static Pressure Gradient.....	62
2.2.2 Dynamic Gradient.....	69
References .....	79
<b>CHAPTER 3 Multiphase Flow .....</b>	<b>81</b>
3.1 Qualitative Aspects .....	81
3.2 General Quantitative Aspects in Multiphase Flow .....	88
3.2.1 General Definitions.....	89
3.2.2 Equations for Multiphase Flow Pressure and Temperature Gradients .....	93
3.3 Examples of Correlations and Mechanistic Models Developed for Vertical Upward Multiphase Flow .....	108
3.4 Horizontal Multiphase Flow .....	113
3.5 Unified Models .....	117
3.5.1 Horizontal Flow .....	117
3.5.2 Vertical Flow .....	118
3.5.3 Unified Models .....	118
3.6 Fluid Flow Through Annular Cross-Sections .....	118
3.6.1 Flow Pattern Prediction .....	119
3.6.2 Models Developed for Liquid Holdup and Pressure Drop Calculations.....	121
References .....	122

<b>CHAPTER 4 Single and Multiphase Flow Through Restrictions .....</b>	<b>127</b>
4.1 Gas Flow Through Restrictions .....	131
4.2 Liquid Flow Through Restrictions.....	139
4.3 Multiphase Flow Through Restrictions .....	140
References .....	148
<b>CHAPTER 5 Total System Analysis Applied to Gas Lift Design .....</b>	<b>151</b>
5.1 Determination of the Depth of the Operating Point of Injection .....	152
5.1.1 Determination of the Injection Point Depth Assuming Constant Wellhead Production Pressure.....	154
5.1.2 Finding the Injection Point Depth with Variable Wellhead Pressure.....	161
5.1.3 Use of Computer Programs to Find the Point of Injection and Perform Additional Useful Operations .....	163
5.2 Examples of the Effect that Different Gas Lift System's Components or Fluid Properties Might have on the Liquid Production of a Well on Gas Lift.....	182
5.3 Calculation Examples .....	187
5.3.1 Example of Preliminary Calculations Needed to Implement the Gas Lift Method to Boost the Liquid Production of a Well that can Produce on Natural Flow .....	187
5.3.2 Example of Preliminary Calculations to Design a Gas Lift Well that Cannot Produce on Natural Flow .....	203
<b>CHAPTER 6 Gas Lift Equipment .....</b>	<b>211</b>
6.1 Gas Lift Valves and Latches .....	211
6.2 Gas Lift Mandrels .....	226
6.3 Wireline Equipment.....	237
6.4 Types of Completions for Gas Lift Installations.....	250
6.4.1 Single Completions.....	250
6.4.2 Gas Lift as a Backup Method for Electric Submersible Pumps.....	255
6.4.3 Accumulation Chambers.....	260
6.4.4 Dual Wells.....	276
6.4.5 Use of Coiled Tubing.....	282
6.4.6 Intermittent Gas Lift with Metallic Plungers.....	287
<b>CHAPTER 7 Gas Lift Valve Mechanics .....</b>	<b>295</b>
7.1 Force-Balance Equations for the Different Types of Gas Lift Valves.....	295
7.1.1 Injection-Pressure-Operated Valves.....	296
7.1.2 Production-Pressure-Operated Valves.....	301

