Piping System Fundamentals
The Complete Guide to Gaining a Clear Picture of Your Piping System

SECOND EDITION U.S.

Ray T. Hardee, P.E. & Jeffrey L. Sines

ESI PRESS ■ Engineered Software Inc.
4529 Intelco Loop SE ■ Lacey, WA 98503
360-412-0702 ■ ESIPRESS.COM
# Contents

1. **Introduction** ..............................................................................................................1

The Value of a Clear Picture .........................................................................................3
   Clear Picture of System Operation ...........................................................................3
   Clear Picture for Troubleshooting .........................................................................3
   Clear Picture of System Energy Consumption and Costs .......................................3

Elements of a Piping System .........................................................................................4
   Terminology, Units, and Physical Laws .................................................................5
   Tanks and Vessels .................................................................................................5
   Pumps ....................................................................................................................6
   Pipelines ................................................................................................................6
   Valves and Fittings ...............................................................................................6
   Control Valves ......................................................................................................6
   Process Measurements and Controls ....................................................................6
   Processes and Process Equipment ..........................................................................6
   The Total System ..................................................................................................6
   Understanding Energy Consumption and Cost ......................................................6

2. **Terminology, Units, and Physical Laws** .............................................................7

Fluid Properties ..........................................................................................................8
   Mass and Weight .................................................................................................8
   Density ..............................................................................................................8
   Specific Gravity .................................................................................................8
   Specific Volume ...............................................................................................8
   Viscosity ............................................................................................................8
   Vapor Pressure ...................................................................................................9

Flow Rate Terms and Units .......................................................................................9
   Volumetric Flow Rate ........................................................................................9
   Mass Flow Rate .................................................................................................10
   Fluid Velocity ....................................................................................................10

Fluid Energy ..............................................................................................................10
   Pressure ............................................................................................................10
   Absolute and Gage Pressure ................................................................................10
   Vacuum ..............................................................................................................11
   Total, Static, and Dynamic Pressure ....................................................................11
   Head and Hydraulic Energy ................................................................................12
   Hydraulic Grade and Static and Dynamic Head ..................................................12
   Pressure and Head Equivalencies .......................................................................12
   Head Loss ..........................................................................................................13

Physical Laws That Govern Fluid Flow ..................................................................13
   Conservation of Mass .........................................................................................13
   Conservation of Momentum ...............................................................................14
   Conservation of Energy ......................................................................................14
   Units of Energy and Power ................................................................................15
   Bernoulli Equation .............................................................................................15
   Kirchhoff’s Laws ...............................................................................................20
   Pascal’s Law ......................................................................................................22
3. Tanks and Vessels ........................................................23

Applications of Tanks and Vessels ........................................................24

Types of Tanks and Vessels .................................................................24
  Open Tanks ..............................................................................................24
  Closed Tanks ...........................................................................................25

Key Hydraulic Measurements ...............................................................25
  Bottom Elevation ......................................................................................25
  Tank Liquid Level ......................................................................................26
  Tank Surface Pressure .............................................................................26
  Penetration Heights ..................................................................................26
  Other Key Tank Dimensions ....................................................................27

Tank Level Measurement ..........................................................................29
  Direct Measurement of Tank Level ..........................................................29
  Indirect Measurement of Tank Level ........................................................30

Controlling Tank Level ............................................................................31
  Changing Tank Levels ...............................................................................32
  System Response to Changing Tank Level ................................................33
  Operational Problems Involving Tank Level ............................................33

Tank Surface Pressure ...............................................................................34
  Controlling Tank Pressure .......................................................................35
  System Response to Changing Tank Pressure .........................................35
  Operational Problems with Tank Pressure ..............................................36

Tank Temperature Measurements ..........................................................36
  Controlling Tank Temperature .................................................................37
  System Response to Changing Tank Temperature ...................................37
  Operational Problems Involving Tank Temperature ..................................38

Tank Penetrations ....................................................................................38

Common Operating Procedures .............................................................39

Abnormal Operations ................................................................................39
  Over-filling a Tank ....................................................................................39
  Tank Ruptures .........................................................................................39
  Tank Failure Due to Excessive Vacuum ....................................................40

4. Pumps ...............................................................................................41

How a Centrifugal Pump Works ..............................................................42

Major Parts of a Centrifugal Pump ...........................................................43
  Impeller Types ..........................................................................................44
  Pump Casings ...........................................................................................46
  Pump Seals ...............................................................................................48
  Pump Drivers (Fixed vs. Variable Speed) ................................................50

Pump Types .............................................................................................50
  Basic Pump Configurations & Arrangements ...........................................50
  Centrifugal Pumps ..................................................................................50
  Regenerative Turbine Pumps .................................................................53
  Vertical Turbine Pumps ..........................................................................53

Pump Selection Considerations ..............................................................54
# Contents

