

Bahman Zohuri · Patrick McDaniel

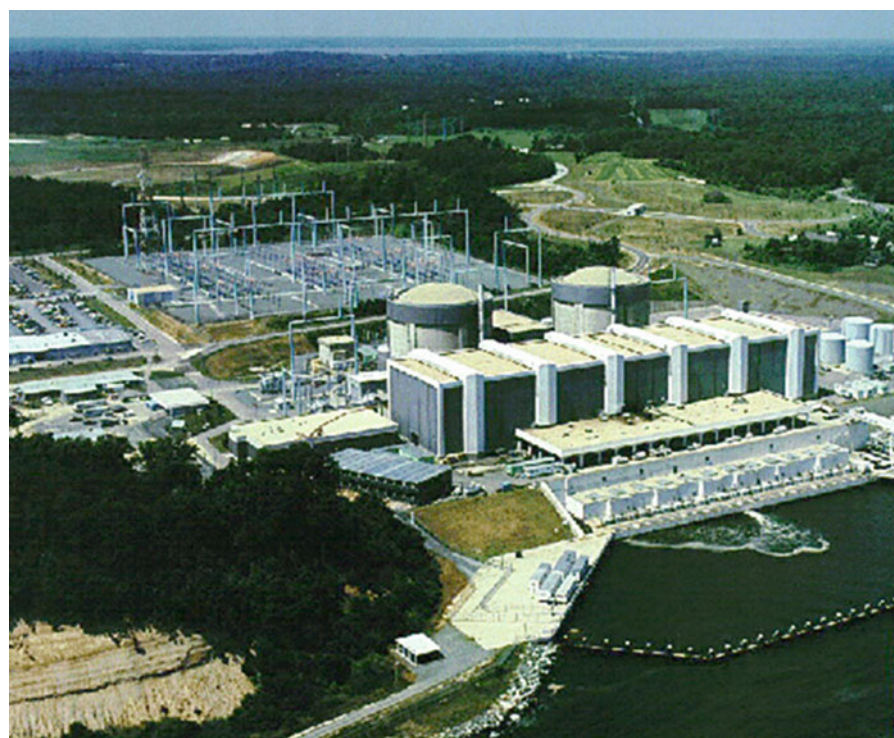
# Thermodynamics in Nuclear Power Plant Systems

*Second Edition*

**EXTRAS ONLINE**

 Springer

# Thermodynamics in Nuclear Power Plant Systems



Bahman Zohuri • Patrick McDaniel

# Thermodynamics in Nuclear Power Plant Systems

Second Edition

 Springer

Bahman Zohuri  
University of New Mexico  
Department of Electrical and Computer  
Engineering  
Galaxy Advanced Engineering, Inc.  
Albuquerque, NM, USA

Patrick McDaniel  
Department of Chemical and Nuclear  
Engineering  
University of New Mexico  
Albuquerque, NM, USA

A solution manual for this book is available on [Springer.com](https://www.springer.com).

ISBN 978-3-319-93918-6      ISBN 978-3-319-93919-3 (eBook)  
<https://doi.org/10.1007/978-3-319-93919-3>

Library of Congress Control Number: 2018949907

© Springer International Publishing AG, part of Springer Nature 2015, 2019

This work is subject to copyright. All rights are reserved by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, express or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG  
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

*This book is dedicated to my parents Marzieh  
and Akbar Zohuri*

Bahman Zohuri

*This book is dedicated to Ben Pollared*

Patrick McDaniel

# Preface

This book covers the fundamentals of thermodynamics required to understand electrical power generation systems. It also covers the application of these principles to nuclear reactor power systems. It is not a general thermodynamics text, but is a thermodynamics text aimed at explaining the fundamentals and applying them to the challenges facing actual nuclear power systems. It is written at an undergraduate level but should also be useful to practicing engineers.

This book starts with the fundamental definitions of thermodynamic variables such as temperature, pressure, and specific volume. It defines the zeroth law of thermodynamics. It then explains open and closed systems. The ideal gas law is introduced, along with some of its limitations for real gases. Gas kinetic theory is then introduced to provide a background for the ideal gas law and a foundation for understanding for the theory of specific heats. Then it moves on to the first law of thermodynamics and its realization in the internal energy and enthalpy potentials. After addressing several applications, it moves on to the second law of thermodynamics and the concept of entropy. It then approaches entropy from the statistical mechanics viewpoint to validate that it truly is a measurable physical quantity. It concludes the fundamental theory portion of this book by discussing irreversibility, availability, and the Maxwell relations, touching slightly on the third law of thermodynamics.

The second portion of this book is devoted to specific applications of the fundamentals to Brayton and Rankine cycles for power generation. Brayton cycle compressors, turbines, and recuperators are covered, along with the fundamentals of heat exchanger design. Rankine steam generators, turbines, condensers, and pumps are discussed. Reheaters and feed water heaters are also covered. Ultimate heat rejections by circulating water systems are also discussed.

The third part of this book covers current and projected reactor systems and how the thermodynamic principles are applied to their design, operation, and safety analyses.

Detailed appendices cover metric and English system units and conversions, detailed steam and gas tables, heat transfer properties, and nuclear reactor system descriptions.

Albuquerque, NM, USA

Bahman Zohuri



# Acknowledgments

The authors would like to acknowledge all the individuals for their help, encouragement, and support. We have decided not to name them all since some of them may not be around to see the end result of their encouragement, but we hope they can at least read this acknowledgment wherever they may be.

Last but not least, special thanks to our parents, wives, children, and friends for providing constant encouragement, without which this book could not have been written. We especially appreciate their patience with our frequent absence from home and long hours in front of the computer during the preparation of this book.

# Disclaimer

This document is protected under the copyright laws of the United States and/or other countries as an unpublished work. This document contains information that is proprietary and confidential to Galaxy Advanced Engineering (GAE) and Applied Energy Consultants, LLC and/or affiliates or its technical alliance partners, which shall not be duplicated, used, or disclosed in whole or in part for any purpose other than to evaluate Galaxy Advanced Engineering, Inc. and Applied Energy Consultants, LLC and/or its affiliate(s). Any use or disclosure in whole or in part of this information without the written permission of Galaxy Advanced Engineering, Inc. and Applied Energy Consultants, LLC and/or its affiliate(s) is prohibited.

© 2006–1014 Galaxy Advanced Engineering, Inc. and Applied Energy Consultants, LLC and/or its affiliates(s) (Unpublished). All rights reserved.

The Proven Course methodology is component of Galaxy Advanced Engineering’s and Applied Energy Consultants, LLC ‘s Proven Course delivery framework and contains process, template, and techniques used to deliver Galaxy Advanced Engineering, Inc. and Applied Energy Consultants, LLC services.

