Preface to The Third Edition

I am pleased to present the **third edition** of this book. The warm reception which the previous editions and reprints of this book have enjoyed all over India and abroad has been a matter of great satisfaction to me.

The entire book has been thoroughly revised ; a large number of solved examples (questions having been selected from various universities and competitive examinations) and ample additional text have been added.

Any suggestions for the improvement of the book will be thankfully acknowledged and incorporated in the next edition.

—Author

Preface to The First Edition

Several books are available in the market on the subject of "Engineering Thermodynamics" but either they are too bulky or are miserly written and as such do not cover the syllabii of various Indian Universities effectively. Hence a book is needed which should assimilate subject matter that should primarily satisfy the requirements of the students from syllabus/examination point of view ; these requirements are completely met by this book.

The book entails the following *features* :

— The presentation of the subject matter is very systematic and language of the text is quite lucid and simple to understand.

— A number of figures have been added in each chapter to make the subject matter self speaking to a great extent.

— A large number of properly graded examples have been added in various chapters to enable the students to attempt different types of questions in the examination without any difficulty.

— Highlights, objective type questions, theoretical questions, and unsolved examples have been added at the end of each chapter to make the book a complete unit in all respects.

The author's thanks are due to his wife Ramesh Rajput for rendering all assistance during preparation and proof reading of the book. The author is thankful to Mr. R.K. Syal for drawing beautiful and well proportioned figures for the book.

The author is grateful to M/s Laxmi Publications for taking lot of pains in bringing out the book in time and pricing it moderately inspite of heavy cost of the printing.

Constructive criticism is most welcome from the readers.

—Author

Contents

Chapter			*Pages*
	Introduction to S.I. Units and Conversion Factors		***(xvi)—(xx)***
	Nomenclature		***(xxi)—(xxii)***
1.	**INTRODUCTION—OUTLINE OF SOME DESCRIPTIVE SYSTEMS**	...	**1—13**
1.1.	Steam Power Plant	...	1
1.1.1.	Layout	...	1
1.1.2.	Components of a modern steam power plant	...	2
1.2.	Nuclear Power Plant	...	3
1.3.	Internal Combustion Engines	...	4
1.3.1.	Heat engines	...	4
1.3.2.	Development of I.C. engines	...	4
1.3.3.	Different parts of I.C. engines	...	4
1.3.4.	Spark ignition (S.I.) engines	...	5
1.3.5.	Compression ignition (C.I.) engines	...	7
1.4.	Gas Turbines	...	7
1.4.1.	General aspects	...	7
1.4.2.	Classification of gas turbines	...	8
1.4.3.	Merits and demerits of gas turbines	...	8
1.4.4.	A simple gas turbine plant	...	9
1.4.5.	Energy cycle for a simple-cycle gas turbine	...	10
1.5.	Refrigeration Systems	...	10
	Highlights	...	12
	Theoretical Questions	...	13
2.	**BASIC CONCEPTS OF THERMODYNAMICS**	...	**14—62**
2.1.	Introduction to Kinetic Theory of Gases	...	14
2.2.	Definition of Thermodynamics	...	18
2.3.	Thermodynamic Systems	...	18
2.3.1.	System, boundary and surroundings	...	18
2.3.2.	Closed system	...	18
2.3.3.	Open system	...	19
2.3.4.	Isolated system	...	19
2.3.5.	Adiabatic system	...	19
2.3.6.	Homogeneous system	...	19
2.3.7.	Heterogeneous system	...	19
2.4.	Macroscopic and Microscopic Points of View	...	19
2.5.	Pure Substance	...	20
2.6.	Thermodynamic Equilibrium	...	20
2.7.	Properties of Systems	...	21
2.8.	State	...	21

