Contents

Preface xi

Acknowledgments xiii

1. Introduction to Internal Combustion Engines 1
   1.1 Introduction 1
   1.2 Historical Background 4
   1.3 Engine Cycles 5
   1.4 Engine Performance Parameters 9
   1.5 Engine Configurations 16
   1.6 Examples of Internal Combustion Engines 23
   1.7 Alternative Power Plants 26
   1.8 References 29
   1.9 Homework 30

2. Heat Engine Cycles 32
   2.1 Introduction 32
   2.2 Constant Volume Heat Addition 33
   2.3 Constant Pressure Heat Addition 36
   2.4 Limited Pressure Cycle 37
   2.5 Miller Cycle 39
   2.6 Finite Energy Release 41
   2.7 Ideal Four-Stroke Process and Residual Fraction 54
   2.8 Discussion of Gas Cycle Models 62
   2.9 References 63
   2.10 Homework 64

3. Fuel, Air, and Combustion Thermodynamics 66
   3.1 Introduction 66
   3.2 Thermodynamic Properties of Ideal Gas Mixtures 66
   3.3 Liquid–Vapor–Gas Mixtures 72
   3.4 Stoichiometry 76
   3.5 Low-Temperature Combustion Modeling 79
   3.6 General Chemical Equilibrium 84
   3.7 Chemical Equilibrium using Equilibrium Constants 89
   3.8 References 94
   3.9 Homework 94

4. Fuel–Air Combustion Processes 97
   4.1 Introduction 97
   4.2 Combustion and the First Law 97
4.3 Maximum Work and the Second Law 103  
4.4 Fuel–Air Otto Cycle 108  
4.5 Four-Stroke Fuel–Air Otto Cycle 113  
4.6 Homogeneous Two-Zone Finite Heat Release Cycle 116  
4.7 Comparison of Fuel–Air Cycles with Actual Spark Ignition Cycles 123  
4.8 Limited Pressure Fuel–Air Cycle 125  
4.9 Comparison of Limited Pressure Fuel–Air Cycles with Actual Compression Ignition Cycles 128  
4.10 References 129  
4.11 Homework 129  

5. **Intake and Exhaust Flow** 131  
5.1 Introduction 131  
5.2 Valve Flow 131  
5.3 Intake and Exhaust Flow 147  
5.4 Superchargers and Turbochargers 150  
5.5 Effect of Ambient Conditions on Engine and Compressor Mass Flow 158  
5.6 References 159  
5.7 Homework 160  

6. **Fuel and Airflow in the Cylinder** 163  
6.1 Introduction 163  
6.2 Carburetion 163  
6.3 Fuel Injection–Spark Ignition 166  
6.4 Fuel Injection–Compression Ignition 168  
6.5 Large-Scale in-Cylinder Flow 174  
6.6 In-Cylinder Turbulence 180  
6.7 Airflow in Two-Stroke Engines 185  
6.8 References 193  
6.9 Homework 195  

7. **Combustion Processes in Engines** 197  
7.1 Introduction 197  
7.2 Combustion in Spark Ignition Engines 198  
7.3 Abnormal Combustion (Knock) in Spark Ignition Engines 206  
7.4 Combustion in Compression Ignition Engines 214  
7.5 Low-Temperature Combustion 225  
7.6 References 229  
7.7 Homework 231  

8. **Emissions** 234  
8.1 Introduction 234  
8.2 Nitrogen Oxides 235  
8.3 Carbon Monoxide 243  
8.4 Hydrocarbons 245  
8.5 Particulates 249
## 9. Fuels 262

9.1 Introduction 262  
9.2 Hydrocarbon Chemistry 263  
9.3 Refining 266  
9.4 Fuel Properties 267  
9.5 Gasoline Fuels 269  
9.6 Alternative Fuels for Spark Ignition Engines 274  
9.7 Hydrogen 281  
9.8 Diesel Fuels 282  
9.9 References 286  
9.10 Homework 287

## 10. Friction and Lubrication 288

10.1 Introduction 288  
10.2 Friction Coefficient 288  
10.3 Friction Mean Effective Pressure 291  
10.4 Friction Measurements 291  
10.5 Friction Modeling 294  
10.6 Journal Bearing Friction 295  
10.7 Piston and Ring Friction 298  
10.8 Valve Train Friction 306  
10.9 Accessory Friction 308  
10.10 Pumping Mean Effective Pressure 310  
10.11 Overall Engine Friction Mean Effective Pressure 311  
10.12 Lubrication 312  
10.13 References 315  
10.14 Homework 316

## 11. Heat and Mass Transfer 318

11.1 Introduction 318  
11.2 Engine Cooling Systems 319  
11.3 Engine Energy Balance 320  
11.4 Cylinder Heat Transfer 324  
11.5 Heat Transfer Modeling 326  
11.6 Heat Transfer Correlations 330  
11.7 Heat Transfer in the Exhaust System 338  
11.8 Radiation Heat Transfer 339  
11.9 Mass Loss or Blowby 340  
11.10 References 342  
11.11 Homework 344

## 12. Engine Testing and Control 346

12.1 Introduction 346  
12.2 Instrumentation 347
Contents

12.3 Combustion Analysis 354
12.4 Exhaust Gas Analysis 358
12.5 Control Systems in Engines 366
12.6 Vehicle Emissions Testing 369
12.7 References 370
12.8 Homework 370

13. Overall Engine Performance 372

13.1 Introduction 372
13.2 Effect of Engine and Piston Speed 372
13.3 Effect of Air–Fuel Ratio and Load 373
13.4 Engine Performance Maps 376
13.5 Effect of Engine Size 379
13.6 Effect of Ignition and Injection Timing 380
13.7 Effect of Compression Ratio 383
13.8 Vehicle Performance Simulation 383
13.9 References 384
13.10 Homework 385

Appendices 387

A Physical Properties of Air 387
B Thermodynamic Property Tables for Various Ideal Gases 389
C Curve-Fit Coefficients for Thermodynamic Properties of Various Fuels and Ideal Gases 397
D Conversion Factors and Physical Constants 401
E Thermodynamic Analysis of Mixtures 403
E.1 Thermodynamic Derivatives 403
E.2 Numerical Solution of Equilibrium Combustion Equations 405
E.3 Isentropic Compression/Expansion with Known $\Delta P$ 408
E.4 Isentropic Compression/Expansion with Known $\Delta v$ 409
E.5 Constant Volume Combustion 410
E.6 Quality of Exhaust Products 411
E.7 References 412
F Computer Programs 413
F.1 Volume.m 414
F.2 Velocity.m 414
F.3 BurnFraction.m 414
F.4 FiniteHeatRelease.m 415
F.5 FiniteHeatMassLoss.m 417
F.6 FourStrokeOtto.m 420
F.7 RunFarg.m 421
F.8 farg.m 422
F.9 fuel.m 425
F.10 RunEcp.m 426
F.11 ecp.m 427
F.12 AdiabaticFlameTemp.m 437
F.13 OttoFuel.m 438
Contents

F.14  FourStrokeFuelAir.m  440
F.15  Homogeneous.m  444
F.16  Friction.m  450
F.17  WoschniHeatTransfer.m  451

Index  455