Proven Course<sup>SM</sup>, Galaxy Advanced Engineering <sup>TM</sup>, and GAE<sup>TM</sup> and AEC <sup>TM</sup> Business Empowered is trademarks or service marks of Galaxy Advanced Engineering, Inc. Applied Energy Consultants, LLC and/or its affiliates.

# Contents

<b>1</b>	<b>Definitions and Basic Principles</b> . . . . .	1
1.1	Typical Pressurized Water Reactor . . . . .	1
1.2	Scope of Thermodynamics . . . . .	3
1.3	Units . . . . .	5
1.3.1	Fundamental Units . . . . .	5
1.3.2	Thermal Energy Units . . . . .	6
1.3.3	Unit Conversion . . . . .	6
1.4	Classical Thermodynamics . . . . .	7
1.5	Open and Closed Systems . . . . .	8
1.6	System Properties . . . . .	10
1.6.1	Density . . . . .	10
1.6.2	Pressure . . . . .	11
1.6.3	Temperature . . . . .	13
1.7	Properties of the Atmosphere . . . . .	15
1.8	The Laws of Thermodynamics . . . . .	15
1.9	Problems . . . . .	16
	References . . . . .	23
<b>2</b>	<b>Properties of Pure Substances</b> . . . . .	25
2.1	Introduction . . . . .	25
2.2	Properties of Pure Substances: Phase Changes . . . . .	27
2.2.1	Phases of Pure Substances . . . . .	29
2.2.2	Equations of State . . . . .	29
2.3	Ideal Gas . . . . .	30
2.4	Real Gases and Vapors . . . . .	32
2.4.1	Simple Real Gas Equations of State . . . . .	32
2.4.2	Determining the Adjustable Parameters . . . . .	33
2.4.3	Other Useful Two-Parameter Equations of State . . . . .	36

2.4.4	Common Equations of State with Additional Parameters . . . . .	37
2.4.5	The Liquid-Vapor Region . . . . .	45
2.5	$T$ - $V$ Diagram for a Simple Compressible Substance . . . . .	47
2.6	$P$ - $V$ Diagram for a Simple Compressible Substance . . . . .	47
2.7	$P$ - $V$ - $T$ Diagram for a Simple Compressible Substance . . . . .	49
2.8	Problems . . . . .	53
	Bibliography . . . . .	54
<b>3</b>	<b>Mixture . . . . .</b>	<b>55</b>
3.1	Ideal Gas Mixtures . . . . .	55
3.1.1	Avogadro's Number . . . . .	55
3.1.2	Mass Fractions . . . . .	56
3.1.3	Mole Fractions . . . . .	56
3.1.4	Dalton's Law and Partial Pressures . . . . .	57
3.1.5	Amagat's Law and Partial Volumes . . . . .	58
3.2	Real Gas Mixtures . . . . .	59
3.2.1	Pseudo-critical States for Mixtures: Kay's Rule . . . . .	59
3.2.2	Real Gas Equations of State . . . . .	59
3.3	Liquid Mixtures . . . . .	60
3.3.1	Conservation of Volumes . . . . .	60
3.3.2	Non-conservation of Volumes and Molecular Packing . . . . .	60
3.4	Problems . . . . .	61
	References . . . . .	63
<b>4</b>	<b>Work and Heat . . . . .</b>	<b>65</b>
4.1	Introduction of the Work and Heat . . . . .	65
4.2	Definition of Work . . . . .	65
4.3	Quasi-static Processes . . . . .	68
4.4	Quasi-equilibrium Work Due to Moving Boundary . . . . .	69
4.5	Definition of a Cycle in Thermodynamics . . . . .	73
4.6	Path Functions and Point or State Functions . . . . .	74
4.7	$PdV$ Work for Quasi-static Process . . . . .	76
4.8	Non-equilibrium Work . . . . .	79
4.9	Other Work Modes . . . . .	80
4.10	Reversible and Irreversible Process . . . . .	88
4.11	Definition of Energy (Thermal Energy or Internal Energy) . . . . .	90
4.12	Definition of Heat . . . . .	90
4.13	Comparison of Work and Heat . . . . .	92
4.14	Problems . . . . .	94
	Bibliography . . . . .	97
<b>5</b>	<b>First Law of Thermodynamics . . . . .</b>	<b>99</b>
5.1	Introduction . . . . .	99
5.2	System and Surroundings . . . . .	102

5.2.1	Internal Energy . . . . .	102
5.2.2	Heat Engines . . . . .	103
5.3	Signs for Heat and Work in Thermodynamics . . . . .	104
5.4	Work Done During Volume Changes . . . . .	105
5.5	Paths Between Thermodynamic States . . . . .	108
5.6	Path Independence . . . . .	111
5.7	Heat and Work . . . . .	112
5.8	Heat as Energy in Transition . . . . .	113
5.9	The First Law of Thermodynamics Applied to a Cycle . . . . .	114
5.10	Sign Convention . . . . .	115
5.11	Heat is a Path Function . . . . .	116
5.12	Energy is a Property of System . . . . .	117
5.13	Energy of an Isolated System is Conserved . . . . .	118
5.14	Internal Energy and the First Law of Thermodynamics . . . . .	120
5.15	Internal Energy of an Ideal Gas . . . . .	125
5.16	Introduction to Enthalpy . . . . .	126
5.17	Latent Heat . . . . .	128
5.18	Specific Heats . . . . .	130
5.19	Heat Capacities of an Ideal Gas . . . . .	135
5.20	Adiabatic Processes for an Ideal Gas . . . . .	138
5.21	Summary . . . . .	142
5.22	Problems . . . . .	144
	Bibliography . . . . .	148
<b>6</b>	<b>The Kinetic Theory of Gases . . . . .</b>	<b>149</b>
6.1	Kinetic Theory Basis for the Ideal Gas Law . . . . .	149
6.2	Collisions with a Moving Wall . . . . .	153
6.3	Real Gas Effects and Equations of State . . . . .	154
6.4	Principle of Corresponding States . . . . .	155
6.5	Kinetic Theory of Specific Heats . . . . .	156
6.6	Specific Heats for Solids . . . . .	159
6.7	Mean Free Path of Molecules in a Gas . . . . .	160
6.8	Distribution of Mean Free Paths . . . . .	162
6.9	Coefficient of Viscosity . . . . .	163
6.10	Thermal Conductivity . . . . .	167
6.11	Problems . . . . .	168
	Bibliography . . . . .	168
<b>7</b>	<b>Second Law of Thermodynamics . . . . .</b>	<b>169</b>
7.1	Introduction . . . . .	169
7.2	Heat Engines, Heat Pumps, and Refrigerators . . . . .	169
7.3	Statements of the Second Law of Thermodynamics . . . . .	171
7.4	Reversibility . . . . .	171
7.5	The Carnot Engine . . . . .	172
7.6	The Concept of Entropy . . . . .	175