Chapter *Pages*

2.9. Process ... 21
2.10. Cycle ... 22
2.11. Point Function ... 22
2.12. Path Function ... 22
2.13. Temperature ... 23
2.14. Zeroth Law of Thermodynamics ... 23
2.15. The Thermometer and Thermometric Property ... 24
2.15.1. Introduction ... 24
2.15.2. Measurement of temperature ... 24
2.15.3. The international practical temperature scale ... 31
2.15.4. Ideal gas ... 33
2.16. Pressure ... 33
2.16.1. Definition of pressure ... 33
2.16.2. Unit for pressure ... 34
2.16.3. Types of pressure measurement devices ... 34
2.16.4. Mechanical type instruments ... 34
2.17. Specific Volume ... 45
2.18. Reversible and Irreversible Processes ... 46
2.19. Energy, Work and Heat ... 46
2.19.1. Energy ... 46
2.19.2. Work and heat ... 46
2.20. Reversible Work ... 48
Highlights ... 58
Objective Type Questions ... 59
Theoretical Questions ... 61
Unsolved Examples ... 61

3. PROPERTIES OF PURE SUBSTANCES ... 63—100

3.1. Definition of the Pure Substance ... 63
3.2. Phase Change of a Pure Substance ... 64
3.3. p-T (Pressure-temperature) Diagram for a Pure Substance ... 66
3.4. p-V-T (Pressure-Volume-Temperature) Surface ... 67
3.5. Phase Change Terminology and Definitions ... 67
3.6. Property Diagrams in Common Use ... 68
3.7. Formation of Steam ... 68
3.8. Important Terms Relating to Steam Formation ... 70
3.9. Thermodynamic Properties of Steam and Steam Tables ... 72
3.10. External Work Done During Evaporation ... 73
3.11. Internal Latent Heat ... 73
3.12. Internal Energy of Steam ... 73
3.13. Entropy of Water ... 73
3.14. Entropy of Evaporation ... 73
3.15. Entropy of Wet Steam ... 74
3.16. Entropy of Superheated Steam ... 74
3.17. Enthalpy-Entropy (h-s) Chart or Mollier Diagram ... 75

Chapter *Pages*

3.18. Determination of Dryness Fraction of Steam ... 89
3.18.1. Tank or bucket calorimeter ... 89
3.18.2. Throttling calorimeter ... 92
3.18.3. Separating and throttling calorimeter ... 93
Highlights ... 96
Objective Type Questions ... 97
Theoretical Questions ... 99
Unsolved Examples ... 99

4. FIRST LAW OF THERMODYNAMICS ... 101—226

4.1. Internal Energy ... 101
4.2. Law of Conservation of Energy ... 101
4.3. First Law of Thermodynamics ... 101
4.4. Application of First Law to a Process ... 103
4.5. Energy—A Property of System ... 103
4.6. Perpetual Motion Machine of the First Kind-PMM1 ... 104
4.7. Energy of an Isolated System ... 105
4.8. The Perfect Gas ... 105
4.8.1. The characteristic equation of state ... 105
4.8.2. Specific heats ... 106
4.8.3. Joule's law ... 107
4.8.4. Relationship between two specific heats ... 107
4.8.5. Enthalpy ... 108
4.8.6. Ratio of specific heats ... 109
4.9. Application of First Law of Thermodynamics to Non-flow or Closed System ... 109
4.10. Application of First Law to Steady Flow Process ... 150
4.11. Energy Relations for Flow Process ... 152
4.12. Engineering Applications of Steady Flow Energy Equation (S.F.E.E.) ... 155
4.12.1. Water turbine ... 155
4.12.2. Steam or gas turbine ... 156
4.12.3. Centrifugal water pump ... 157
4.12.4. Centrifugal compressor ... 157
4.12.5. Reciprocating compressor ... 158
4.12.6. Boiler ... 159
4.12.7. Condenser ... 159
4.12.8. Evaporator ... 160
4.12.9. Steam nozzle ... 161
4.13. Throttling Process and Joule-Thompson Porous Plug Experiment ... 162
4.14. Heating-Cooling and Expansion of Vapours ... 183
4.15. Unsteady Flow Processes ... 210
Highlights ... 215
Objective Type Questions ... 216
Theoretical Questions ... 219
Unsolved Examples ... 219