**Understanding the Pump Performance Curve** ..............................................54  
Types of Curves .................................................................................................54  
Pump Curve Operating Data and Landmarks .........................................................57  
Total Head and Flow Rate ....................................................................................57  
Pump Input Power ..................................................................................................58  
Pump Output Power ...............................................................................................58  
Pump Efficiency and the Best Efficiency Point (BEP) ..............................................59  
Shutoff Head ..........................................................................................................60  
Minimum Flow ........................................................................................................60  
Maximum Flow Rate .............................................................................................61  
Allowable Operating Region ..................................................................................61  
Preferred Operating Region ...................................................................................61  
Net Positive Suction Head Required .......................................................................61  

**Cavitation and Net Positive Suction Head** ..................................................62  
Cavitation ..............................................................................................................62  
Net Positive Suction Head ......................................................................................62  
Calculating NPSHa .................................................................................................63  
Solutions for a Cavitating Pump ............................................................................64  

**Pump Affinity Rules** ....................................................................................67  
Changes in Impeller Speed ....................................................................................68  
Misconceptions About the Affinity Rules .............................................................69  
Changes in Impeller Diameter ..............................................................................71  

**Pump and System Interaction** .....................................................................72  
Parallel Pump Operation .........................................................................................72  
Series Pump Operation ..........................................................................................73  
Dissimilar Parallel or Series Pump Operation .......................................................74  

**Effect of Fluid Properties on the Pump Curve** .........................................75  
Fluid Density ..........................................................................................................75  
Fluid Viscosity .......................................................................................................75  

**Pump Selection Process** ...........................................................................76  
Flow Rate Requirements .........................................................................................76  
Total Head Requirements .......................................................................................76  
NPSHr and NPSHa ..................................................................................................76  
Fluid / Material Compatibility ................................................................................77  

**Operating Pumps Properly** ......................................................................77  
Startup and Shutdown ...........................................................................................77  
Minimum Flow Issues ............................................................................................77  
Pump Run Out .........................................................................................................78  
NPSH .......................................................................................................................78  

**Pump Power & Cost Calculations** .................................................................78  
Calculating Pump Energy Cost ..............................................................................78  
Fixed Speed Flow Control ......................................................................................79  
Variable Speed Flow Control ...............................................................................80  

5. **Pipelines** ...............................................................................................82  

**Piping Terminology** .....................................................................................83  
Pipe and Tubing .....................................................................................................83  
Nominal Pipe Size (NPS) .......................................................................................83  
Pipe Inside Diameter (ID) .....................................................................................83  
Pipe Outside Diameter (OD) .................................................................................83
Contents

Wall Thickness and Schedule ................................................................. 84
Pipe Standard Specifications ................................................................. 84
Absolute Roughness ........................................................................... 84
Relative Roughness ........................................................................... 84

**Pipeline Head Loss Calculations** ..................................................... 84
Darcy Head Loss Calculation ............................................................... 85
Reynolds Number ................................................................................ 86
Relative Roughness ........................................................................... 87
Determining the Darcy Friction Factor .................................................... 87

**Pipeline Head Loss Graph** ................................................................. 91

**Head Loss for Series and Parallel Piping** ......................................... 91
Pipelines in Series .............................................................................. 91
Pipelines in Parallel ............................................................................ 92

**Factors Affecting Pipeline Head Loss** .............................................. 92
Effect of Fluid Properties on Head Loss .................................................. 92
Effect of Pipe Properties on Head Loss ................................................... 94

**Pipe Sizing and Selection** ................................................................. 97
Pipe Material Selection ....................................................................... 97
Pipe Sizing ......................................................................................... 98
Pipe Aging ......................................................................................... 100

**Calculating the Cost of Pipeline Head Loss** ....................................... 100

6. **Valves and Fittings** ................................................................. 102

**Characterizing the Hydraulic Performance Valves and Fittings** ........ 103
Equivalent Length (L/D) .................................................................... 103
Flow Coefficient (C_v) ......................................................................... 103
Resistance Coefficient (K) ................................................................... 105

**Resistance of Valves and Fittings** .................................................... 106
Reducers and Enlargers ....................................................................... 107
Pipe Entrances and Exits .................................................................... 107
Elbows and Bends .............................................................................. 108
Isolation Valves .................................................................................. 110
Check Valves ..................................................................................... 114
Calculating the Hydraulic Performance of Valves and Fittings .......... 117
Comparing the Hydraulic Performance of Valves and Fittings .......... 119

**Valves and Fittings Head Loss Graph** ............................................... 119

**Cost of Head Loss Across Valves and Fittings** ................................. 119
Comparing the Operating Cost of Valves and Fittings ......................... 120
Graphing the Energy Cost of Valves and Fittings ................................. 120

**Selecting Valves and Fittings for a Given Application** ....................... 121

7. **Control Valves** ................................................................. 122

