

---

# Contents

## *PART I Pipe Flows*

<b>Chapter 1</b>	<b>Introduction</b>	<b>3</b>
1.1	Definition and Scope	3
1.2	Brief History of Pipelines	3
1.3	Existing Major Pipelines	4
1.4	Importance of Pipelines	9
1.5	Freight (Solids) Transport by Pipelines	9
1.6	Types of Pipelines	11
1.7	Components of Pipelines	12
1.8	Advantages of Pipelines	12
	References	16
<b>Chapter 2</b>	<b>Single-Phase Incompressible Flow of Newtonian Fluid</b>	<b>17</b>
2.1	Introduction	17
2.2	Flow Regimes	19
2.3	Local Mean Velocity and Its Distribution (Velocity Profile)	19
2.3.1	Variation of Velocity along Pipe	21
2.3.2	Velocity Profile of Fully Developed Flow	23
2.4	Flow Equations for One-Dimensional Analysis	26
2.4.1	Continuity Equation	26
2.4.2	Energy Equation	27
2.4.3	Momentum Equation	29
2.4.4	Headloss Formulas	32
2.4.4.1	Fitting Loss	32
2.4.4.2	Pipe Loss	37
2.4.4.3	Total Loss	41
2.4.5	Shear on Pipe Wall	42
2.5	Hydraulic and Energy Grade Lines	44
2.6	Cavitation in Pipeline Systems	44
2.7	Pipes in Series and Parallel	47
2.7.1	Pipe in Series	47
2.7.2	Parallel Pipes	48
2.8	Interconnected Reservoirs	51
2.9	Pipe Network	55
2.10	Unsteady Flow in Pipe	57

2.10.1	Quasi-Steady Solution	58
2.10.1.1	Drainage of a Reservoir or Pipe	58
2.10.1.2	Flow Establishment (Fluid Acceleration Due to Sudden Valve Opening)	61
2.10.1.3	Flow Oscillations in Interconnected Tanks	63
2.10.2	Unsteady Solution: Water Hammer	65
2.10.2.1	Propagation of Small Pressure Disturbances in Pipes	66
2.10.2.2	Celerity of Water Hammer Waves	66
2.10.2.3	Rise and Drop of Pressure in Pipe Due to Sudden Valve Closure	67
2.10.2.4	Water Hammer Force on Valve	68
2.10.2.5	Water Hammer Wave Propagation Due to Sudden Valve Closure	69
2.10.2.6	Water Hammer Caused by Partial Closure of Valve	71
2.10.2.7	Water Hammer with Finite Closure Time	72
2.10.2.8	Characteristic Method	73
2.10.3	Surge Tanks	74
	Problems	78
	References	82
<b>Chapter 3</b>	<b>Single-Phase Compressible Flow in Pipe</b>	<b>83</b>
3.1	Flow Analysis for Ideal Gas	83
3.1.1	General Analysis	83
3.1.2	Isothermal Compressible Pipe Flow with Friction	86
3.1.3	Adiabatic Compressible Pipe Flow with Friction	90
3.1.4	Isentropic (Adiabatic Frictionless) Pipe Flow	95
3.2	Flow Analysis for Real (Nonideal) Gas	97
3.2.1	Equation of State	97
3.2.2	Gas Gravity	101
3.2.3	Viscosity of Gas Mixture	102
3.2.4	Flow Equations	104
3.2.5	Approximate Flow Equations	108
3.3	Work, Energy, and Power Required for Compression of Gas	109
3.3.1	General Relationships	109
3.3.2	Isothermal Compression of Ideal Gas	110
3.3.3	Isothermal Compression of Real Gas	110
3.3.4	Isentropic Compression of Ideal Gas	110
3.3.5	Isentropic Compression of Real Gas	113
	Problems	113
	References	114
<b>Chapter 4</b>	<b>Non-Newtonian Fluids</b>	<b>115</b>
4.1	Introduction	115
4.2	Classification of Non-Newtonian Fluids	116

