

TRANSMISSION PIPELINE CALCULATIONS AND SIMULATIONS MANUAL

E. SHASHI MENON





TRANSMISSION PIPELINE CALCULATIONS AND SIMULATIONS MANUAL

E. SHASHI MENON

Vice President

SYSTEK Technologies, Inc.

USA



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
225 Wyman Street, Waltham, MA 02451, USA
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK

Copyright © 2015 E. Shashi Menon. Published by 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 arrangement with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: 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.

ISBN: 978-1-85617-830-3

Library of Congress Cataloging-in-Publication Data

A catalog record for this book is available from the Library of Congress

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

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 • www.bookaid.org



TRANSMISSION PIPELINE CALCULATIONS AND SIMULATIONS MANUAL

PREFACE

This book was written to provide guidance on the design of liquid and gas pipelines for both practicing engineers as well as graduate engineers entering the pipeline field as their first employment.

We assume the engineer is familiar with basic fluid mechanics including the Bernoulli's equation. Some knowledge of pumps and compressors is also assumed.

This book covers pipeline hydraulics as it applies to transportation of liquids and gases through pipelines in a single phase steady state environment. It will serve as a practical handbook for engineers, technicians, and others involved in the design and operation of pipelines transporting liquids and gases. Currently, existing books on the subject are mathematically rigorous, theoretical, and lack practical applications. Using this book, engineers can better understand and apply the principles of hydraulics to their daily work in the pipeline industry without resorting to complicated formulas and theorems. Numerous examples from the author's real life experiences are included to illustrate the application of pipeline hydraulics.

The application of hydraulics to liquid and gas pipelines involve understanding of various properties of fluids, concept of pressure, friction and calculation of the energy required to transport fluids from point A to point B through a pipeline. You will not find rigorous mathematical derivation of formulas in this book. The formulas necessary for calculations are presented and described without using calculus or complex mathematical methods. If the reader is interested in how the formulas and equations are derived, he should refer to any of the books and publications listed under the Reference section toward the end of this book.

This book covers liquid and gas properties that affect flow through pipelines, calculation of pressure drop due to friction, horsepower required, and the number of pumps or compressor stations required for transporting the fluid through a pipeline. Topics covered include basic equations necessary for pipeline design, commonly used formulas to calculate frictional pressure drop and necessary horsepower, the feasibility of improving an existing pipeline performance using drag reduction additives (for liquid lines), and power optimization studies. The use of pumps, compressors, and valves in pipelines are addressed along with modifications necessary to improve pipeline throughput. Economic analysis and transportation tariff calculations

are also included. This book can be used for the analysis of both pipeline gathering systems, plant or terminal piping, as well as long distance trunk lines. The primary audience for the book is engineers and technicians working in the petroleum, water, and process industry. This book could also be used as a textbook for a college level course in pipeline hydraulics.

We are indebted to Ken McCombs of Elsevier for encouraging us to write this book and also for waiting patiently for two years for us to complete this book while Shashi was recuperating from a quintuple heart bypass and sepsis. We would also like to acknowledge our sincere appreciation to Katie Hammon and Kattie Washington who were both very instrumental in getting the book in print. Finally, I would like to dedicate this book to my father and mother, who always believed I could write a technical book, but unfortunately did not live long enough to see it completed.

We invite comments and suggestions for improvements of the book from readers of the book and to point out any errors and omissions they feel. We sincerely hope this book will be an excellent addition to the Pipeline Engineer's library.

E. Shashi Menon, PhD, PE

Pramila S. Menon, MBA

Lake Havasu City, AZ

CONTENTS

Preface

xi

1. Introduction to Transmission Pipelines	1
1. Trans-Alaska Pipeline (North America)	5
2. Tennessee Gas Pipeline (North America)	7
3. Rockies Express Pipeline (North America)	7
4. TransCanada Pipeline (North America)	8
5. The Bolivia–Brazil Pipeline (South America)	8
6. GasAndes Pipeline (South America)	9
7. Balgzand Bacton Pipeline (Europe)	9
8. Trans-Mediterranean Natural Gas Pipeline (Europe–Africa)	9
9. Yamal–Europe Pipeline (Europe–Asia)	10
10. South Caucasus Pipeline (Asia)	11
11. West-East Natural Gas Pipeline Project (China–Asia)	11
12. The Caspian Pipeline (Russia–Asia)	12
Reference	13
 2. Standards and Codes	 15
1. Codes, Standards, and Regulations	15
2. Boiler and Pressure Vessel Code	19
3. Federal and State Laws	20
4. ASME Council for Codes and Standards	21
5. API Standards and Recommended Practices	22
6. Manufacturers Standardization Society	23
7. Pipe Fabrication Institute Standards	24
8. American Institute of Steel Construction	24
9. American Concrete Institute	25
10. National Association of Corrosion Engineers	26
11. Fluid Control Institute Standards	26
12. Hydraulics Institute Pump Standards	26
 3. Physical Properties	 29
1. Properties of Liquids and Gases	29
2. Units of Measurement	30
3. Mass, Volume, Density, and Specific Weight	34
4. Specific Gravity and API Gravity	37