**Role of the Control Valve** .............................................................. 123
**How a Control Valve Works** .......................................................... 123
**Major Parts of a Control Valves** .................................................... 125
Valve Body Assembly ....................................................................... 125
Classifying Control Valves .........................................................127
Classifying Control Valves Based on Valve Actuation ...............127
Classifying Control Valves Based on Characteristic Trim ..........129
Classifying Control Valves Based on Valve Body Style ..........130
Classifying Control Valves Based on Pressure and Temperature Ratings ..........136
Classifying Control Valves Based on Leak Tightness at Shutoff .........137

Considerations for Sizing and Selecting Control Valves ..........138
Control Valve Sizing .................................................................138
Flow Characteristics ...................................................................140
Controllability ..............................................................................140
Rangeability ...............................................................................141
Reliability ...................................................................................141
Fluid / Material Compatibility ......................................................143
Pressure and Temperature ........................................................143
Leak Tightness ...........................................................................143

Cost of Head Loss Across a Control Valve ..............................143

Examples Using the Control Valve Equations .........................143
Sizing a Control Valve for a Given Flow Rate and Pressure Drop ..................................................143
Calculating Pressure Drop and Head Loss ...............................144
Calculating the Cost of Control Valve Head Loss .......................145
Determine the Flow Rate Through a Control Valve ..................145

8. Process Measurement and Controls .................................146

Architecture of Process Measurement and Control ..................147
Functionalities ...........................................................................147
Local Indication ........................................................................147
Process Control .........................................................................148
Alarms ......................................................................................149
Protection ..................................................................................149
Networks ....................................................................................150
Operator Consoles ....................................................................150

Process Control ........................................................................151
Primary Elements & Transmitters ...........................................151
Flow Rate Measurements .........................................................152
Pressure and Differential Pressure Measurement .................158
Liquid Level Measurement .........................................................159
Temperature Measurements ......................................................161
Analytical Measurements ........................................................164
Speed and Vibration Measurements .........................................164
Final Control Elements ...............................................................164
Control Valves ........................................................................164
Positioners ...............................................................................165
Transducers .............................................................................166
Controllers ...............................................................................166
Controller Algorithm ...............................................................167
Controller Actions ....................................................................167
Controller Tuning .................................................................168

Control Methods ........................................................................169
On / Off Control ......................................................................170
## Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manual Control (Open Loop)</td>
<td>170</td>
</tr>
<tr>
<td>Automatic Control (Feed back)</td>
<td>170</td>
</tr>
<tr>
<td>Feed Forward Control</td>
<td>171</td>
</tr>
<tr>
<td>Cascade Control</td>
<td>172</td>
</tr>
<tr>
<td>Split Range Control</td>
<td>172</td>
</tr>
<tr>
<td>Ratio Control</td>
<td>173</td>
</tr>
<tr>
<td><strong>9. Processes and Process Equipment</strong></td>
<td>174</td>
</tr>
<tr>
<td><strong>Momentum Transfer</strong></td>
<td>175</td>
</tr>
<tr>
<td>Types of Momentum Transfer Processes</td>
<td>175</td>
</tr>
<tr>
<td>Momentum Transfer Equipment</td>
<td>175</td>
</tr>
<tr>
<td><strong>Heat Transfer</strong></td>
<td>175</td>
</tr>
<tr>
<td>Types of Heat Transfer Mechanisms</td>
<td>176</td>
</tr>
<tr>
<td>Conduction</td>
<td>176</td>
</tr>
<tr>
<td>Convection</td>
<td>176</td>
</tr>
<tr>
<td>Radiation</td>
<td>176</td>
</tr>
<tr>
<td>Types of Heat Transfer Processes</td>
<td>176</td>
</tr>
<tr>
<td>Heating and Cooling</td>
<td>176</td>
</tr>
<tr>
<td>Drying</td>
<td>176</td>
</tr>
<tr>
<td>Evaporation</td>
<td>176</td>
</tr>
<tr>
<td>Boiling</td>
<td>176</td>
</tr>
<tr>
<td>Condensation</td>
<td>177</td>
</tr>
<tr>
<td>Heat Transfer Equations</td>
<td>177</td>
</tr>
<tr>
<td>Heat Transfer Equipment</td>
<td>178</td>
</tr>
<tr>
<td>Types of Heat Exchangers</td>
<td>178</td>
</tr>
<tr>
<td>Hydraulic Performance of Heat Exchangers</td>
<td>180</td>
</tr>
<tr>
<td>Changes to Hydraulic Performance of Heat Exchangers</td>
<td>181</td>
</tr>
<tr>
<td><strong>Mass Transfer</strong></td>
<td>184</td>
</tr>
<tr>
<td>Types of Mass Transfer Processes</td>
<td>184</td>
</tr>
<tr>
<td>Absorption</td>
<td>184</td>
</tr>
<tr>
<td>Adsorption</td>
<td>184</td>
</tr>
<tr>
<td>Distillation</td>
<td>184</td>
</tr>
<tr>
<td>Extraction</td>
<td>184</td>
</tr>
<tr>
<td>Drying</td>
<td>184</td>
</tr>
<tr>
<td>Membrane Separation</td>
<td>184</td>
</tr>
<tr>
<td>Mechanical - Physical Separation</td>
<td>185</td>
</tr>
<tr>
<td>Hydraulic Performance of Mass Transfer Equipment</td>
<td>185</td>
</tr>
<tr>
<td>Hydraulic Performance of Strainers and Filters</td>
<td>185</td>
</tr>
<tr>
<td>Hydraulic Performance of Nozzles and Sprinklers</td>
<td>186</td>
</tr>
<tr>
<td><strong>10. The Total System</strong></td>
<td>188</td>
</tr>
<tr>
<td><strong>Understanding the Total Piping System</strong></td>
<td>189</td>
</tr>
<tr>
<td>Types of Piping Systems</td>
<td>189</td>
</tr>
<tr>
<td>Single Path Open Systems</td>
<td>189</td>
</tr>
<tr>
<td>Branching Systems</td>
<td>190</td>
</tr>
<tr>
<td>Single Path Closed Loop Systems</td>
<td>190</td>
</tr>
<tr>
<td>Multi-Loop Closed Systems</td>
<td>191</td>
</tr>
<tr>
<td><strong>Key Concepts to Understand the Performance of Piping Systems</strong></td>
<td>191</td>
</tr>
<tr>
<td>Head Loss for Pipelines and Components in Series</td>
<td>191</td>
</tr>
<tr>
<td>Steady State Flow Between Two Pressure Boundaries</td>
<td>194</td>
</tr>
<tr>
<td>The Siphon Effect</td>
<td>196</td>
</tr>
</tbody>
</table>
About the Authors