7.7	The Concept of Entropy in Ideal Gas . . . . .	177
7.8	Entropy for an Ideal Gas with Variable Specific Heats . . . . .	179
7.9	Entropy for Steam, Liquids, and Solids . . . . .	181
7.10	The Inequality of Clausius . . . . .	182
7.11	Entropy Change for an Irreversible Process . . . . .	184
7.12	The Second Law Applied to a Control Volume . . . . .	185
7.13	Problems . . . . .	187
	References . . . . .	189
<b>8</b>	<b>Reversible Work, Irreversibility, and Exergy (Availability) . . . . .</b>	<b>191</b>
8.1	Reversible Work and Irreversibility . . . . .	191
8.2	Exergy . . . . .	194
8.3	Problems . . . . .	198
	References . . . . .	199
<b>9</b>	<b>Gas Kinetic Theory of Entropy . . . . .</b>	<b>201</b>
9.1	Some Elementary Microstate and Macrostate Models . . . . .	202
9.2	Stirling's Approximation for Large Values of $N$ . . . . .	207
9.3	The Boltzmann Distribution Law . . . . .	208
9.4	Estimating the Width of the Most Probable Macrostate Distribution . . . . .	211
9.5	Estimating the Variation of $W$ with the Total Energy . . . . .	214
9.6	Analyzing an Approach to Thermal Equilibrium . . . . .	215
9.7	The Physical Meaning of $\beta$ . . . . .	216
9.8	The Concept of Entropy . . . . .	217
9.9	Partition Functions . . . . .	218
9.10	Indistinguishable Objects . . . . .	219
9.11	Evaluation of Partition Functions . . . . .	226
9.12	Maxwell-Boltzmann Velocity Distribution . . . . .	230
9.13	Problems . . . . .	231
	References . . . . .	231
<b>10</b>	<b>Thermodynamic Relations . . . . .</b>	<b>233</b>
10.1	Thermodynamic Potentials . . . . .	233
10.2	Maxwell Relations . . . . .	236
10.3	Clapeyron Equation . . . . .	240
10.4	Specific Heat Relations Using the Maxwell Relations . . . . .	241
10.5	The Difference Between the Specific Heats for a Real Gas . . . . .	243
10.6	Joule-Thomson Coefficient . . . . .	244
10.7	Problems . . . . .	245
	References . . . . .	246
<b>11</b>	<b>Combustion . . . . .</b>	<b>247</b>
11.1	Introduction . . . . .	247
11.2	Chemical Combustion . . . . .	249
11.3	Combustion Equations . . . . .	250

11.4	Mass and Mole Fractions . . . . .	253
11.5	Enthalpy of Formation . . . . .	255
11.6	Enthalpy of Combustion . . . . .	259
11.7	Adiabatic Flame Temperature . . . . .	259
11.8	Problems . . . . .	262
	Bibliography . . . . .	264
<b>12</b>	<b>Heat Transfer . . . . .</b>	<b>265</b>
12.1	Fundamental Modes of Heat Transfer . . . . .	265
12.2	Conduction . . . . .	266
12.3	Convection . . . . .	266
12.4	Radiation . . . . .	267
12.5	Heat Conduction in a Slab . . . . .	270
12.6	Heat Conduction in Curvilinear Geometries . . . . .	271
12.7	Convection . . . . .	275
12.8	Boundary Layer Concept . . . . .	276
12.9	Dimensionless Numbers or Groups . . . . .	280
12.10	Correlations for Common Geometries . . . . .	283
12.11	Enhanced Heat Transfer . . . . .	292
12.12	Pool Boiling and Forced Convection Boiling . . . . .	294
12.13	Nucleate Boiling Regime . . . . .	298
12.14	Peak Heat Flux . . . . .	301
12.15	Film Boiling Regime . . . . .	304
12.16	Problems . . . . .	306
	Bibliography . . . . .	315
<b>13</b>	<b>Heat Exchangers . . . . .</b>	<b>317</b>
13.1	Heat Exchangers Types . . . . .	317
13.2	Classification of Heat Exchanger by Construction Type . . . . .	320
13.2.1	Tubular Heat Exchangers . . . . .	320
13.2.2	Plate Heat Exchangers . . . . .	321
13.2.3	Plate-Fin Heat Exchangers . . . . .	322
13.2.4	Tube-Fin Heat Exchangers . . . . .	322
13.2.5	Regenerative Heat Exchangers . . . . .	323
13.3	Condensers . . . . .	323
13.4	Boilers . . . . .	324
13.5	Classification According to Compactness . . . . .	324
13.6	Types of Applications . . . . .	325
13.7	Cooling Towers . . . . .	325
13.8	Regenerators and Recuperators . . . . .	327
13.9	Heat Exchanger Analysis: Use of the LMTD . . . . .	332
13.10	Effectiveness-NTU Method for Heat Exchanger Design . . . . .	339
13.11	Special Operating Conditions . . . . .	344
13.12	Compact Heat Exchangers . . . . .	345
13.13	Problems . . . . .	349
	Bibliography . . . . .	350

- 14 Gas Power Cycles . . . . . 351**
  - 14.1 Introduction . . . . . 351
    - 14.1.1 Open Cycle . . . . . 355
    - 14.1.2 Closed Cycle . . . . . 356
  - 14.2 Gas Compressors and Brayton Cycle . . . . . 357
  - 14.3 The Non-ideal Brayton Cycle . . . . . 363
  - 14.4 The Air-Standard Cycle . . . . . 367
  - 14.5 Equivalent Air Cycle . . . . . 371
  - 14.6 Carnot Cycle . . . . . 371
  - 14.7 Otto Cycle . . . . . 376
    - 14.7.1 Mean Effective Pressure (Otto Cycle) . . . . . 379
  - 14.8 Diesel Cycle . . . . . 381
    - 14.8.1 Mean Effective Pressure (Diesel Cycle) . . . . . 385
  - 14.9 Comparison of Otto and Diesel Cycles . . . . . 386
  - 14.10 Dual Cycle . . . . . 388
    - 14.10.1 Mean Effective Pressure for Dual Cycle . . . . . 391
  - 14.11 Stirling Cycle . . . . . 392
  - 14.12 Ericsson Cycle . . . . . 395
  - 14.13 Atkinson Cycle . . . . . 397
  - 14.14 Lenoir Cycle . . . . . 398
  - 14.15 Deviation of Actual Cycles from Air-Standard Cycles . . . . . 400
  - 14.16 Recuperated Cycle . . . . . 401
  - 14.17 Problems . . . . . 403
  - Bibliography . . . . . 412
- 15 Vapor Power Cycles . . . . . 413**
  - 15.1 The Basic Rankine Cycle . . . . . 413
  - 15.2 Process Efficiency . . . . . 418
  - 15.3 The Rankine Cycle with a Superheater . . . . . 423
  - 15.4 External Reversibilities . . . . . 425
  - 15.5 Superheated Rankine Cycle with Reheaters . . . . . 427
  - 15.6 Feedwater Heaters . . . . . 429
    - 15.6.1 Open or Direct Contact Feedwater Heaters . . . . . 430
    - 15.6.2 Closed Feedwater Heaters with Drain Pumped Forward Second Type . . . . . 431
    - 15.6.3 Closed Feedwater Heaters with Drain Pumped Forward Third Type . . . . . 433
  - 15.7 The Supercritical Rankine Cycle . . . . . 437
  - 15.8 Problems . . . . . 437
  - Reference . . . . . 438
- 16 Circulating Water Systems . . . . . 439**
  - 16.1 Introduction . . . . . 439
  - 16.2 Cooling Power Plants . . . . . 443