4.3	Rheological Properties and Laws of Non-Newtonian Fluids	118
4.3.1	Power-Law Fluids	118
4.3.2	Bingham Fluids	119
4.3.3	Yield Fluids	119
4.3.4	Other Non-Newtonian Fluids	119
4.4	Non-Newtonian Pipe Flow: Laminar	119
4.4.1	Power-Law Fluids	120
4.4.2	Bingham Fluids	123
4.5	Non-Newtonian Pipe Flow: Turbulent	127
4.5.1	Tomita's Equations	127
4.5.2	Hanks-Dadia Analysis	128
4.5.3	Torrance Equation	128
	Problems	128
	References	129
<b>Chapter 5</b>	<b>Flow of Solid-Liquid Mixture in Pipe (Slurry Pipelines)</b>	<b>131</b>
5.1	Flow Regimes	131
5.2	Pseudohomogeneous Flows	136
5.3	Heterogeneous Flows	138
5.3.1	Limit-Deposit Velocity	138
5.3.2	Pressure Gradient in Heterogeneous Flow	138
5.4	Intermediate Flow Regime	142
5.5	Practical Considerations	143
5.5.1	Wear of Slurry Pipelines	143
5.5.2	Cavitation	144
5.5.3	Slurry Pumps, Valves, and Flowmeters	144
5.5.4	Application of Slurry Pipelines	145
	Problems	146
	References	148
<b>Chapter 6</b>	<b>Flow of Solid-Gas Mixture in Pipe (Pneumotransport)</b>	<b>149</b>
6.1	Introduction	149
6.2	Types of Pneumatic Conveying	150
6.2.1	Negative-Pressure Systems	150
6.2.2	Positive-Pressure Systems	151
6.2.3	Combined (Negative-Positive Pressure) Systems	152
6.2.4	Other Related Systems	152
6.3	Flow Characteristics	152
6.4	System Layouts	156
6.4.1	General Systems	156
6.4.2	Intakes	158
6.4.3	Prime Movers (Air Pumps)	159
6.4.4	Separator and Cleaner	160

6.5	System Design	161
6.6	Safety Considerations	162
6.7	Analyses	163
6.7.1	Pickup Velocity	163
6.7.2	Density and Pickup Velocity Variation along Pipeline	165
6.7.3	Loading Ratio	166
6.7.4	Pressure Drop along Pipe in Dilute-Phase Transport	167
6.7.4.1	Pipe Loss (Loss in Straight Uniform Pipe)	167
6.7.4.2	Local Losses	169
6.7.5	Vertical Conveying	172
6.7.6	Dense-Phase Flow	172
	Problems	173
	References	174
<b>Chapter 7</b>	<b>Capsule Pipelines</b>	<b>175</b>
7.1	Introduction and History	175
7.2	Pneumatic Capsule Pipeline (PCP)	179
7.2.1	System Description	179
7.2.2	Analysis	180
7.2.2.1	Capsule Pressure Drop and Drag	180
7.2.2.2	Steady-State Capsule Velocity	181
7.2.2.3	Pressure Variation along PCP	183
7.2.2.4	Power of PCP	185
7.3	Hydraulic Capsule Pipeline (HCP)	186
7.3.1	System Description	186
7.3.2	Analysis	187
7.3.2.1	Basic Capsule Flow Relationships	187
7.3.2.2	Four Regimes of HCP Flow	189
7.3.2.3	Incipient Velocity	190
7.3.2.4	Lift-Off Velocity	192
7.3.2.5	Critical Velocity	193
7.3.2.6	Capsule Velocity	194
7.3.2.7	Steady Flow Analysis of HCP System	195
7.3.2.8	Pressure Gradient in HCP	195
7.3.3	Capsule Injection and Ejection	195
7.3.3.1	Injection	195
7.3.3.2	Ejection	197
7.3.4	Capsule Pumps	197
7.3.4.1	Pump Bypass	197
7.3.4.2	Electromagnetic Capsule Pumps	198
7.4	Coal Log Pipeline (CLP)	200
7.5	Conclusion	201
	Problems	202
	References	203

## ***PART II Engineering Considerations***

<b>Chapter 8</b>	<b>Pipes, Fittings, Valves, and Pressure Regulators</b>	<b>207</b>
8.1	Types of Pipe	207
8.1.1	Metallic Pipes	207
8.1.1.1	Ordinary Steel Pipe	207
8.1.1.2	Corrugated Steel Pipe	209
8.1.1.3	Cast-Iron Pipe	209
8.1.1.4	Ductile-Iron Pipe	210
8.1.1.5	Stainless Steel Pipe	210
8.1.1.6	Aluminum Pipe	210
8.1.1.7	Copper Pipe	210
8.1.1.8	Other Metal Pipes	210
8.1.2	Nonmetallic Pipe	211
8.1.2.1	Concrete Pipe	211
8.1.2.2	Plastic Pipe	215
8.1.2.3	Clay (Ceramic) Pipe	216
8.1.2.4	Wood and Bamboo Pipes	216
8.1.2.5	Graphite and Carbon Pipes	216
8.1.2.6	Asbestos Cement Pipe	217
8.1.2.7	Rubber and Elastomer Piping	217
8.1.2.8	Glass Pipe	217
8.1.3	Tubing	217
8.2	Pipe Designation	217
8.3	Connections (Joints)	218
8.4	Fittings	224
8.5	Valves	224
8.6	Pressure Relief Valves and Pressure Regulating Valves	227
	Problems	229
	References	229
<b>Chapter 9</b>	<b>Pumps and Turbines</b>	<b>231</b>
9.1	Energy Conversions by Pumps and Turbines	231
9.2	Types of Pumps and Turbines	233
9.2.1	Centrifugal Pumps	233
9.2.1.1	Main Components	233
9.2.1.2	Fluid Mechanics of Centrifugal Pumps	234
9.2.1.3	Euler's Pump Performance Curves	236
9.2.1.4	Pump and System Curves	238
9.2.1.5	Pumps in Combination	244
9.2.2	Positive Displacement Pumps	246
9.2.2.1	Piston Pumps	246
9.2.2.2	Plunger Pumps	250