Ray T. Hardee, P.E.
CEO & Chief Engineer of Engineered Software, Inc.

One of the principal founders of Engineered Software, Ray Hardee is also co-owner and Chief Engineer. Starting in 1982, Hardee was chiefly responsible for engineering and sales for Engineered Software. Prior to establishing Engineered Software, Hardee had over 13 years in the power generation industry. Hardee graduated with Honors from the United States Merchant Marine Academy in Kings Point, NY. Upon graduation, Hardee became an officer in the U.S. Naval Nuclear Power program and qualified submarines. After the Navy, Hardee worked for Ebasco Services and was involved in the start-up and test group where he would perform the pre-operational tests for both nuclear and fossil power plants. Hardee has contributed dozens of articles and papers to various magazines and standards publications and has given over a thousand presentations on fluid piping around the world.

Jeffrey L. Sines
Engineering Training Lead with Engineered Software, Inc.

Currently the Engineering Training Lead, Jeff Sines has also been an instructor and support engineer for Engineered Software products since joining the company in 2008. Sines began his career as an electrician in the U.S. Navy Nuclear Power Program in 1986. He was selected for the Enlisted Commissioning Program and earned his Bachelor’s of Science degree in Mechanical Engineering from the University of Texas in Austin. Following commissioning and completion of additional nuclear power training, he served as reactor mechanical division officer and Chemistry and Radiological Controls Assistant aboard a nuclear-powered cruiser. After nine years in the Navy, Sines worked for 11 years at Weyerhaeuser as a production supervisor, operations training coordinator, and power house engineer at a specialty pulp mill. He worked closely with operators, maintenance technicians, and staff engineers to troubleshoot and repair system problems, meet production goals, and implement numerous modernization projects.
Foreword

by Ray T. Hardee

In 2007, as a member of a Hydraulic Institute committee developing a book on Optimizing Pumping Systems, I was asked to write a chapter on pump and system interaction. This effort was initiated because of the committee’s concern about the general lack of understanding about pumped system operation. During that same period, I was asked by the Crane Company to conduct a half-day course at a refinery in Louisiana on how the Crane Technical Paper 410, Flow of Fluids Through Valves, Fittings, and Pipe could be used in an operating plant.

After completing the sections for the Hydraulic Institute's publication and the course for the Crane Company, I realized that the material would be an excellent starting point for a book about piping system fundamentals. The focus of the first edition was to demonstrate the value of gaining a clear picture of the operation of the total piping system by building upon the interrelationship between the various elements that make up the system. In addition, I focused on the need to understand how various items of equipment should be operated to reduce operating, maintenance, and capital costs.

After completing the first edition of Piping System Fundamentals: The Complete Guide to Gaining a Clear Picture of Your Piping System in 2008, I developed a two-day companion training course with the same name. I originally anticipated the course attendees would be recent college graduates or engineers with limited experience. After two other engineers at Engineered Software and I taught around 75 courses totaling around 2,000 attendees, we discovered that many of the attendees were engineers with 5 to 15 years of experience seeking a good refresher on the fundamentals. The customer mix included engineers at design firms, owners/operators of industrial plants, and process equipment sales representatives who needed to gain a better understanding of the total system. One of the benefits of having such a diverse group of attendees is their ability to share their specialized knowledge of piping systems with others in the course and with their instructors.