- 16.2.1 Steam Cycle Heat Transfer . . . . . 443
- 16.2.2 Cooling to Condense the Steam and Discharge Surplus Heat . . . . . 444
- 16.3 Circulating Water Systems . . . . . 446
- 16.4 Service or Cooling Water Systems . . . . . 448
- Bibliography . . . . . 450
- 17 Electrical System . . . . . 451**
- 17.1 Introduction . . . . . 451
- 17.2 Balancing the Circuit to Maximize the Energy Delivered to the Load . . . . . 452
- 17.3 Optimizing the Transmission of Energy to the Load . . . . . 455
- 17.4 Overview of an Electrical Grid System . . . . . 455
- 17.5 How Power Grids System Work . . . . . 456
- 17.5.1 Electrical Alternating (AC) . . . . . 457
- 17.5.2 Three-Phase Power . . . . . 459
- 17.5.3 Transmission System . . . . . 460
- 17.5.4 Substation (Terminal Station) System . . . . . 461
- 17.5.5 Zone Substation System . . . . . 461
- 17.5.6 Regulator Bank System . . . . . 461
- 17.5.7 Taps System . . . . . 462
- 17.5.8 At the House Level . . . . . 464
- 17.5.9 Safety Devices: Fuses, Circuit Breakers, Plugs, and Outlets . . . . . 466
- 17.5.10 Control Centers . . . . . 468
- 17.5.11 Interstate Power Grids . . . . . 470
- 17.6 United States Power Grid . . . . . 471
- 17.7 The Smart Power Grid (SG) . . . . . 473
- 17.8 Problems . . . . . 475
- Reference . . . . . 476
- 18 Nuclear Power Plants . . . . . 477**
- 18.1 Fission Energy Generation . . . . . 477
- 18.2 The First Chain Reaction . . . . . 478
- 18.3 Concepts in Nuclear Criticality . . . . . 481
- 18.4 Fundamental of Fission Nuclear Reactors . . . . . 481
- 18.5 Reactor Fundamentals . . . . . 484
- 18.6 Thermal Reactors . . . . . 485
- 18.7 Nuclear Power Plants and Their Classifications . . . . . 485
- 18.8 Classified by Moderator Material . . . . . 486
- 18.8.1 Light Water Reactors (LWR) . . . . . 486
- 18.8.2 Graphite-Moderated Reactors (GMR) . . . . . 486
- 18.8.3 Heavy Water Reactors (HWR) . . . . . 487
- 18.9 Classified by Coolant Material . . . . . 490
- 18.9.1 Pressurized Water Reactors (PWR) . . . . . 490

18.9.2	Boiling Water Reactor (BWR) . . . . .	492
18.9.3	Gas-Cooled Reactors (GCR) . . . . .	493
18.10	Classified by Reaction Type . . . . .	495
18.10.1	Fast Neutron Reactor (FNR) . . . . .	495
18.10.2	Thermal Neutron Reactor . . . . .	498
18.10.3	Liquid Metal Fast Breeder Reactors (LMFBR) . . . . .	499
18.11	Nuclear Fission Power Generation . . . . .	503
18.12	Generation IV Nuclear Energy Systems . . . . .	503
18.13	Technological State-of-the-Art and Anticipated Developments . . . . .	505
18.14	Next-Generation Nuclear Plant (NGNP) . . . . .	508
18.15	Generation IV Systems . . . . .	510
18.15.1	Very High-Temperature Reactor (VHTR) . . . . .	511
18.15.2	Molten Salt Reactor (MSR) . . . . .	513
18.15.3	Sodium-Cooled Fast Reactor (SFR) . . . . .	515
18.15.4	Supercritical Water-Cooled Reactor (SCWR) . . . . .	516
18.15.5	Gas-Cooled Fast Reactor (GFR) . . . . .	519
18.15.6	Lead-Cooled Fast Reactor (LFR) . . . . .	521
18.16	Next Generation of Nuclear Power Reactors for Power Production . . . . .	522
18.17	Goals for Generation IV Nuclear Energy Systems . . . . .	524
18.18	Why We Need to Consider the Future Role of Nuclear Power Now . . . . .	526
18.19	The Generation IV Roadmap Project . . . . .	529
18.20	Licensing Strategy Components . . . . .	530
18.21	Market and Industry Status and Potentials . . . . .	531
18.22	Barriers . . . . .	533
18.23	Needs . . . . .	533
18.24	Synergies with Other Sectors . . . . .	534
	Bibliography . . . . .	535
<b>19</b>	<b>Nuclear Fuel Cycle . . . . .</b>	<b>541</b>
19.1	The Nuclear Fuel Cycle . . . . .	541
19.2	Fuel Cycle Choices . . . . .	545
19.3	In Core Fuel Management . . . . .	548
19.4	Nuclear Fuel and Waste Management . . . . .	549
19.4.1	Managing HLW from Used Fuel . . . . .	550
19.4.2	Recycling Used Fuel . . . . .	552
19.4.3	Storage and Disposal of Used Fuel and Other HLW . . . . .	554
19.4.4	Regulation of Disposal . . . . .	558
19.5	Processing of Used Nuclear Fuel . . . . .	560
19.5.1	Reprocessing Policies . . . . .	561
19.6	Back End of Fuel Cycle . . . . .	562
	Bibliography . . . . .	563