	9.2.2.3	Diaphragm Pumps	252
	9.2.2.4	Rotary PD Pumps	252
	9.2.2.5	Screw Pumps	252
	9.2.3	Propeller Pumps	253
	9.2.4	Other Types of Pumps	253
	9.2.4.1	Jet Pumps	253
	9.2.4.2	Airlift Pumps	254
	9.2.4.3	Electromagnetic (EM) Pumps	255
9.3		Pump Drivers	258
	9.3.1	Electric Motors	258
	9.3.1.1	Induction Motors	260
	9.3.1.2	Synchronous Motors	260
	9.3.1.3	DC Motors	261
	9.3.2	Engine and Turbine Drivers	262
	9.3.2.1	Engines	262
	9.3.2.2	Turbines	262
9.4		Coupling Pumps to Drivers	263
	9.4.1	Common-Shaft Coupling	263
	9.4.2	Direct Mechanical Coupling	263
	9.4.3	Gears	263
	9.4.4	Belts	264
	9.4.5	Fluid coupling	264
	9.4.6	Eddy-Current Coupling	264
9.5		Pump Control, Operation, and Maintenance	265
	9.5.1	Pump Control	265
	9.5.1.1	Discharge Control by Valves	265
	9.5.1.2	Controlling Pump Speed by Motor Speed	266
	9.5.1.3	Motor Starters	266
	9.5.2	Pump Operation	267
	9.5.2.1	Priming	267
	9.5.2.2	Cavitation	269
	9.5.2.3	Vibration and Noise	269
	9.5.2.4	Overheating	270
	9.5.3	Maintenance	271
9.6		Pump Selection	272
	9.6.1	Fluid Type	272
	9.6.2	Flow Parameters	272
	9.6.3	Number of Pumps	273
	9.6.4	Operating Frequency	273
	9.6.5	Reliability	273
	9.6.6	Safety	274
	9.6.7	Pump Type	274
	9.6.8	Plot of $H\sim Q$ Curves	274
	9.6.9	Pump Efficiency	274
	9.6.10	Cavitation	275
	9.6.11	Pump Drivers	275

9.6.12	Control System	275
9.6.13	Cost	275
9.7	Compressors, Blowers, and Fans	275
9.8	Turbines	278
9.8.1	Introduction	278
9.8.2	Types of Turbines	278
9.8.2.1	Hydraulic Turbines	278
9.8.2.2	Steam and Gas Turbines	283
9.9	Dimensionless Parameters	283
	Problems	285
	References	287
<b>Chapter 10</b>	<b>Instrumentation and Pigging</b>	<b>289</b>
10.1	Flowmeters	289
10.1.1	Types of Flowmeters	289
10.1.1.1	Venturi	289
10.1.1.2	Orifice	291
10.1.1.3	Elbow Flowmeter	292
10.1.1.4	Rotating Flowmeters	294
10.1.1.5	Vibratory Flowmeters	294
10.1.1.6	Rotameters	294
10.1.1.7	Magnetic Flowmeter	295
10.1.1.8	Acoustic Flowmeter	297
10.1.2	Calibration of Flowmeters	299
10.1.2.1	Constant-Head System	299
10.1.2.2	Meter Prover	300
10.1.2.3	Meter-to-Meter Calibration	301
10.2	Sensors and Equipment	301
10.2.1	Manometers	302
10.2.2	Pressure Transducers	303
10.2.3	Temperature Sensors	303
10.2.4	Velocity Sensors	304
10.2.5	Vibration Sensor	306
10.2.6	Strain Gauges	307
10.2.7	Density Measurements	307
10.2.8	Pig and Capsule Sensors	308
10.3	Pigs (Scrapers)	309
10.3.1	Purposes and Types	309
10.3.2	Pigging System	311
10.3.3	Pig Motion Analysis	313
	Problems	315
	References	317
<b>Chapter 11</b>	<b>Protection of Pipelines against Abrasion, Freezing, and Corrosion</b>	<b>319</b>