After reviewing feedback from the attendees, in 2011 the course content underwent a major revision to better meet the needs and expectations of our customers to include content we didn’t originally cover and remove content that didn’t add as much value. Due to the extent of the course changes it was decided at that time we needed to come out with a second edition of Piping System Fundamentals. As Engineered Software’s Training Lead, Jeffrey Sines, had been instrumental in the major revision to the training course, I determined that the second edition of the book would be greatly enhanced by utilizing his skills as a co-author on this release. His research, writing and real-world engineering knowledge were invaluable in developing this book.

The objective of the second edition was to help people involved with industrial piping systems gain a better understanding enabling them to increase plant safety and reliability while reducing operating, maintenance, and capital costs. In this second edition, more emphasis has been placed on understanding
the flow of energy within the piping system and giving the reader the ability to quantify that energy in terms of various engineering units enabling them to calculate the financial cost of that energy.

More emphasis has also been placed on building the foundation of knowledge needed to understand the total piping system by providing clear definitions for common terminology, engineering units, and the physical laws that govern the flow of fluid in a piping system.

With this in mind, three key topics have been added to the book or greatly expanded since the first edition.

- Considering tanks and vessels provide a key piece of information about the piping system, namely a boundary condition defining the total energy state of the fluid in the tank, they warranted a much more in-depth treatment. In the first edition, tanks and vessels were briefly mentioned in the "Piping System Components" chapter. We have since dedicated a full chapter on tanks and vessels.

- Secondly, piping systems exist to carry out processes that alter the properties of the working fluid. To emphasize the importance of this, a high level look at various types of processes are discussed in a new chapter, along with the unique equipment designed to carry out these processes. This chapter now includes some material originally located in the "Piping System Components" chapter in the first edition. Now a full chapter titled "Processes and Process Equipment" has been added.

- Finally, because it is important to measure and control the processes that occur in the piping system, a high-level look at the role of process measurement and controls is examined. The "Flow Meter" chapter from the first edition was pulled into this chapter, but more types of flow meters are now covered along with instruments used to measure fluid pressure, temperature, and tank level. Major elements in a process control loop are discussed including the PID controller, the importance of tuning a control loop, and various types of control methods.

Common pieces of equipment found in a piping system are described in detail throughout the book, including the function of the equipment, the theory of operation, how it should be properly operated to reduce operating cost and maintenance cost, how to troubleshoot operating problems with the equipment, and what information is required to be an educated consumer.

Each chapter has been greatly expanded to include additional key equations, concepts, and images to support the discussion in the text of the chapter. For example, the chapter on pumps now includes an equation to calculate the total head of a pump, better cutaway images to explain the theory of how a pump works, concepts such as the importance of running the pump within a reasonable range of the BEP, and what things can be done to stop a pump from cavitating. A concise equation is presented to calculate the cost of the power that is being added to the fluid by the pump and calculations are done to determine if a variable speed drive is economically feasible compared to flow control with a control valve.

A separate chapter on valves and fittings was written to allow additional discussion on the application of different types of valves, how their hydraulic resistance can be characterized, and what contributes to the amount of head loss across the fitting. Equations are presented to calculate the cost of head loss and compare energy and power consumption of various types.

The control valve chapter has been expanded to provide more discussion of the purpose and role of the components of a control valve, how the trim affects the valve’s characteristic curve, and how valves are classified by leak tightness and pressure and temperature considerations. More attention is given to
cavitation and choking in a control valve and the considerations for sizing and selecting control valves. Lastly, examples are given to demonstrate the use of the control valve equations to size a valve, calculate the pressure drop and head loss across the valve, calculate the cost of the head loss, and determine flow rate through a control valve.

The chapter entitled "Total System" has been expanded to describe the operation of single path open systems, branching systems, single loop closed systems, and multiple loop closed systems. The siphon effect is explored in more depth, including understanding what would cause a siphon, when would this be advantageous or undesirable, and what can be done to alleviate the siphon effect. Understanding the performance of a branching system is covered in more detail, along with new equations given for calculating static head in a system. Considerable time is spent in developing visualization techniques to provide a clear picture of the energy addition and consumption in different types of systems. In addition to more discussion on the use of the pump and system resistance curves, another method is presented that shows the graph of the total fluid energy state as a function of the distance traveled in the piping system, which provides a clear picture of how more complicated systems with multiple destinations can be evaluated.