Chapter *Pages*

5. SECOND LAW OF THERMODYNAMICS AND ENTROPY ... 227—305

5.1. Limitations of First Law of Thermodynamics and Introduction to Second Law ... 227
5.2. Performance of Heat Engines and Reversed Heat Engines ... 227
5.3. Reversible Processes ... 228
5.4. Statements of Second Law of Thermodynamics ... 229
5.4.1. Clausius statement ... 229
5.4.2. Kelvin-Planck statement ... 229
5.4.3. Equivalence of Clausius statement to the Kelvin-Planck statement ... 229
5.5. Perpetual Motion Machine of the Second Kind ... 230
5.6. Thermodynamic Temperature ... 231
5.7. Clausius Inequality ... 231
5.8. Carnot Cycle ... 233
5.9. Carnot's Theorem ... 235
5.10. Corollary of Carnot's Theorem 237
5.11. Efficiency of the Reversible Heat Engine ... 237
5.12. Entropy ... 252
5.12.1. Introduction ... 252
5.12.2. Entropy—a property of a system ... 252
5.12.3. Change of entropy in a reversible process ... 253
5.13. Entropy and Irreversibility ... 254
5.14. Change in Entropy of the Universe ... 255
5.15. Temperature Entropy Diagram ... 257
5.16. Characteristics of Entropy ... 257
5.17. Entropy Changes for a Closed System ... 258
5.17.1. General case for change of entropy of a gas ... 258
5.17.2. Heating a gas at constant volume ... 259
5.17.3. Heating a gas at constant pressure ... 260
5.17.4. Isothermal process ... 260
5.17.5. Adiabatic process (reversible) ... 261
5.17.6. Polytropic process ... 262
5.17.7. Approximation for heat absorbed ... 263
5.18. Entropy Changes for an Open System ... 264
5.19. The Third Law of Thermodynamics ... 265
Highlights ... 298
Objective Type Questions ... 299
Theoretical Questions ... 302
Unsolved Examples ... 302

6. AVAILABILITY AND IRREVERSIBILITY ... 306—340

6.1. Available and Unavailable Energy ... 306
6.2. Available Energy Referred to a Cycle ... 306
6.3. Decrease in Available Energy When Heat is Transferred Through a Finite Temperature Difference ... 308
6.4. Availability in Non-flow Systems ... 310

Chapter			*Pages*
6.5.	Availability in Steady-flow Systems	...	311
6.6.	Helmholtz and Gibb's Functions	...	311
6.7.	Irreversibility	...	312
6.8.	Effectiveness	...	313
	Highlights	...	336
	Objective Type Questions	...	337
	Theoretical Questions	...	338
	Unsolved Examples	...	338
7. THERMODYNAMIC RELATIONS		...	**341—375**
7.1.	General Aspects	...	341
7.2.	Fundamentals of Partial Differentiation	...	341
7.3.	Some General Thermodynamic Relations	...	343
7.4.	Entropy Equations (Tds Equations)	...	344
7.5.	Equations for Internal Energy and Enthalpy	...	345
7.6.	Measurable Quantities	...	346
	7.6.1. Equation of state	...	346
	7.6.2. Co-efficient of expansion and compressibility	...	347
	7.6.3. Specific heats	...	348
	7.6.4. Joule-Thomson co-efficient	...	351
7.7.	Clausius-Claperyon Equation	...	353
	Highlights	...	373
	Objective Type Questions	...	374
	Exercises	...	375
8. IDEAL AND REAL GASES		...	**376—410**
8.1.	Introduction	...	376
8.2.	The Equation of State for a Perfect Gas	...	376
8.3.	p-V-T Surface of an Ideal Gas	...	379
8.4.	Internal Energy and Enthalpy of a Perfect Gas	...	379
8.5.	Specific Heat Capacities of an Ideal Gas	...	380
8.6.	Real Gases	...	381
8.7.	Van der Waal's Equation	...	381
8.8.	Virial Equation of State	...	390
8.9.	Beattie-Bridgeman Equation	...	390
8.10.	Reduced Properties	...	391
8.11.	Law of Corresponding States	...	392
8.12.	Compressibility Chart	...	392
	Highlights	...	407
	Objective Type Questions	...	408
	Theoretical Questions	...	408
	Unsolved Examples	...	409
9. GASES AND VAPOUR MIXTURES		...	**411—448**
9.1.	Introduction	...	411