5. Viscosity	41
6. Vapor Pressure	51
7. Bulk Modulus	51
8. Fundamental Concepts of Fluid Flow	53
9. Gas Properties	56
10. Mass	56
11. Volume	57
12. Density and Specific Weight	58
13. Specific Gravity	58
14. Viscosity	59
15. Ideal Gases	64
16. Real Gases	69
17. Natural Gas Mixtures	69
18. Pseudo Critical Properties from Gravity	71
19. Adjustment for Sour Gas and Nonhydrocarbon Components	72
20. Compressibility Factor	72
21. Heating Value	79
22. Summary	81
23. Problems	81
4. Pipeline Stress Design	83
1. Allowable Operating Pressure and Hydrostatic Test Pressure	83
2. Barlow's Equation for Internal Pressure	85
3. Gas Transmission Pipeline: Class Location	89
4. Line Fill Volume and Batches	93
5. Gas Pipelines	95
6. Barlow's Equation	96
7. Thick Wall Pipes	97
8. Derivation of Barlow's Equation	99
9. Pipe Material and Grade	101
10. Internal Design Pressure Equation	102
11. Mainline Valves	103
12. Hydrostatic Test Pressure	104
13. Blowdown Calculations	144
14. Determining Pipe Tonnage	145
15. Summary	148
5. Fluid Flow in Pipes	149
1. Liquid Pressure	149
2. Liquid: Velocity	154

3. Liquid: Reynolds Number	156
4. Flow Regimes	158
5. Friction Factor	159
6. Pressure Drop from Friction	165
7. Colebrook–White Equation	167
8. Hazen–Williams Equation	168
9. Shell-MIT Equation	170
10. Miller Equation	172
11. T.R. Aude Equation	173
12. Minor Losses	175
13. Internally Coated Pipes and Drag Reduction	179
14. Fluid Flow in Gas Pipelines	181
15. Flow Equations	183
16. General Flow Equation	184
17. Effect of Pipe Elevations	187
18. Average Pipe Segment Pressure	188
19. Velocity of Gas in a Pipeline	189
20. Erosional Velocity	192
21. Reynolds Number of Flow	194
22. Friction Factor	197
23. Colebrook–White Equation	198
24. Transmission Factor	202
25. Modified Colebrook–White Equation	206
26. AGA Equation	209
27. Weymouth Equation	213
28. Panhandle A Equation	216
29. Panhandle B Equation	219
30. Institute of Gas Technology Equation	222
31. Spitzglass Equation	225
32. Mueller Equation	227
33. Fritzsche Equation	228
34. Effect of Pipe Roughness	229
35. Comparison of Flow Equations	231
36. Summary	233
6. Pressure Required to Transport	235
1. Total Pressure Drop Required to Pump a Given Volume of Fluid through a Pipeline	236
2. Frictional Component	237
3. Effect of Pipeline Elevation	237

4. Effect of Changing Pipe Delivery Pressure	241
5. Pipeline with Intermediate Injections and Deliveries	242
6. System Head Curves: Liquid Pipelines	255
7. Hydraulic Pressure Gradient: Liquid Pipeline	258
8. Transporting High Vapor Pressure Liquids	263
9. Hydraulic Pressure Gradient: Gas Pipeline	264
10. Pressure Regulators and Relief Valves	268
11. Summary	271
7. Thermal Hydraulics	273
1. Temperature-Dependent Flow	273
2. Formulas for Thermal Hydraulics: Liquid Pipelines	277
3. Isothermal versus Thermal Hydraulics: Gas Pipelines	289
4. Temperature Variation and Gas Pipeline Modeling	292
5. Review of Simulation Model Reports	294
6. Summary	315
7. Practice Problems	316
8. Power Required to Transport	317
1. Horsepower Required	317
2. Effect of Gravity and Viscosity	321
3. Gas: Horsepower	322
4. Summary	327
9. Pump Stations	329
1. Introduction	329
2. Liquid-Pump Stations	329
3. Summary	367
10. Compressor Stations	369
1. Introduction	369
2. Compressor Station Locations	369
3. Hydraulic Balance	376
4. Isothermal Compression	376
5. Adiabatic Compression	378
6. Polytropic Compression	381
7. Discharge Temperature of Compressed Gas	382
8. Compression Power Required	383
9. Optimum Compressor Locations	387
10. Compressors in Series and Parallel	393