- 20 The Economic Future of Nuclear Power . . . . . 565**
  - 20.1 Introduction . . . . . 565
  - 20.2 Overall Costs: Fuel, Operation, and Waste Disposal . . . . . 566
    - 20.2.1 Fuel Costs . . . . . 567
    - 20.2.2 Future Cost Competitiveness . . . . . 571
    - 20.2.3 Major Studies on Future Cost Competitiveness . . . . . 572
    - 20.2.4 Operations and Maintenance (O&M) Costs . . . . . 578
    - 20.2.5 Production Costs . . . . . 579
    - 20.2.6 Costs Related to Waste Management . . . . . 581
    - 20.2.7 Life Cycle Costs (US Figures) . . . . . 584
    - 20.2.8 Construction Costs . . . . . 584
  - 20.3 Comparing the Economics of Different Forms of Electricity Generation . . . . . 585
  - 20.4 System Cost . . . . . 586
  - 20.5 External Costs . . . . . 586
  - Bibliography . . . . . 590
- 21 Safety, Waste Disposal, Containment, and Accidents . . . . . 591**
  - 21.1 Safety . . . . . 591
  - 21.2 Nuclear Waste Disposal . . . . . 592
  - 21.3 Contamination . . . . . 594
  - 21.4 Accidents . . . . . 596
  - Bibliography . . . . . 598
- Appendix A: Table and Graphs Compilations . . . . . 599**
- Index . . . . . 709**

# Authors

**Bahman Zohuri** is currently at the Galaxy Advanced Engineering, Inc., a consulting company that he started himself in 1991 when he left both semiconductor and defense industries after many years working as a chief scientist. After graduating from the University of Illinois in the field of Physics and Applied Mathematics, he joined the Westinghouse Electric Corporation where he performed thermal hydraulic analysis and natural circulation for inherent shutdown heat removal system (ISHRS) in the core of a liquid metal fast breeder reactor (LMFBR) as a secondary fully inherent shut system for secondary loop heat exchange. All these designs were used for Nuclear Safety and Reliability Engineering for Self-Actuated Shutdown System. He designed the Mercury Heat Pipe and Electromagnetic Pumps for Large Pool Concepts of LMFBR for heat rejection purpose for this reactor around 1978 where he received a patent for it. He later on was transferred to the defense division of Westinghouse where he was responsible for the dynamic analysis and method of launch and handling of MX missile out of canister. The results are applied to MX launch seal performance and muzzle blast phenomena analysis (i.e., missile vibration and hydrodynamic shock formation). He also was involved in analytical calculation and computation in the study of nonlinear ion wave in rarefying plasma. The results are applied to the propagation of “soliton wave” and the resulting charge collector traces, in the rarefactions characteristic of the corona of a laser-irradiated target pellet. As part of his graduate research work at the Argonne National Laboratory, he performed computation and programming of multi-exchange integral in surface physics and solid-state physics. He holds different patent in areas such as diffusion processes and design of diffusion furnace while he was senior process engineer working for different semiconductor industries such as Intel, Varian, and National Semiconductor corporations. Later on, he joined Lockheed Missile and Aerospace Corporation as a senior chief scientist. At this position, he was responsible for research and development (R&D) and the study of vulnerability, survivability, and both radiation and laser hardening of different components of payload (i.e., IR Sensor) for Defense Support Program (DSP), Boost Surveillance and Tracking Satellite (BSTS), and Space Surveillance and Tracking Satellite (SSTS)

against laser or nuclear threat. While in there, he also studied and performed the analysis of characteristics of laser beam and nuclear radiation interaction with materials, transient radiation effects in electronics (TREE), electromagnetic pulse (EMP), system-generated electromagnetic pulse (SGEMP), single-event upset (SEU), blast, and, thermomechanical, hardness assurance, maintenance, and device technology.

He did few years of consulting under his company Galaxy Advanced Engineering with Sandia National Laboratories (SNL), where he was supporting development of operational hazard assessments for the Air Force Safety Center (AFSC) in connection with other interest parties. Intended use of the results was their eventual inclusion in Air Force Instructions (AFIs) specifically issued for directed-energy weapons (DEW) operational safety. He completed the first version of a comprehensive library of detailed laser tools for Airborne Laser (ABL), Advanced Tactical Laser (ATL), Tactical High-Energy Laser (THEL), Mobile/Tactical High-Energy Laser (M-THEL), etc.

He also was responsible on SDI computer programs involved with Battle Management C<sup>3</sup>I and artificial intelligent and autonomous system. He is the author of few publications and holds various patents such as laser-activated radioactive decay and results of thru-bulkhead initiation.

Recently, he has published the following books with CRC press and Taylor & Francis:

1. Heat Pipe Design and Technology: A Practical Approach
2. Dimensional Analysis and Self-Similarity Methods For Engineers and Scientists
3. Directed Energy Weapons Technologies

**Patrick McDaniel** is currently adjunct and research professor at the Department of Chemical and Nuclear Engineering, University of New Mexico. Patrick began his career as a pilot and maintenance officer in the USAF. After leaving the Air Force and obtaining his doctorate at Purdue University, he worked at the Sandia National Laboratories in fast reactor safety, integral cross-sectional measurements, nuclear weapons vulnerability, space nuclear power, and nuclear propulsion. He left Sandia to become the technical leader for Phillips Laboratory's (became part of the Air Force Research Laboratory) Satellite Assessment Center. After 10 years at PL/AFRL, he returned to Sandia to lead and manage DARPA's Stimulated Isomer Energy Release project, a \$10 M per year effort. While at Sandia, he worked on the Yucca Mountain Project and DARPA's classified UER-X program. Having taught at the University of New Mexico in the graduate nuclear engineering program for 25 years, when he retired from Sandia in the early 2009, he joined the faculty at the University of New Mexico full time. He has worked on multiple classified and unclassified projects in the application of nuclear engineering to high-energy systems. Dr. McDaniel holds PhD in Nuclear Engineering from the Purdue University.