7.2 Calculation of the Nitrogen Pressure at Different Conditions .....	304
7.3 Determination of the Port and Bellows Areas .....	308
7.4 Examples of Problems Using the Force-Balance Equations for Designing and Troubleshooting Gas Lift Installations .....	309
Reference .....	313
<b>CHAPTER 8 Gas Flow Through Gas Lift Valves .....</b>	<b>315</b>
8.1 Use of the Thornhill–Craver Equation for Gas Lift Valves .....	320
8.2 Mathematical Models for the Dynamic Behavior of Gas Lift Valves .....	331
8.2.1 Simple Mechanistic Model for Single Element, IPO, Gas Lift Valves (without Dynamic Effect) .....	336
8.2.2 Mechanistic Model for Single Element, IPO, Gas Lift Valves (with Dynamic Effect) .....	340
8.2.3 Dynamic Model for Pilot Valves.....	353
8.3 Use of Chokes Installed Downstream of the Seat.....	357
8.4 Use of Chokes Installed Upstream of the Seat .....	359
8.5 Orifice Valves with Special Geometry Seats .....	361
References .....	363
<b>CHAPTER 9 Design of Continuous Gas Lift Installations.....</b>	<b>365</b>
9.1 Determination of the Operating Injection Point Depth, Target Injection Gas Flow Rate, and the Liquid Flow Rate the Well can Produce .....	377
9.1.1 Iterative Procedure .....	377
9.1.2 Fixed Drawdown or Fixed Liquid Production .....	383
9.1.3 Constant Liquid Production.....	384
9.2 Gas Lift Mandrel Spacing Procedures and Valve Design Calculations....	385
9.2.1 Mandrel Spacing for IPO Valves .....	387
9.2.2 Mandrel Spacing for PPO Valves .....	420
9.2.3 Unloading Liquid Flow Rate and Required Injection Gas Flow Rate at Each Unloading Valve .....	424
9.2.4 Injection Gas Temperature at Depth and Valve Operating Temperature Calculation .....	433
9.2.5 Determination of the Seat Diameters of the Operating and Unloading Valves .....	444
9.2.6 Dual Wells (with a Common Injection Gas Source).....	446
9.2.7 Redesign .....	455
9.2.8 Mandrel Spacing from the Reservoir Static Liquid Level .....	461
9.3 Stability Check of the Gas Lift Design.....	463
9.4 Examples of Gas Lift Designs .....	471
References .....	477

<b>CHAPTER 10 Design of Intermittent Gas Lift Installations .....</b>	<b>479</b>
10.1 Description of the Production Cycle.....	479
10.2 General Fundamentals and Implementation Guidance for Intermittent Gas Lift.....	481
10.3 Types of Completions for Intermittent Gas Lift.....	494
10.4 Description of Pilot Valves.....	500
10.5 Types of Control of the Surface Gas Injection.....	507
10.6 Intermittent Gas Lift Design for Simple Type Completions.....	518
10.6.1 Design of the Operating Valve for Choke-Control Intermittent Gas Lift.....	521
10.6.2 Design Procedure with the Use of Surface Controllers (Intermitters) .....	570
10.6.3 Mechanistic Models for the Design of Simple Type Completions on Choke-Control Intermittent Gas Lift .....	572
10.7 Design of Accumulation Chambers .....	582
10.8 Simple Type Accumulator.....	592
10.9 Inserted Chambers and Inserted Accumulators.....	594
10.10 Intermittent Gas Lift In Dual Wells.....	597
10.10.1 One Zone on Continuous Gas Lift and the other on Intermittent Gas Lift.....	598
10.10.2 Both Zones on Intermittent Gas Lift .....	600
10.11 Plunger-Assisted Intermittent Gas Lift .....	601
10.12 General Considerations for Gas Lift Systems with Wells on Intermittent Gas Lift.....	604
References .....	609
<b>CHAPTER 11 Continuous Gas Lift Troubleshooting.....</b>	<b>611</b>
11.1 Introduction.....	611
11.2 General Difficulties Encountered when Trying to Perform Troubleshooting Analyses of Gas Lift Wells .....	612
11.3 Causes and Corrective Actions for Possible Failures and/or Loss of Lifting Efficiency.....	619
11.3.1 Most Common Failures and/or Loss of Lifting Efficiency...	619
11.3.2 Multiple Points of Injection .....	635
11.3.3 Handling Problems Associated with Emulsion Generation..	639
11.4 Methodology for Troubleshooting Analyses .....	642
11.4.1 High Wellhead Injection Pressure and the Well Does not Receive Injection Gas .....	646
11.4.2 Methodology for One or Several Stable Points of Injection below the Reservoir Static Liquid Level .....	651
11.4.3 Continuous Gas Injection but the Well Does not Produce Liquids.....	667