Finally, a key addition to this second edition is the application of the system knowledge to develop troubleshooting techniques. These techniques can be applied to recognize abnormal operating conditions and evaluate if the condition is understandable considering the hydraulic performance of all the components in the system. The troubleshooting technique then methodically narrows down the root cause to explain what is being seen in the actual system. This section has a tremendous amount of value to those who operate, maintain, supervise, or are in any capacity responsible for troubleshooting problems affecting the production rate and bottom line of companies with piping systems in their facilities.

The second edition incorporates over 90 additional pages of information, charts, graphs, and images providing a comprehensive view of the interaction for the various components found in industrial pumped systems. We've also included a CD at the back of this book that contains a PIPE-FLO Professional demo program and 36 demo files that support various calculations shown in this book. If there is a PIPE-FLO demo file associated with an image or example exercise, the following symbols are used to reference the demo file: 📀 📁

Ultimately, the second edition of Piping System Fundamentals should provide tools and knowledge to better understand system operation and how to troubleshoot problems in a piping system.
Acknowledgements

Writing a book is a daunting task that requires the efforts, knowledge, and skills of many people. We'd like to thank all of the individuals who contributed to this second edition.

First and foremost, we would like to thank the customers and training attendees who provided feedback and professed the need for a comprehensive book about piping systems. Without their suggestions and willingness to share their examples, this book might not have had three new chapters.

Special thanks go to Natalie Jensen, the Marketing Manager for Engineered Software. Without her assistance with the use of the InDesign software this project would have taken much longer to complete. In addition, she spent many hours obtaining permissions to use the images in the book, which greatly enhances the ability to convey key concepts.

There were several engineers at Engineered Software who contributed to the success of this book as well. George Stephens, Roy Lightle, Jesse Bahr, Christy Bermensolo, Buck Jones, and Chris Luzik contributed knowledge and time to review various sections of the book to ensure technical accuracy as well as correct misspellings and grammatical errors.

This edition was also reviewed by several engineers outside of Engineered Software. Special thanks go to the following:

- Mike Pemberton, Manager of Energy Performance Services for ITT (Goulds)
- Mike Volk, owner of Volk & Associates and noted pump system author, trainer and consultant
- Tom Angle, Vice President of Engineering for Hidrostal AG (a Swiss-based pump manufacturer)
- Greg Case, owner of PD³ (Pump Design, Development & Diagnostics)
- Hans Vogelesang, owner of Pump Support in the Netherlands and noted pump trainer and consultant
- Gunnar Hovstadius, PhD, US Department of Energy consultant and owner of Hovstadius Consulting

Finally, we’d like to thank all the companies who have given permission for the use of their images in both the first and second editions. Without their images this book would surely miss it's mark.

While the authors bear sole responsibility for the content and any possible inaccuracies, this book expounds on the principles of understanding energy flow through a piping system, and quantifying it in order to design piping systems more efficiently. We hope this book clarifies why total system understanding is important, and how it can be used to improve future system designs.

Jeffrey L. Sines
March 2012
Chapter One

Introduction
Chapter 1: Introduction

A piping system consists of tanks, pumps, valves, and components connected together by pipelines to deliver a fluid at a specific flow rate and/or pressure in order to transport mass and energy to perform work or make a product. The piping system may also contain a variety of instrumentation and controls to regulate the processes that are occurring within the boundaries of the piping system.

The configuration, working fluid, and purpose of the piping system will vary depending on the application, but there are fundamental concepts, principles, and mathematical relationships that apply across industries and disciplines. Piping systems meet the needs of a variety of applications including:

- Industrial and commercial heating & cooling applications
- Process piping systems in chemical plants and refineries
- HVAC chilled water systems and hydronic heating systems
- Municipal water supply, irrigation, and dewatering applications
- Pharmaceutical process systems
- Ultra pure water systems used in pharmaceutical and integrated chip manufacturing
- Marine and shipboard applications
- Waste collection and treatment systems

Most textbooks on fluid dynamics limit the study of piping systems by isolating the various items in the system and evaluating them individually. For example, one learns how to calculate the energy of a fluid anywhere in the system using the Bernoulli equation and how to determine the head loss in a fully charged pipe with a Newtonian fluid, but little effort goes into learning what happens when multiple pipelines are connected. The study of pumps is often limited to how the impeller imparts kinetic energy to the fluid and how the casing converts the energy of the fluid to potential energy, but may not cover Net Positive Suction Head and what can be done about a cavitating pump.

After entering the work force, we continue to look at the piping system as a collection of the various parts. We talk to a valve vendor when we have a problem with a control valve, a pump vendor for pump problems, and an instrument vendor when there are control issues. However, seldom is there a vendor to call when there is a problem with the overall piping system that affects its operation. As a result, we are typically left to our own devices to gain a clear understanding of how the total piping system operates.

The objective of this book is to provide piping system practitioners (engineers, designers, maintenance supervisors, and plant operators) with the fundamentals of how the total piping system operates. Our approach is to look at the big picture of what elements are in the system, focus in on each element to provide a basic understanding of how each works, and then gain an understanding of how the elements operate together as a whole.