Chapter *Pages*

9.2. Dalton's Law and Gibbs-Dalton Law ... 411
9.3. Volumetric Analysis of a Gas Mixture ... 413
9.4. The Apparent Molecular Weight and Gas Constant ... 414
9.5. Specific Heats of a Gas Mixture ... 417
9.6. Adiabatic Mixing of Perfect Gases ... 418
9.7. Gas and Vapour Mixtures ... 419
Highlights ... 444
Objective Type Questions ... 444
Theoretical Questions ... 445
Unsolved Examples ... 445

10. PSYCHROMETRICS ... 449—486

10.1. Concept of Psychrometry and Psychrometrics ... 449
10.2. Definitions ... 449
10.3. Psychrometric Relations ... 450
10.4. Psychrometers ... 455
10.5. Psychrometric Charts ... 456
10.6. Psychrometric Processes ... 458
10.6.1. Mixing of air streams ... 458
10.6.2. Sensible heating ... 459
10.6.3. Sensible cooling ... 460
10.6.4. Cooling and dehumidification ... 461
10.6.5. Cooling and humidification ... 462
10.6.6. Heating and dehumidification ... 463
10.6.7. Heating and humidification ... 463
Highlights ... 483
Objective Type Questions ... 483
Theoretical Questions ... 484
Unsolved Examples ... 485

11. CHEMICAL THERMODYNAMICS ... 487—592

11.1. Introduction ... 487
11.2. Classification of Fuels ... 487
11.3. Solid Fuels ... 488
11.4. Liquid Fuels ... 489
11.5. Gaseous Fuels ... 489
11.6. Basic Chemistry ... 490
11.7. Combustion Equations ... 491
11.8. Theoretical Air and Excess Air ... 493
11.9. Stoichiometric Air Fuel (A/F) Ratio ... 493
11.10. Air-Fuel Ratio from Analysis of Products ... 494
11.11. How to Convert Volumetric Analysis to Weight Analysis ... 494
11.12. How to Convert Weight Analysis to Volumetric Analysis ... 494
11.13. Weight of Carbon in Flue Gases ... 494
11.14. Weight of Flue Gases per kg of Fuel Burnt ... 495
11.15. Analysis of Exhaust and Flue Gas ... 495

Chapter *Pages*

11.16. Internal Energy and Enthalpy of Reaction ... 497
11.17. Enthalpy of Formation (ΔH_f) ... 500
11.18. Calorific or Heating Values of Fuels ... 501
11.19. Determination of Calorific or Heating Values ... 501
11.19.1. Solid and Liquid Fuels ... 502
11.19.2. Gaseous Fuels ... 504
11.20. Adiabatic Flame Temperature ... 506
11.21. Chemical Equilibrium ... 506
11.22. Actual Combustion Analysis ... 507
Highlights ... 537
Objective Type Questions ... 538
Theoretical Questions ... 539
Unsolved Examples ... 540

12. VAPOUR POWER CYCLES ... 543—603

12.1. Carnot Cycle ... 543
12.2. Rankine Cycle ... 544
12.3. Modified Rankine Cycle ... 557
12.4. Regenerative Cycle ... 562
12.5. Reheat Cycle ... 576
12.6. Binary Vapour Cycle ... 584
Highlights ... 601
Objective Type Questions ... 601
Theoretical Questions ... 602
Unsolved Examples ... 603