11. Types of Compressors: Centrifugal and Positive Displacement	397
12. Compressor Performance Curves	398
13. Compressor Head and Gas Flow Rate	400
14. Compressor Station Piping Losses	401
15. Compressor Station Schematic	404
16. Summary	404
11. Series and Parallel Piping	405
1. Series Piping	405
2. Parallel Piping	415
3. Locating Pipe Loop: Gas Pipelines	429
12. Meters and Valves	431
1. History	431
2. Flow Meters	432
3. Venturi Meter	433
4. Flow Nozzle	436
5. Orifice Meter	437
6. Turbine Meter	439
7. Positive Displacement Meter	440
8. Purpose of Valves	443
9. Types of Valves	444
10. Material of Construction	446
11. Codes for Design and Construction	447
12. Gate Valve	448
13. Ball Valve	449
14. Plug Valve	450
15. Butterfly Valve	450
16. Globe Valve	452
17. Check Valve	452
18. Pressure Control Valve	453
19. Pressure Regulator	453
20. Pressure Relief Valve	455
21. Flow Measurement	455
22. Flow Meters	456
23. Venturi Meter	467
24. Flow Nozzle	469
25. Summary	470

13. Pipeline Economics	473
1. Economic Analysis	473
2. Capital Costs	475
3. Operating Costs	480
4. Feasibility Studies and Economic Pipe Size	480
5. Gas Pipeline	487
6. Capital Costs	489
7. Operating Costs	495
8. Determining Economic Pipe Size	499
9. Summary	514
10. Problems	516
14. Case Studies	519
1. Introduction	519
2. Case Study 1: Refined Products Pipeline (Isothermal Flow) Phoenix to Las Vegas Pipeline	519
3. Case Study 2: Heavy Crude Oil Pipeline 2 Miles Long without Heaters	527
4. Case Study 3: Heavy Crude Oil Pipeline from Joplin to Beaumont (Thermal Flow with Heaters and no Batching)	537
5. Case Study 4: Heavy Crude Oil Pipeline (Thermal Flow with Heaters and DRA)	543
6. Case Study 5: Water Pipeline from Page to Las Cruces	546
7. Case Study 6: Gas Pipeline with Multiple Compressor Stations from Taylor to Jenks	549
8. Case Study 7: Gas Pipeline Hydraulics with Injections and Deliveries	558
9. Case Study 8: Gas Pipeline with Two Compressor Stations and Two Pipe Branches	562
10. Sample Problem 9: A Pipeline with Two Compressor Stations, Two Pipe Branches, and a Pipe Loop in the Second Segment of the Pipeline to Handle an Increase in Flow	567
11. Sample Problem 10: San Jose to Portas Pipeline with Injection and Delivery in SI Units	571
<i>Appendix</i>	577
<i>References</i>	587
<i>Index</i>	589



Introduction to Transmission Pipelines

Pipelines are used to transport liquids or gases from point of origin to point of consumption of liquids or gases. Transmission pipelines may be small diameter such as 4 in or the average size may range from 24 to 32 in or more in diameter. Over the course of several years, much larger pipelines have been built in the United States and abroad ranging from 48 to 60 in or larger diameter. These pipelines may be short lines, such as gathering lines ranging from a few feet to as much as a couple of miles. They may also be long trunk lines a few thousand miles long. In addition to providing the necessary pipe material, we must also provide the necessary pressure in terms of pumping equipment and drivers as well as other related appurtenances such as valves, regulators, and scraper traps. The Trans-Alaska Pipeline is a well-known large-diameter pipeline built in the United States during the past 25 years at a cost of more than \$8 (US Billion) dollars.

In this book, we will concentrate on transmission pipelines used to transport liquids such as water, refined petroleum products as well as natural gas or compressible fluids such as propane and ethane. More sophisticated pipelines have also been built to transport exotic gases and liquids such as ethylene or compressed high-density carbon dioxide (CO_2). The latter pipelines require extensive hydraulic simulation or modeling taking into account the thermodynamic properties of CO_2 including liquid vapor diagrams as well as the complex formulas that define the behavior of high density CO_2 .