<b>11.5</b>	Field Techniques for Troubleshooting a Gas Lift Well.....	674
11.5.1	Communication Tests .....	674
11.5.2	Downhole Pressure and Temperature Surveys.....	681
11.5.3	Use of Sonic Devices.....	689
11.5.4	Use of CO <sub>2</sub> Injection to Determine the Point of Injection.....	695
11.5.5	Downhole Pressure and Temperature Measurements Using Permanent Downhole Sensors.....	706
11.5.6	Total Well Depth and Liquid Level Measurements Using Wireline Tools .....	711
11.5.7	Downhole Temperature Measurement Using Fiber-Optic Surveys (Distributed Temperature Sensors or DTS).....	712
11.5.8	Measurement of the Liquid Level (or Instantaneous Liquid Flow Rate) Inside the Test Separator .....	718
11.5.9	Use of Injection Gas Flow Rate Measurement Charts.....	720
11.5.10	Use of Wellhead Pressure Charts .....	724
<b>11.6</b>	Automated Systems to Detect and Analyze Wells with Operational Problems in Gas Lift Fields with a Large Number of Wells (i-Field Solution) .....	738
<b>11.7</b>	Troubleshooting Examples .....	743
11.7.1	Example #1: Continuous Liquid Production and Gas Injection; Injection Point Might be Plugged.....	743
11.7.2	Example #2: Fluctuating Injection Pressure and Continuous Liquid Production .....	746
11.7.3	Example #3: Time Intervals of Continuous Gas Injection and Liquid Production Followed by Time Intervals in which the Liquid Production and the Gas Injection Flow Rate Drop to Zero.....	749
11.7.4	Example #4: Well's Responses to Different Choke Diameters After a Workover Job .....	752
11.7.5	Example #5: Continuous Gas Injection but the Well Does not Produce Liquids.....	755
<b>11.8</b>	Gas Lift Troubleshooting Guide .....	756
11.8.1	Well is Flowing and Takes Gas (Stable Gas Injection and Liquid Production) .....	756
11.8.2	Well is Flowing and Takes Gas (Unstable Gas Injection and Liquid Production) .....	759
11.8.3	Well is only Circulating the Injection Gas (Well Takes Gas but Does not Produce Liquids) .....	761
11.8.4	Well is not Flowing and Does not Take Gas .....	763
	References .....	763

<b>CHAPTER 12 Intermittent Gas Lift Troubleshooting</b>	<b>765</b>
12.1 Introduction	765
12.2 Analysis of the Operation of Wells with Intermittent Gas Injection	769
12.2.1 Wells that should not be Analyzed as Intermittent Gas Lift Wells	770
12.2.2 Calculation Techniques for Wells that should be Analyzed as Intermittent Gas Lift Wells	783
12.3 Pressure and Temperature Surveys for Wells on Intermittent Gas Lift	833
12.3.1 Survey Procedure	833
12.3.2 Survey Analysis	837
12.3.3 Examples of Downhole Pressure and Temperature Surveys in Intermittent Gas Lift Wells	845
12.4 Use of Sonic Devices and Distributed Temperature Sensor (DTS) Using Fiber Optics	874
12.5 Wellhead Pressure Chart Interpretation	877
12.5.1 General Examples	877
12.5.2 Examples of Specific Field Cases	899
12.6 Intermittent Gas Lift Troubleshooting Examples	912
12.6.1 Example #1 (Well Might be Loaded with Liquids)	913
12.6.2 Example #2 (Tubing-Annulus Communication)	918
12.6.3 Example #3 (Formation Damage)	920
12.6.4 Example #4 (Optimized Well)	924
12.6.5 Example #5 (Large Fallback Losses)	926
12.6.6 Example #6 (Tubing-Annulus Communication)	929
12.6.7 Example #7 (Pilot Valve Failure/Inadequate Spread)	930
12.6.8 Example #8 (Inadequate Continuous Gas Lift Design)	935
12.6.9 Example #9 (Production Tubing Diameter too Large)	942
12.6.10 Example #10 (Formation Damage when the Well was Shifted to Produce on Intermittent Gas Lift)	945
12.6.11 Example #11 (Intermittent Gas Lift with Surface Intermittent)	952
Subject Index	955