13. GAS POWER CYCLES ... 604—712

13.1. Definition of a Cycle ... 604
13.2. Air Standard Efficiency ... 604
13.3. The Carnot Cycle ... 605
13.4. Constant Volume or Otto Cycle ... 613
13.5. Constant Pressure or Diesel Cycle ... 629
13.6. Dual Combustion Cycle ... 639
13.7. Comparison of Otto, Diesel and Dual Combustion Cycles ... 655
13.7.1. Efficiency versus compression ratio ... 655
13.7.2. For the same compression ratio and the same heat input ... 655
13.7.3. For constant maximum pressure and heat supplied ... 656
13.8. Atkinson Cycle ... 657
13.9. Ericsson Cycle ... 660
13.10. Gas Turbine Cycle-Brayton Cycle ... 661
13.10.1. Ideal Brayton cycle ... 661
13.10.2. Pressure ratio for maximum work ... 663
13.10.3. Work ratio ... 664
13.10.4. Open cycle gas turbine-actual brayton cycle ... 665
13.10.5. Methods for improvement of thermal efficiency of open cycle gas turbine plant ... 667

Chapter *Pages*

13.10.6. Effect of operating variables on thermal efficiency ... 671
13.10.7. Closed cycle gas turbine ... 674
13.10.8. Gas turbine fuels ... 679
Highlights ... 706
Theoretical Questions ... 707
Objective Type Questions ... 707
Unsolved Examples ... 709

14. REFRIGERATION CYCLES ... 713—777

14.1. Fundamentals of Refrigeration ... 713
14.1.1. Introduction ... 713
14.1.2. Elements of refrigeration systems ... 714
14.1.3. Refrigeration systems ... 714
14.1.4. Co-efficient of performance (C.O.P.) ... 714
14.1.5. Standard rating of a refrigeration machine ... 715
14.2. Air Refrigeration System ... 715
14.2.1. Introduction ... 715
14.2.2. Reversed Carnot cycle ... 716
14.2.3. Reversed Brayton cycle ... 722
14.2.4. Merits and demerits of air refrigeration system ... 724
14.3. Simple Vapour Compression System ... 730
14.3.1. Introduction ... 730
14.3.2. Simple vapour compression cycle ... 730
14.3.3. Functions of parts of a simple vapour compression system ... 731
14.3.4. Vapour compression cycle on temperature-entropy (T-s) diagram ... 732
14.3.5. Pressure-enthalpy (p-h) chart ... 734
14.3.6. Simple vapour compression cycle on p-h chart ... 735
14.3.7. Factors affecting the performance of a vapour compression system ... 736
14.3.8. Actual vapour compression cycle ... 737
14.3.9. Volumetric efficiency ... 739
14.3.10. Mathematical analysis of vapour compression refrigeration ... 740
14.4. Vapour Absorption System ... 741
14.4.1. Introduction ... 741
14.4.2. Simple vapour absorption system ... 742
14.4.3. Practical vapour absorption system ... 743
14.4.4. Comparison between vapour compression and vapour absorption systems ... 744
14.5. Refrigerants ... 764
14.5.1. Classification of refrigerants ... 764
14.5.2. Desirable properties of an ideal refrigerant ... 766
14.5.3. Properties and uses of commonly used refrigerants ... 768
Highlights ... 771
Objective Type Questions ... 772
Theoretical Questions ... 773
Unsolved Examples ... 774