# Chapter 1

## Definitions and Basic Principles

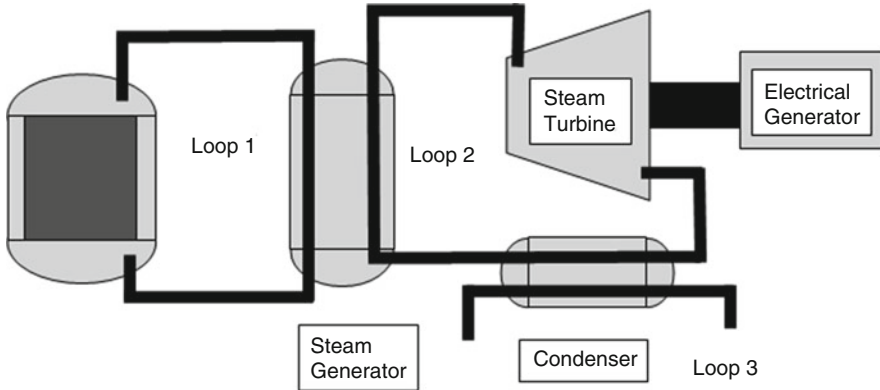


Nuclear power plants currently generate better than 20% of the central station electricity produced in the United States. The United States currently has 104 operating power-producing reactors, with 9 more planned. France has 58 with 1 more planned. China has 13 with 43 planned. Japan has 54 with 3 more planned. In addition, Russia has 32 with 12 more planned. Nuclear-generated electricity has certainly come into its own existence and is the safest, cleanest, and greenest form of electricity currently produced on this planet. However, many current thermodynamics texts ignore nuclear energy and use few examples of nuclear power systems. Nuclear energy presents some interesting thermodynamic challenges, and it helps to introduce them at the fundamental level. Our goal here will be to introduce thermodynamics as the energy conversion science that it is and apply it to nuclear systems. Certainly, there will be many aspects of thermodynamics that are given little or no coverage. However, that is true for any textual introduction to this science; however by considering concrete systems, it is easier to give insight into the fundamental laws of science and to provide an intuitive feeling for further study. For further information, please refer to references [1–4] at the end of this chapter.

### 1.1 Typical Pressurized Water Reactor

By far the most widely built nuclear system is the pressurized water reactor (PWR). There are a number of reasons for this. Steam turbines have for many decades been the dominant means of generating mechanical energy to turn electrical generators. The temperatures reached in the thermodynamic cycle of a PWR are within the range of fairly, common engineering materials. They were the first system built and operated reliably to produce electricity. A typical PWR system is described in Fig. 1.1.

The basic PWR consists of five major components, the reactor core, steam generator(s), steam turbine, condenser, and electrical generator and three water/



**Fig. 1.1** Pressurized water reactor schematic

steam loops. Each loop requires a pump that is not shown to keep the diagram cleaner. The nuclear energy is converted to thermal energy in the reactor core. This thermal energy is then transported via the first loop to the steam generator where it is passed to the water in the second loop. The water in the second loop enters as a liquid and is turned to steam. The steam then passes to the turbine where the thermal energy is converted to mechanical energy to rotate the electrical generator. After the thermal energy has been converted to mechanical energy in the steam turbine, the low-pressure steam passes to the condenser to be cooled by the water in the third loop. The second law of thermodynamics tells us that we cannot simply expand the steam to a low enough energy state that it can return to the steam generator in its original liquid state. Therefore, we must extract more thermal energy from the low-pressure steam to return it to its liquid state where it can be pumped back into the steam generator. The third loop is called the circulating water system, and it is open to the environment. There are multiple ways of providing this cooling water including intake and return to a river or the ocean, intake and return to a cooling pond, or intake from a river and exhaust through a cooling tower. However, we are getting ahead of ourselves.

Consider for a minute why nuclear energy is so useful. A great deal of energy is produced by a very little mass.

**Example calculation** Calculate the U-235 consumed to produce 1 MW of thermal energy for 1 day. Note that a megawatt is a unit of power or energy per unit time.

$$1 \text{ MW} = 10^6 \text{ W} = 10^6 \text{ J/s} \quad 1 \text{ day} = 24 \text{ h} = 24 \times 3600 \text{ s}$$

The energy released in fission of a U-235 atom is  $\sim 200 \text{ MeV}$ .

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J} \quad 1 \text{ MeV} = 1.6 \times 10^{-13} \text{ J} \quad 200 \text{ MeV} = 32 \text{ PJ}$$

Fissioning one atom of U-235 produces  $3.2 \times 10^{-11} \text{ J}$ .

To produce  $10^6 \text{ J}$  requires  $10^6 / 3.2 \times 10^{-11} \text{ atoms} = 3.125 \times 10^{16} \text{ atoms}$   
and for a duration of  $8.64 \times 10^4 \text{ s}$ .

The total number of atoms consumed will be  $3.125 \times 8.64 \times 10^{20}$  atoms.

Therefore  $2.7 \times 10^{21}$  atoms will be consumed.

A gram-mole of U-235 is  $6.022 \times 10^{23}$  atoms.

So a gram is  $6.022 \times 10^{23}/235 = 2.563 \times 10^{21}$  atoms/g.

Therefore 1 MW-day of nuclear energy consumes 1.05 g of U-235.

The fundamental thing to understand is that a PWR converts nuclear energy to electrical energy and it does this by converting the nuclear energy first to thermal energy and then converting the thermal energy to mechanical energy, which is finally converted to electrical energy. The science of thermodynamics deals with each of these conversion processes. To quantify how each of these processes takes place, we must understand and apply the laws of thermodynamics.

## 1.2 Scope of Thermodynamics

Thermodynamics is the science that deals with energy production, storage, transfer, and conversion. It is a very broad subject which affects most fields of science including biology and microelectronics. The primary forms of energy considered in this text will be nuclear, thermal, chemical, mechanical, and electrical. Each of these can be converted to a different form with widely varying efficiencies. Predominantly thermodynamics is most interested in the conversion of energy from one form to another via thermal means. However, before addressing the details of thermal energy conversion, consider a more familiar example. Newtonian mechanics defines work as force acting through a distance on an object. Performing work is a way of generating mechanical energy. Work itself is not a form of energy, but a way of transferring energy to a mass. So when one mass gains energy, another mass, or field, must lose that energy.

Consider a simple example. A 65-kg woman decides to go over Niagara Falls in a 25-kg wooden barrel. (The first person to go over the fall in a barrel was a woman, Annie Taylor.) Niagara Falls has a vertical drop of 50 m and has the highest flow rate of any waterfall in the world. The force acting on the woman and barrel is the force of gravity, which at the surface of the Earth produces a force of 9.8 N for every kilogram of matter that it acts on. So we have:

$$W = F \times D \quad F = (65 + 25) \times 9.8 = 882.0 \text{ N} \quad D = 50 \text{ m}$$

$$W = 882.0 \times 50.0 = 44,100 \text{ N-m} = 44.1 \text{ K-J}$$

A Newton-meter is a joule and 1000 J is a kJ. Therefore, when the woman and barrel went over the falls, by the time they had reached the bottom, the force of gravity had performed 44.1 kJ of work on them. The gravitational field had 44.1 kJ of potential energy stored in it, when the woman and the barrel were at the top of the falls. This potential energy was converted to kinetic energy by the time the barrel reached the bottom of the falls. Kinetic energy is also measured in joules, as with all



other forms of energy. However, we are usually most interested in velocities when we talk about kinetic energies, so let us extract the velocity with which she hit the waters of the inlet to Lake Ontario.

$$\Delta KE = \Delta PE = 44.1 \text{ kJ} = 1/2 mV^2 = (90/2)\text{kg} \times V^2 \quad V^2 = 44.1 \text{ kJ}/(90/2) \text{ kg}$$

Now it is a matter of converting units. A joule is a Newton-meter. 1 N is defined as 1 kg accelerated at the rate of 1 m/s/s. So:

$$\begin{aligned} 44.1 \text{ kJ} &= 44,100 \text{ N}\cdot\text{m} \\ &= 44,100 \text{ kg}\cdot\text{m}^2/\text{s}^2 \\ &= 44,100 \text{ kg (m/s)}^2 \\ V^2 &= 44,100 \text{ kg (m/s)}^2 / (90/2) \text{ kg} \\ &= 490 / (1/2) = 980 (\text{m/s})^2 \\ V &= 31.3 \text{ m/s } (\sim 70 \text{ mph}) \end{aligned}$$

Needless to say she recommended that no one ever try that again. Of course, others have, some have made it, and some have drowned.