Starting with 1866 in Pennsylvania, United States, when the first practical pipeline was constructed by the entrepreneur and scientist Edwin Drake, the United States set the stage for the proliferation of practical utilization of pipelines ranging from a few miles to tens of thousands of miles all over the world.

It must be noted that although the US pioneered pipeline efforts in the 1800s, credit must be given to engineers, technicians, and scientists that paved the way for progress in transporting “black gold” to satisfy the twentieth century requirements of mankind, which has reached a level unimaginable particularly during the past few decades. Considering that oil was available for about \$20 per barrel (bbl) in the 1800s, we are now experiencing a tremendous price increase of \$100 to \$150 bbl in recent years. There does

not seem to be a let up in the consumption of crude oil and petroleum products despite the fact that the industrialized nations have spent enormous amounts of research and development efforts in replacing oil with a more renewable energy sources such as solar and wind power. The largest consumption by the public for crude oil is the application of diesel and gasoline for motor vehicles. Despite the enormous progress made with electric cars and non-crude oil-based fuels such as compressed natural gas, liquified natural gas, and hydrogen gas, for a long time to come crude oil and their derivatives will remain a major portion of the energy source for worldwide use. For comparison, consider the cost of crude oil today at \$100–120 per bbl versus electricity at \$0.15 per KWH compared with natural gas cost of \$8–10 per MCF. Of course these are only approximations and can vary from country to country depending on Organization of Petroleum Exporting Countries, and other natural gas and crude oil price regulating organizations.

The most important oil well ever drilled in the United States was in the middle of quiet farm country in northwestern Pennsylvania in a town called Titusville. In 1859, the newly formed Seneca Oil Company hired retired railroad conductor Edwin L. Drake to investigate suspected oil deposits. Drake used an old steam engine to drill a well that began the first large-scale commercial extraction of petroleum. This was one of the first successful oil wells drilled for the sole purpose of finding oil. This was known as the Drake Well. By the early 1860s, western Pennsylvania had been transformed by the oil boom. This started an international search for petroleum, and in many ways eventually changed the way we live.

The reason Drake chose Titusville as the spot to drill for oil was the many active oil seeps in the region. As it turns out, there had already been wells drilled that had struck oil in the region. The only problem was, they were not drilling for oil. Instead, they were looking for salt water or drinking water. When they struck oil, they considered it a nuisance and abandoned the well. At the time, no one really knew how valuable oil was.

Later on, they hoped that “rock oil” could be recovered from the ground in large enough quantities to be used commercially as a fuel for lamps. Oil had already been used, refined, and sold commercially for one of its byproducts: kerosene. Along came a gentleman named Bissell who would try to extract the rock oil from the ground by drilling, using the same techniques as had been used in salt wells. Bissell was simply looking for a better, more reliable, and plentiful source.

Table 1.1 shows a list of long-distance pipelines being used around the world to transport gas, crude oil, and products from the fields to areas of

Table 1.1 Various Transmission Pipelines in North America

Project Name	Start Point	End Point	Diameter (inches)	Length (Km)	Capacity (1000 b/d or bn cm)
—	Bakersfield	Los Angeles	—	—	—
—	Chicago	Cushing	2 × 12, 22	—	—
—	Clearbrook	Minneapolis	16	—	—
—	Clearbrook	Bismark	10	—	—
—	Cushing	Wood River	22	703	275
—	Dallas	Lima	20	—	—
—	Guernsey	Chicago	8, 12, 20, 24	—	—
—	Los Angeles	San Juan	16	—	—
—	Los Angeles	San Francisco	34	—	—
—	Louisiana	Lima	22	—	—
—	Midland	Corpus Christi	10, 12	—	—
—	Midland	Cushing	2 × 16	—	—
—	Midland	Borger	12	—	—
—	Midland	Houston	1, 24	742	310
—	Minneapolis	St. Louis	20	—	—
—	Minneapolis	St. Louis	24	—	—
—	New Mexico	Cushing	20, 24	832	350
—	Port Arthur	Midland	10	—	—
—	Prudhoe Bay, Alaska	Valdez	34	—	—
—	San Juan	Houston	12, 16	—	—
—	Santa Barbara	Houston	10	—	—
—	Saint James	Patoka	40	1068	1175
—	Wichita	Kansas City	34	—	—
Portland natural gas transmission	Westbrook	Colebrook	—	—	—
—	Hugoton	Denver	2 × 20	—	—
—	Los Angeles	San Diego	36	—	—
—	Los Angeles	Houston	36	—	—
—	Louisiana	Pittsburgh	—	—	—
—	Louisiana	Detroit	—	—	—
—	Mountain Home	Reno	16	—	—
—	New Orleans	Portland	42	—	—
—	Salt Lake City	Pendleton	22	—	—
—	Sal Lake City	Bakersfield	—	—	—
—	San Juan	Bakersfield	24, 30	—	—
—	San Juan	El Paso	2 × 30	—	—
—	C33	Raleigh	—	—	—