Chapter *Pages*

15. HEAT TRANSFER ... 778—856

15.1. Modes of Heat Transfer ... 778
15.2. Heat Transmission by Conduction ... 778
15.2.1. Fourier's law of conduction ... 778
15.2.2. Thermal conductivity of materials ... 780
15.2.3. Thermal resistance (R_{th}) ... 782
15.2.4. General heat conduction equation in cartesian coordinates ... 783
15.2.5. Heat conduction through plane and composite walls ... 787
15.2.6. The overall heat transfer coefficient ... 790
15.2.7. Heat conduction through hollow and composite cylinders ... 799
15.2.8. Heat conduction through hollow and composite spheres ... 805
15.2.9. Critical thickness of insulation ... 808
15.3. Heat Transfer by Convection ... 812
15.4. Heat Exchangers ... 815
15.4.1. Introduction ... 815
15.4.2. Types of heat exchangers ... 815
15.4.3. Heat exchanger analysis ... 820
15.4.4. Logarithmic temperature difference (LMTD) ... 821
15.5. Heat Transfer by Radiation ... 832
15.5.1. Introduction ... 832
15.5.2. Surface emission properties ... 833
15.5.3. Absorptivity, reflectivity and transmittivity ... 834
15.5.4. Concept of a black body ... 836
15.5.5. The Stefan-Boltzmann law ... 836
15.5.6. Kirchhoff's law ... 837
15.5.7. Planck's law ... 837
15.5.8. Wien's displacement law ... 839
15.5.9. Intensity of radiation and Lambert's cosine law ... 840
15.5.10. Radiation exchange between black bodies separated by a non-absorbing medium ... 843
Highlights ... 851
Objective Type Questions ... 852
Theoretical Questions ... 854
Unsolved Examples ... 854

16. COMPRESSIBLE FLOW ... 857—903

16.1. Introduction ... 857
16.2. Basic Equations of Compressible Fluid Flow ... 857
16.2.1. Continuity equation ... 857
16.2.2. Momentum equation ... 858
16.2.3. Bernoulli's or energy equation ... 858
16.3. Propagation of Disturbances in Fluid and Velocity of Sound ... 862
16.3.1. Derivation of sonic velocity (velocity of sound) ... 862
16.3.2. Sonic velocity in terms of bulk modulus ... 864
16.3.3. Sonic velocity for isothermal process ... 864
16.3.4. Sonic velocity for adiabatic process ... 865

Chapter			*Pages*
16.4.	Mach Number	...	865
16.5.	Propagation of Disturbance in Compressible Fluid	...	866
16.6.	Stagnation Properties	...	869
	16.6.1. Expression for stagnation pressure (p_s) in compressible flow	...	869
	16.6.2. Expression for stagnation density (ρ_s)	...	872
	16.6.3. Expression for stagnation temperature (T_s)	...	872
16.7.	Area—Velocity Relationship and Effect of Variation of Area for Subsonic, Sonic and Supersonic Flows	...	876
16.8.	Flow of Compressible Fluid Through a Convergent Nozzle	...	878
16.9.	Variables of Flow in Terms of Mach Number	...	883
16.10.	Flow Through Laval Nozzle (Convergent-divergent Nozzle)	...	886
16.11.	Shock Waves	...	892
	16.11.1. Normal shock wave	...	892
	16.11.2. Oblique shock wave	...	895
	16.11.3. Shock Strength	...	895
	Highlights	...	896
	Objective Type Questions	...	899
	Theoretical Questions	...	901
	Unsolved Examples	...	902
•	**Competitive Examinations Questions with Answers**	...	**904—919**
	Index	...	**920—922**
•	**Steam Tables and Mollier Diagram**	...	***(i)—(xx)***

Introduction to SI Units and Conversion Factors

A. INTRODUCTION TO SI UNITS

SI, the international system of units are divided into three classes :

1. Base units
2. Derived units
3. Supplementary units.

From the scientific point of view division of SI units into these classes is to a certain extent arbitrary, because it is not essential to the physics of the subject. Nevertheless the General Conference, considering the advantages of a single, practical, world-wide system for international relations, for teaching and for scientific work, decided to base the international system on a choice of six well-defined units given in Table 1 below :

Table 1. SI Base Units

Quantity	*Name*	*Symbol*
length	metre	m
mass	kilogram	kg
time	second	s
electric current	ampere	A
thermodynamic temperature	kelvin	K
luminous intensity	candela	cd
amount of substance	mole	mol

The second class of SI units contains derived units, *i.e.,* units which can be formed by combining base units according to the algebraic relations linking the corresponding quantities. Several of these algebraic expressions in terms of base units can be replaced by special names and symbols can themselves be used to form other derived units.

Derived units may, therefore, be classified under three headings. Some of them are given in Tables 2, 3 and 4.