Before leaving this example, it is worth pointing out that when we went to calculate the velocity, it was unaffected by the mass of the object that had dropped 50 m. So one-half the velocity squared represents what we will call a specific energy or energy per kilogram. In addition, the potential energy at the top of the falls could be expressed as a specific potential energy relative to the waters below. The potential energy per pound-mass would just be the acceleration of gravity times the height of the falls. Typically, we will use lowercase letters to represent specific quantities and uppercase letters to represent extensive quantities. Extensive quantities are dependent upon the amount of mass present. Specific quantities are also referred to as intensive variables, though there are some intensive variables that have no extensive counterpart, such as pressure or temperature.

$$p.e. = mgh/m = gh = 9.8 \times 50 = 0.49 \text{ kJ/kg}$$

It is also worth pointing out that Newton's law of gravity states that:

$$F = G \frac{m_1 M_2}{R^2} \quad (1.1)$$

where  $m_1$  is the smaller mass and  $M_2$  is the mass of the Earth. We can find the specific force on an object by dividing the gravitational force by the mass of the object. For distances like 50 m on the surface of the Earth ( $R = 6,378,140$  m), we can treat  $R$  as constant, but if the distance the gravitational force acts through is comparable to the radius of the Earth, an integration would be required. Even on the top of Mount Everest, the gravitational potential is within 0.25% of that at sea level, so gravity is essentially constant for all systems operating on the face of the Earth.

## 1.3 Units

In this section, we will discuss the Système International (SI) and English (E) systems.

### 1.3.1 Fundamental Units

Before going further it will be a very good idea to discuss units for physical quantities and the conversion of units from one system to another. Unfortunately, the field of thermodynamics is beset with two popular systems of units. One is the Système International (SI) system consisting of the kilogram, meter, and second. The other is the English (E) system consisting of the pound-mass, foot, and second.

Starting with the SI system, the unit of force is the Newton. The unit of work or energy is the joule, and the unit of pressure is the Pascal. We have:

$$\begin{aligned} 1 \text{ N} &= 1 \text{ k-m/s}^2 \\ 1 \text{ J} &= 1 \text{ N-m} \\ 1 \text{ Pa} &= 1 \text{ N/m}^2 \end{aligned}$$

Now the acceleration of gravity at sea level on Earth is  $9.8066 \text{ m/s}^2$ , so a 100 kg mass will weigh 980.66 N. Also when we want to avoid spelling out very large or small quantities, we will usually use the standard abbreviations for powers of ten in units of 1000. We have:

$$\begin{aligned} \text{kilo} &= 10^3 \\ \text{mega} &= 10^6 \\ \text{giga} &= 10^9 \\ \text{deci} &= 10^{-1} \\ \text{centi} &= 10^{-2} \\ \text{milli} &= 10^{-3} \\ \text{micro} &= 10^{-6} \\ \text{nano} &= 10^{-9} \end{aligned}$$

For the English system, we have:

$$\begin{aligned} \text{lbm} &=> 1 \text{ lbf (at Sea Level)} \\ 1 \text{ ft-lbf} &= 1 \text{ lbf} \times 1 \text{ ft} \\ 1 \text{ British Thermal Unit (BTU)} &= 778 \text{ ft-lbf} \\ 1 \text{ psi} &= 1 \text{ lbf/in}^2 \end{aligned}$$

Note that the fact that  $1 \text{ lbf} = 1 \text{ lbm}$  at sea level on Earth means that a mass of 100 lbm will weigh 100 lbf at sea level on Earth.

The acceleration of gravity at sea level on Earth is  $32.174 \text{ ft/s}^2$ . Thus we have  $1 \text{ lbf}/(1 \text{ lbm-ft/s}^2) = 32.174$ . If we move to another planet where the acceleration of gravity is different, the statement that  $1 \text{ lbm} \geq 1 \text{ lbf}$  doesn't hold.

Consider comparative weights on Mars. The acceleration of gravity on Mars is 38.5% of the acceleration of gravity on Earth. So in the SI system, we have:

$$W = 0.385 * 9.8066 \text{ m/s}^2 \times 100 \text{ kg} = 377.7 \text{ N}$$

In the English system, we have:

$$W = 0.385 * 100 \text{ lbm} = 38.5 \text{ lbf}$$

### ***1.3.2 Thermal Energy Units***

The British thermal unit (Btu) is defined to be the amount of heat that must be absorbed by a 1 lb-mass to raise its temperature 1 °F. The calorie is the SI unit that is defined in a similar way. It is the amount of heat that must be absorbed by 1 g of water to raise its temperature 1 °C. This raises the question as to how a calorie compares with a joule since both appear to be measures of energy in the SI system. James Prescott Joule spent a major part of his life proving that thermal energy was simply another form of energy like mechanical kinetic or potential energy. Eventually his hypothesis was accepted, and the conversion factor between the calorie and joule has been defined by:

$$1 \text{ cal} = 4.1868 \text{ J}$$

The constant 4.1868 is called the mechanical equivalent of heat.

### ***1.3.3 Unit Conversion***

As long as one remains in either the SI system or the English system, calculations and designs are simple. However, that is no longer possible as different organizations and different individuals usually think and work in their favorite system. In order to communicate with an audience that uses both SI and English systems, it is important to be able to convert back and forth between the two systems. The basic conversion factors are:

$$1 \text{ kg} = 2.20462 \text{ lbm}$$

$$1 \text{ lbm} = 0.45359 \text{ kg}$$

$$1 \text{ m} = 3.2808 \text{ feet}$$

$$1 \text{ foot} = 0.3048 \text{ m}$$

$$1 \text{ J} = 0.00094805 \text{ Btu}$$

$$1 \text{ Btu} = 1055 \text{ J}$$

$$1 \text{ atm} = 14.696 \text{ psi}$$

$$1 \text{ atm} = 101325 \text{ Pa}$$

$$1 \text{ psi} = 6894.7 \text{ Pa}$$

$$1 \text{ bar} = 100000.0 \text{ Pa}$$

$$1 \text{ bar} = 14.504 \text{ psi}$$

The bar unit is simply defined by rounding off sea-level atmospheric pressure to the nearest 100 K-Pa. There are many more conversion factors defined in the Appendix, but they are all derived from this basic few.