11.1	Lining, Coating, and Wrapping	319
11.2	Insulation, Tracing, Jacketing, and Electric Heating	320
11.3	Protection against Corrosion	321
11.3.1	Types of Corrosion	321
11.3.1.1	Chemical Corrosion	322
11.3.1.2	Electrochemical Corrosion	322
11.3.1.3	Galvanic Corrosion	322
11.3.1.4	Electrolytic Corrosion	324
11.3.1.5	Other Types of Corrosion	325
11.3.2	Corrosion-Related Measurements	326
11.3.2.1	Corrosion Coupon Test	326
11.3.2.2	Soil Resistivity Measurement	326
11.3.2.3	Pipe-to-Soil Potential	328
11.3.2.4	Line Current Measurement	329
11.3.3	Cathodic Protection	330
Problems		331
References		331
<b>Chapter 12</b>	<b>Planning and Construction of Pipelines</b>	<b>333</b>
12.1	Procedures Involved in Planning and Construction of New Pipelines	333
12.2	Measures to Allow Pipeline Expansion	336
12.3	Bending of Pipes	336
12.4	Connecting Pipes	338
12.4.1	Flanged Joints	339
12.4.2	Other Mechanical Joints	339
12.4.3	Welding	339
12.5	Boring and Tunneling to Install Pipe—Trenchless Technologies	341
12.5.1	Horizontal Earth Boring	342
12.5.1.1	Horizontal Auger Boring	342
12.5.1.2	Microtunneling	343
12.5.1.3	Horizontal Directional Drilling (HDD)	344
12.5.2	Pipe Jacking	346
12.5.3	Tunneling	346
12.5.4	Comments on Trenchless Construction	347
12.6	Pipeline Construction in Marsh and Swamp	348
12.7	Offshore Construction	349
12.8	Cold-Region Construction	351
12.8.1	Freezing	351
12.8.2	Temperature Variation	352
12.8.3	Environmental Concerns	352
12.8.4	Other Considerations	352
References		352
<b>Chapter 13</b>	<b>Structural Design of Pipelines</b>	<b>355</b>
13.1	Introduction	355

13.2	Load Considerations	357
13.2.1	Stress Due to Internal Fluid Pressure	357
13.2.1.1	Steady Pressure	359
13.2.1.2	Unsteady Pressure (Water Hammer)	360
13.2.1.3	Hydrostatic Pressure	361
13.2.2	Stress Due to External Fluid Pressure	362
13.2.3	Static Earth Load on Buried Pipe	362
13.2.3.1	Marston's Theory and Classification of Buried Conduits	362
13.2.3.2	Rigid Conduit in Ditch	363
13.2.3.3	Flexible Conduit in Ditch	366
13.2.3.4	Embankment Conduit	367
13.2.3.5	Tunnel Conduit	369
13.2.4	Live Loads on Buried Pipe	369
13.2.5	Other Loads on Pipelines	369
13.3	Performance Analysis and Design	370
13.3.1	High-Pressure Pipes	370
13.3.1.1	Effect of Temperature Change	371
13.3.1.2	Effects of Pipe Bending	371
13.3.1.3	Seismic Design of Pipelines	373
13.3.2	Low-Pressure Pipes	374
13.3.2.1	Soil Classification	374
13.3.2.2	Soil-Pipe Interaction	375
13.3.2.3	Rigid-Pipe Analysis and Design	375
13.3.2.4	Flexible-Pipe Analysis and Design	377
	Problems	380
	References	382
<b>Chapter 14</b>	<b>Pipeline Operations, Monitoring, Maintenance, and Rehabilitation</b>	<b>383</b>
14.1	General Operation of Pipelines	383
14.2	Automatic Control Systems	384
14.3	Integrity Monitoring and Leak Detection	385
14.3.1	Integrity Monitoring	385
14.3.2	Leak Detection	386
14.3.2.1	Mass-Balance Method	387
14.3.2.2	Pressure-Drop Method	388
14.3.2.3	Computational Modeling of Pipeline Systems	388
14.3.2.4	Visual and Photographic Observations	389
14.3.2.5	Ground-Penetrating Radar	389
14.3.2.6	Pigs	389
14.3.2.7	Dogs	390
14.4	Integrity Management Program	390
14.5	Risk-Based Management	391
14.6	Pipeline Maintenance	392

14.7 Trenchless Rehabilitation Methods	393
14.7.1 Cured-in-Place Lining	393
14.7.2 Slip-Lining	394
14.7.3 Pipe-Bursting	394
14.7.4 Pipe-Shrinking	394
14.7.5 Patching and Sealing	395
References	395
<b>Appendix A</b> Notation	397
English	397
Greek	402
Others	403
<b>Appendix B</b> Conversion between SI and English (ft-lb-s) Units	405
Length	405
Volume	405
Velocity	405
Mass	405
Density	405
Force	406
Pressure and Shear	406
Work, Energy, and Heat	406
Power	406
Dynamic Viscosity	406
Kinematic Viscosity	406
Electric Units	406
Temperature	406
<b>Appendix C</b> Physical Properties of Certain Fluids and Solids	407