(Continued)

Table 1.1 Various Transmission Pipelines in North America—Cont'd

Project Name	Start Point	End Point	Diameter (inches)	Length (Km)	Capacity (1000 b/d or bn cm)
—	Amarillo	El Paso	6	—	—
—	Baton Rouge	Washington, DC	6, 30	5081	550
—	Billings	Minot	8	—	—
—	Billings	Casper	6, 12	1097	100
—	Bismark	Detroit	10	—	—
—	Casper	Rapid City	12	—	—
—	Chicago	Green Bay	10, 16	516	166
—	Chicago	New York	—	—	—
—	Chicago	Saint Louis	—	—	—
—	Denver	Wichita	—	—	—
—	Denver	Houston	6, 8	—	—
—	Denver	Sinclair	—	—	—
—	Des Moines	Cushing	—	—	—
—	El Paso	Midland	2 × 8	—	—
—	Ferndale	Eugene	16	—	—
—	Houston	Port Isabel	—	—	—
—	Houston	Philadelphia	36, 40	—	—
—	Joliet	Toledo	8, 18	990	300
—	Kansas	Detroit	10, 16	516	166
—	Lake Charles	Hammond	8, 28	2248	283
—	Los Angeles	San Diego	10	—	—
—	Los Angeles	El Paso	12	—	—
—	Midland	Rock Springs	8	—	—
—	Midland	Houston	10	—	—
—	Minneapolis/ St. Paul	Midland basin	8, 10	—	—
—	Minneapolis/ St. Paul	Tulsa	8, 12, 20	—	—
—	Mount Belvieu	Raleigh	6, 12	2097	100
—	Omaha	Chicago	—	—	—
—	Omaha	New Orleans	10	—	—
—	Port Arthur	Abilene	12	—	—
—	Port Arthur	Albany	2 × 16, 20	—	—
—	Salt Lake City	Spokane	8	—	—
—	San Bernardino	Las Vegas	8, 14	—	—
Sacramento line	San Francisco	Bakersfield	8, 12, 14	—	—
—	Spokane	Billings	10	—	—
—	Tulsa	Detroit	2 × 10, 12, 14	566, 493	75, 100

Table 1.1 Various Transmission Pipelines in North America—Cont'd

Project Name	Start Point	End Point	Diameter (inches)	Length (Km)	Capacity (1000 b/d or bn cm)
<i>Canada/United States</i>					
—	Edmonton	Puget Sound	2	—	92
—	Edmonton	Guernsey	8, 12	—	—
—	Edmonton	Detroit	20, 24, 34	—	1400
—	Montreal	Chicago	30	—	—
—	Regina	Guernsey	6, 16	600	85
—	Calgary	Barstow	2 × 34, 36	—	—
—	Fort Nelson	Melford	10, 30, 36	—	—
Maritimes and Northeast	Goldsboro	Westbrook	30	56	—
—	Edmonton	Windsor	12	3170	92
—	Portland	Montreal	24	770	109
—	Portland	Montreal	18	770	—
Alaska Gas Pipeline	Prudhoe Bay	Edmonton	—	—	—

use. Sometimes these fields are located in one country or continent and then transported by pipeline for distribution through several countries.



1. TRANS-ALASKA PIPELINE (NORTH AMERICA)

This 48-in-diameter steel pipeline zigzags across the frozen tundra of Alaska for 800 miles. It stretches from Prudhoe Bay, on Alaska's North Slope, to the northernmost ice-free port at Valdez, Alaska, on Prince William Sound. Along the way, it must travel over three mountain ranges, cross more than 500 rivers and streams, over three unstable earthquakes faults, and through the migration paths of the caribou and moose. The construction of the Trans-Alaska Pipeline (the most expensive private undertaking) cost \$8 billion. The completed, 48-inch -diameter pipeline was opened for business in 1977.

The pipeline was purposely built in a zigzag configuration to allow the pipe to move more easily from side to side and lengthwise in cases of earthquakes or temperature-related fluctuations. The effectiveness of this design was proven in 2002 when the pipeline survived a 7.9-magnitude earthquake. Where it runs over fault lines, the pipeline rests on perpendicular so-called "slider supports," which are long rails that will allow the