# Gas properties

The working fluid of a gas lift installation is, in most cases, the natural gas associated with the oil that is produced from the same field or from a nearby gas source. The calculation of the injection gas properties is a necessary first step to predict pressures, temperatures, flow rates, etc. at in-situ conditions in the different components of a gas lift installation. Without the knowledge of these properties, it is simply not possible to determine the important parameters that are frequently used in gas lift designs and troubleshooting analyses, such as the pressure and temperature gradients along the injection annulus that are used to locate the depths of the gas lift valves.

The correlations that can be used to calculate the properties of hydrocarbon gases are described in their general forms in the chapter. Many of the correlations given in the list of references in the chapter were developed a long time ago and have been successfully applied during the last decades; however, it is important to always use values of these properties that have been measured in field laboratories in order to: (1) corroborate the accuracy of these correlations for different operational conditions, and (2) calibrate the correlations that are used by commercially available gas lift design and troubleshooting software to calculate these properties.

The natural gas used as the injection gas in most gas lift installations is a mixture of different hydrocarbon substances of low molecular weight in gaseous state, such as methane, and some nonhydrocarbon impurities like nitrogen, hydrogen sulfide ( $\text{H}_2\text{S}$ ), and carbon dioxide ( $\text{CO}_2$ ). If the mixture has significant quantities of  $\text{H}_2\text{S}$  and/or  $\text{CO}_2$ , the gas is an “acid gas” because it forms an acidic solution in presence of water. An acid gas mixture is not recommended for use in a gas lift field because of the problems it creates for the safety of the personnel and the corrosion of tubular goods and equipment.

If the  $\text{H}_2\text{S}$  concentration is greater than 4 parts per million (ppm), the gas is also called a “sour gas,” otherwise the gas is called a sweet gas. It is important



to maintain the  $\text{H}_2\text{S}$  concentration at values less than 4 ppm because higher concentrations could cause the following problems or inconveniences:

- Because these high concentrations are highly toxic, special safety measurements must be taken to avoid health related problems or even deadly accidents when dealing with sour gases.
- Sour gases can cause sulfur precipitation that can accumulate in the production tubing, flowline, injection gas lines, etc.
- Sour gases are also highly corrosive, especially in presence of salt water.

$\text{H}_2\text{S}$  reacts with water and iron to form iron sulfide and hydrogen.  $\text{CO}_2$ , on the other hand, reacts with water to form carbonic acid, which then reacts with iron to form iron carbonate and hydrogen. A gas mixture could be corrosive if its  $\text{CO}_2$  partial pressure (defined in Section 1.1) is greater than 3 psi. Actions that need to be taken to overcome the negative effects of  $\text{CO}_2$ ,  $\text{H}_2\text{S}$ , and water are presented in different sections in this book. The necessary corrections in the calculation of the properties of natural gases and water vapor are addressed in the chapter if impurities such as  $\text{CO}_2$  and  $\text{H}_2\text{S}$  are present in small quantities, but the equations to calculate the properties of these impurities alone are not presented.

## 1.1 EQUATION OF STATE

It is very important in many gas lift calculation procedures to be able to express the volume that a given gas, or a mixture of several gases, occupies in terms of its pressure and temperature. The general gas law given in the form of Eq. 1.1 is one of the many so-called “equations of state” that are used to correlate volume, pressure, and temperature of a gas:

$$PV = nR_uT \quad (1.1)$$

Where  $V$  is the volume the gas occupies,  $P$  is the gas absolute pressure,  $R_u$  is the universal gas constant,  $T$  is the absolute temperature of the gas, and  $n$  is the number of moles inside volume  $V$ .

A mole is a given number of molecules of a particular gas with a mass numerically equal to the molecular weight of the gas in the system of units being used. The number of molecules depends on the mole definition being used. For example: (1) in 1 pound-mole (lb-mol) there are  $2.73 \times 10^{26}$  molecules of the gas, (2) in 1 gram-mole (g-mol) there