It is not our objective to overwhelm the reader with complex mathematical formulas or to derive the equations involved in describing system operation. However, many devices in a piping system have a well-defined mathematical relationship that can best be described with an equation or using a graph. We will present these in such a way that one can gain an understanding of the hydraulic performance of the various devices and what is happening in the overall piping system.

In addition to using equations and graphs, and because good communication is critical to any operation, we will also be concise and consistent with the language and nomenclature we use in this book. Appendix A is the nomenclature for the terminology that is used in the equations, along with the units associated with the terms. Appendix B is a glossary that provides clear definitions for key terms used throughout the book.
The Value of a Clear Picture

Once a piping system is designed and built, it is turned over to the operators to operate and the maintenance crews to maintain. Support personnel such as supervisors, process engineers, environmental engineers, maintenance foremen, and training coordinators provide knowledge and resources to those directly responsible for the daily operation and maintenance of the piping system. The more knowledge each of these groups of personnel have about the system and how it works, the more reliably the system will be operated, resulting in increased worker safety, improved product quality with a reduction in variability, and reduced environmental emissions.

To see the piping system clearly, the system boundaries must be defined, including where the system begins and ends, what devices are installed in the system, and how all the devices in the system are configured. For complex systems, it is often useful to break the system into more manageable sub-systems and understand how the boundary conditions in the sub-system are affected by operation in the rest of the system.

Clear Picture of System Operations

A clear picture of the total piping system provides a better understanding of the “normal” operating conditions of the system, including the expected ranges of flow rates, pressures, temperatures, tank levels, and other system parameters. It involves more than just knowing the values of these parameters, but also understanding why and how they change at different operating conditions.

The clear picture also includes understanding the function and expected hydraulic performance of the individual devices installed in the system. Equipment performance is typically characterized by how the pressure (or head) changes with the flow rate through the device.

Understanding system operation also includes knowing what processes are occurring in the piping system, and how these processes are measured and controlled. A key aspect to this is knowing the relevant physical laws that apply to the system and how the working fluid properties change and affect the system operation.

Clear Picture For Troubleshooting

Because a piping system is a collection of devices interconnected with pipelines, a problem manifested in one part of the system may have its root cause in another part of the system. This makes it difficult to troubleshoot problems in a complex piping system.

A clear picture not only provides a better understanding of the “normal” operating conditions of the system, it also helps to identify abnormal conditions and to quickly troubleshoot the system when an operational problem is encountered.

Clear Picture of System Energy Consumption and Costs

Transporting the working fluid requires the addition of energy to the fluid to overcome the energy losses that occur in every device in the piping system. Energy loss occurs due to friction, noise, and vibration and shows up as inefficiencies in the motor and pump, and as head loss in the pipelines, valves, fittings, and other components.

There are various forms of energy throughout the piping system. The energy source may be AC or DC electricity that turns a motor, chemical energy in a fuel that drives a combustion engine, or thermal energy in steam that drives a turbine. The output of the driver is mechanical energy in the form of a rotating shaft, which is then converted by a pump into hydraulic energy in the fluid in the form of pressure, velocity, and elevation head.
Chapter 1: Introduction

Of course, energy costs money. The more energy loss there is in the system, the more energy has to be added to deliver the working fluid to the end users at their required flow rate and pressure. In addition, the energy loss causes wear and tear on the piping system components, so the more energy loss in the system the higher the maintenance costs will be. For the engineers who design the system, one goal is to reduce the amount of energy required to transport the working fluid to the end users. For the team looking to optimize a piping system, their goal is to reduce the energy losses in the system so that the energy addition (and operating and maintenance costs) can be reduced.

Elements of a Piping System

A piping system is made up of a variety of items or elements that are connected together, as shown in a typical single path open system in Figure 1-1. This system consists of a supply tank that is open to atmosphere, a supply pump, a component such as a heat exchanger, and a pressurized product tank. It also contains various types of instrumentation and controls such as level, temperature, flow, and pressure measurements; as well as flow and temperature meters, controllers, and control valves. All of these individual devices are connected by pipelines, valves, and fittings to transport the working fluid throughout the system. The performance of each device in the system affects the operation of the other devices in the system.

![Figure 1-1. Typical single path open piping system.](image)

There are several processes occurring in this system such as heat and mass transfer. These processes are governed by physical laws that have been well-established by scientists and engineers throughout history. For example, the conservation of mass and energy apply throughout the piping system, as well as the application of Pascal's Law to the pressure distribution in the system.

This piping system can be considered a sub-system of a much larger system that may exist at a facility. What's not shown is the system that transfers fluid to the supply tank, the distribution of the fluid from the product tank, or the piping system for the heating or cooling fluid on the shell side of the heat exchanger. This shows the importance of dividing complex systems into more manageable sub-systems at well-defined boundaries.