## 1.4 Classical Thermodynamics

Classical thermodynamics was developed long before the atomic theory of matter was accepted. Therefore, it treats all materials as continuous and all derivatives well defined by a limiting process. Steam power and an ability to analyze it and optimize it was one of the main drivers for the development of thermodynamic theory. The fluids involved always looked continuous. A typical example would be the definition of the density of a substance at a point. We have:

$$\rho = \lim_{\Delta V \rightarrow 0} \frac{\Delta m}{\Delta V} \quad (1.2)$$

As long as  $\Delta V$  does not get down to the size of an atom, this works. Since classical thermodynamics was developed, however, we have come to understand that all gases and liquids are composed of very small atoms or molecules and a limiting process that gets down to the atomic or molecular level will eventually become discontinuous and chaotic. Nevertheless, the continuous model still works

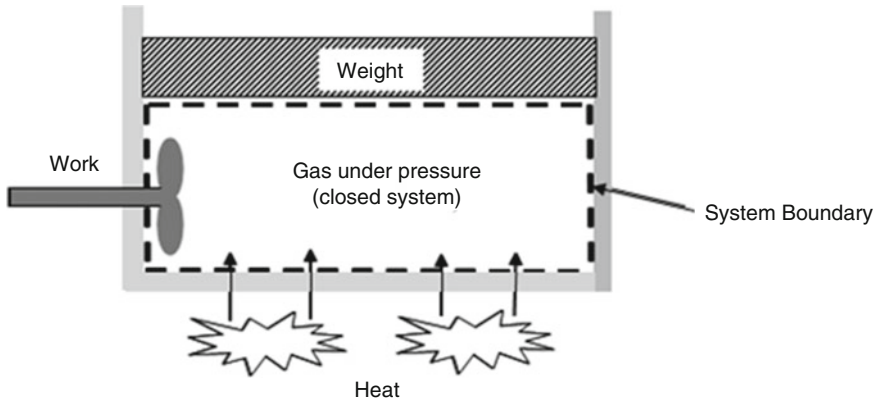
well for the macroscopic systems that will be discussed in this text, and classical thermodynamics is based on it.

At times, we will refer to an atomistic description of materials in order to develop a method of predicting specific thermodynamic variables that classical thermodynamics cannot predict. A typical example is the derivative that is called the constant-volume specific heat. This variable is defined as the rate of change of the internal energy stored in a substance as a function of changes in its temperature. Classical thermodynamics demonstrates that this variable has to exist and makes great use of it, but it has no theory for calculating it from first principles. An atomistic view will allow us to make some theoretical estimates of its value. Therefore, at times we will deviate from the classical model and adopt an atomistic view that will improve our understanding of the subject.

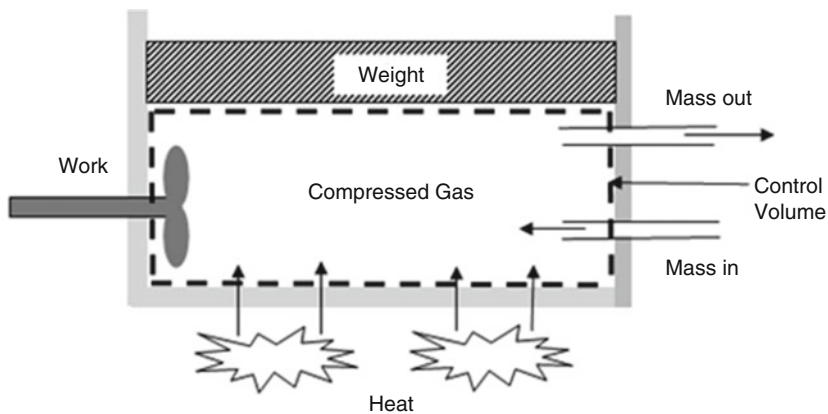
Classical thermodynamics is also an equilibrium science. The laws of thermodynamics apply to objects or systems in equilibrium with themselves and their surroundings. By definition, a system in equilibrium is not likely to change. However, we are generally interested in how systems change as thermal energy is converted to and from other forms of energy. This presents a bit of a dilemma in that the fundamental laws are only good for a system in equilibrium and the parameters we want to predict are a result of thermal energy changes in the system. To get around this dilemma, we define what is called a quasi-equilibrium process. A quasi-equilibrium process is one that moves from one system state to another so slowly and so incrementally that it looks like a series of equilibrium states. This is a concept that classical thermodynamics had a great deal of difficulty clarifying and quantifying. Basically, a process was a quasi-equilibrium process if the laws of equilibrium thermodynamics could characterize it. This is sort of a circular definition, but once again, we will find that the atomistic view allows us to make some predictions and quantifications that identify a quasi-equilibrium process. Quasi-equilibrium processes can occur very rapidly on time scales typical of human observation. For example, the expansion of the hot gases out the nozzle of a rocket engine can be well described as a quasi-equilibrium process with classical thermodynamics.

## 1.5 Open and Closed Systems

In the transfer and conversion of thermal energy, we will be interested in separating the *entire universe* into a *system* and its *environment*. We will mainly be interested in the energy transfers and conversions that go on within the *system*, but in many cases, we will need to consider its interactions with the rest of the world or its *environment*. Systems that consist of a *fixed amount of mass* that is contained within fixed boundaries are called *closed systems*. Systems that *pass the mass back and forth* to the environment will be called *open systems*. Both *open* and *closed systems* allow energy to flow across their borders, but the flow of mass determines whether they are *open* or *closed systems*. *Open systems* will also carry energy across their borders with



**Fig. 1.2** A closed system



**Fig. 1.3** An open system

the mass as it moves. Consider the simple compressed gas in the piston below as a *closed* system (Fig. 1.2).

In analyzing the closed system, we will be concerned about the changes in the internal energy of the compressed gas as it interacts with its environment and the transfers of mechanical and thermal energies across its boundary.

In analyzing open systems, the concept of a *control volume* comes into play. The *control volume* is the boundary for the open system where the energy changes that we are interested in take place. The thing separates the open system from its environment. Consider the following open system where we have now allowed mass to flow in and out of the piston of our closed system above (Fig. 1.3).

The *control volume* looks a lot like our system boundary from before, and it is. The only difference is that we now allow mass to flow in and out of our *control volume*. Thermal and mechanical energy can still flow across the boundary or in and out of the *control volume*. The mass flowing in and out can also carry energy with it either way.