To have a clear picture of how this system operates, we need to have knowledge about the process or system demand, how each device operates, what is happening in each device, and how that affects the fluid properties. We also need to understand how those properties are changed by the processes in the system, and how the properties affect the hydraulic performance of the interconnected devices.
Every piping system has unique operating characteristics depending on how the system is configured. Figure 1-2 shows a typical single path closed loop system that can be found in many heating or cooling applications in various industries. This system contains a lot of the common devices we may see in an open system such as tanks, pumps, heat exchangers, instrumentation, pipelines, valves and fittings.

Of course, in many industries the piping systems are not limited to single path open or closed loop systems. There are many multiple path open branching systems and multiple path closed loop systems depending on the particular application of the system. Each system has unique operating characteristics that provide challenges when trying to understand how they operate and how to troubleshoot problems in the system.

![Figure 1-2. Typical single path closed loop piping system used to control the temperature of a chilled process fluid.](image)

The key to understanding any piping system is to gain an insight into the operation of the individual elements, then to look at the entire piping system to see how the individual parts work together.

This book is divided into chapters to explore each element that makes up a piping system, then looks at the total system to see how the individual parts work together. It concludes by demonstrating how understanding the normal operation of a system can be used to effectively troubleshoot abnormal conditions caused by various problems that can occur in different devices.

**Terminology, Units, and Physical Laws**

Before we look at the individual elements of a piping system, we want to establish a solid foundation for the terminology, nomenclature, units, fluid properties, and basic mathematical relationships that are used throughout this book. Key physical laws that govern how the system operates will also be discussed.

**Tanks and Vessels**

Tanks and vessels play an important role in establishing the boundary conditions for a piping system and provide a location for dividing complex systems into smaller, more manageable systems for analysis.
Chapter 1: Introduction

Pumps
Pumps are unique devices in a piping system in that they add hydraulic energy to the working fluid of the system. Pumps come in two types, kinetic (dynamic) and positive displacement. Since the majority of piping systems employ centrifugal pumps, the most common kinetic type, they will be our focus when looking at pumps.

Pipelines
Pipelines are the building block of every piping system. They contain the working fluid and connect the various elements in the piping system together. Pipelines are a source of energy loss due to friction between the internal pipe walls and the working fluid. Pipelines are generally thought of as circular conduits, but can be other shapes such as rectangular duct, annular piping, or open channels.

Valves and Fittings
Valves and fittings are also a source of energy loss from the fluid, but play a key role by connecting pipelines, isolating equipment, redirecting flow, or preventing reverse flow.

Control Valves
Control valves are variable resistance devices placed in a piping system to regulate a system parameter such as the fluid pressure, flow rate, temperature, etc. They control the amount of energy dissipated across them by varying the shape and size of the flow passage.

Process Measurements and Controls
Key system properties such as pressure, flow, and tank level, or fluid properties such as temperature, pH, or conductivity, must be measured and controlled to ensure the requirements of the end users are met. There are various devices to measure these properties and various methods to control them.

Processes and Process Equipment
The piping system exists to perform a process on the working fluid to achieve an objective, whether it is to transfer energy, perform work, or transform raw materials into an intermediate or final product. Processes include various mechanisms for heat transfer, the transfer of mass or energy, or momentum transfer. Unique equipment such as heat exchangers, filters, washers, and absorption or cooling towers are designed to carry out these processes.

The Total System
In the Total System chapter, we will use the information presented in the previous chapters to obtain an overall system approach to understanding the operation of the piping system. Using smaller systems, key concepts will be presented to help understand the operation of larger, more complex open and closed loop systems. Two methods to visualize the energy addition and consumption in the system will be discussed. We will also look at how to troubleshoot a piping system given normal and abnormal operating conditions.

Understanding Energy Consumption and Cost
Three case studies will be presented to demonstrate how to minimize operating, maintenance, and capital costs.
Piping System Fundamentals
The Complete Guide to Gaining a Clear Picture of Your Piping System

Piping System Fundamentals is the most comprehensive piping system text available covering real-world examples including over 295 images and illustrations.

This book provides piping system practitioners (engineers, designers, maintenance supervisors, and plant operators) with the fundamentals of how total piping systems operate. Our approach provides a basic understanding of the various elements found in a piping system, and then shows how the elements operate together as a whole.

NEW IN THE SECOND EDITION

- Three Completely New Chapters
  - Tanks & Vessels
  - Process Measurement & Controls
  - Processes & Process Equipment

- Troubleshooting & Case Studies
  - Case Studies of Real World Systems
  - Applied Principles to Solve Problems Posed in Troubleshooting Examples

- Free Software CD
  - Contains PIPE-FLO Professional Demo
  - Example Piping System Models Used in the Book
  - Build Your Own Example Systems & Program Tutorial

This book and related training can be found online at ESILearning.com