

Contents

<i>Foreword</i>	<i>vii</i>
<i>Preface</i>	<i>ix</i>
<i>Nomenclature</i>	<i>xxxii</i>
1 Introduction	1
1.1 Energy Conversion	1
1.1.1 Definition of ‘Engine’	1
1.1.2 Definition of ‘Heat Engine’	1
1.1.3 Classification and Some Basic Details of Heat Engines	1
1.1.4 External Combustion and Internal Combustion Engines	2
1.2 Basic Engine Components and Nomenclature	3
1.2.1 Engine Components	3
1.2.2 Nomenclature	5
1.3 The Working Principle of Engines	6
1.3.1 Four-Stroke Spark-Ignition Engine	6
1.3.2 Four-Stroke Compression-Ignition Engine	8
1.3.3 Four-stroke SI and CI Engines	10
1.3.4 Two-Stroke Engine	10
1.3.5 Comparison of Four-Stroke and Two-Stroke Engines	12
1.4 Actual Engines	13
1.5 Classification of IC Engines	13
1.5.1 Cycle of Operation	16
1.5.2 Type of Fuel Used	16
1.5.3 Method of Charging	17
1.5.4 Type of Ignition	17
1.5.5 Type of Cooling	17
1.5.6 Cylinder Arrangements	17
1.6 Application of IC Engines	19
1.6.1 Two-Stroke Gasoline Engines	19
1.6.2 Two-Stroke Diesel Engines	20
1.6.3 Four-Stroke Gasoline Engines	20
1.6.4 Four-Stroke Diesel Engines	21

1.7	The First Law Analysis of Engine Cycle	21
1.8	Engine Performance Parameters	22
1.8.1	Indicated Thermal Efficiency (η_{ith})	22
1.8.2	Brake Thermal Efficiency (η_{bth})	23
1.8.3	Mechanical Efficiency (η_m)	23
1.8.4	Volumetric Efficiency (η_v)	23
1.8.5	Relative Efficiency or Efficiency Ratio (η_{rel})	24
1.8.6	Mean Effective Pressure (p_m)	24
1.8.7	Mean Piston Speed (\bar{s}_p)	25
1.8.8	Specific Power Output (P_s)	25
1.8.9	Specific Fuel Consumption (sfc)	26
1.8.10	Inlet-Valve Mach Index (Z)	26
1.8.11	Fuel-Air (F/A) or Air-Fuel Ratio (A/F)	26
1.8.12	Calorific Value (CV)	27
1.9	Design and Performance Data	28
	Worked out Examples	30
	Review Questions	37
	Exercise	38
	Multiple Choice Questions	42
2	Air-Standard Cycles and Their Analysis	47
2.1	Introduction	47
2.2	The Carnot Cycle	48
2.3	The Stirling Cycle	50
2.4	The Ericsson Cycle	51
2.5	The Otto Cycle	52
2.5.1	Thermal Efficiency	53
2.5.2	Work Output	54
2.5.3	Mean Effective Pressure	55
2.6	The Diesel Cycle	55
2.6.1	Thermal Efficiency	56
2.6.2	Work Output	58
2.6.3	Mean Effective Pressure	58
2.7	The Dual Cycle	58
2.7.1	Thermal Efficiency	58
2.7.2	Work Output	60
2.7.3	Mean Effective Pressure	60
2.8	Comparison of the Otto, Diesel and Dual Cycles	61
2.8.1	Same Compression Ratio and Heat Addition	61
2.8.2	Same Compression Ratio and Heat Rejection	62
2.8.3	Same Peak Pressure, Peak Temperature & Heat Rejection	62
2.8.4	Same Maximum Pressure and Heat Input	63
2.8.5	Same Maximum Pressure and Work Output	64

2.9 The Lenoir Cycle	64
2.10 The Atkinson Cycle	65
2.11 The Brayton Cycle	66
Worked out Examples	68
Review Questions	97
Exercise	98
Multiple Choice Questions	103
3 Fuel–Air Cycles and their Analysis	107
3.1 Introduction	107
3.2 Fuel–Air Cycles and their Significance	107
3.3 Composition of Cylinder Gases	109
3.4 Variable Specific Heats	109
3.5 Dissociation	111
3.6 Effect of Number of Moles	113
3.7 Comparison of Air–Standard and Fuel–Air Cycles	114
3.8 Effect of Operating Variables	115
3.8.1 Compression Ratio	115
3.8.2 Fuel–Air Ratio	117
Worked out Examples	121
Review Questions	128
Exercise	128
Multiple Choice Questions	129
4 Actual Cycles and their Analysis	131
4.1 Introduction	131
4.2 Comparison of Air-Standard and Actual Cycles	131
4.3 Time Loss Factor	132
4.4 Heat Loss Factor	137
4.5 Exhaust Blowdown	137
4.5.1 Loss Due to Gas Exchange Processes	138
4.5.2 Volumetric Efficiency	139
4.6 Loss due to Rubbing Friction	142
4.7 Actual and Fuel-Air Cycles of CI Engines	142
Review Questions	143
Multiple Choice Questions	144
5 Conventional Fuels	147
5.1 Introduction	147
5.2 Fuels	147
5.2.1 Solid Fuels	147
5.2.2 Gaseous Fuels	147
5.2.3 Liquid Fuels	148

xiv *Contents*

5.3	Chemical Structure of Petroleum	148
5.3.1	Paraffin Series	148
5.3.2	Olefin Series	149
5.3.3	Naphthene Series	150
5.3.4	Aromatic Series	150
5.4	Petroleum Refining Process	151
5.5	Important Qualities of Engine Fuels	153
5.5.1	SI Engine Fuels	154
5.5.2	CI Engine Fuels	156
5.6	Rating of Fuels	157
5.6.1	Rating of SI Engine Fuels	157
5.6.2	Rating of CI Engine Fuels	158
	Review Questions	159
	Multiple Choice Questions	160
6	Alternate Fuels	163
6.1	Introduction	163
6.2	Possible Alternatives	164
6.3	Solid Fuels	164
6.4	Liquid Fuels	166
6.4.1	Alcohol	166
6.4.2	Methanol	167
6.4.3	Ethanol	168
6.4.4	Alcohol for SI Engines	168
6.4.5	Reformulated Gasoline for SI Engine	169
6.4.6	Water-Gasoline Mixture for SI Engines	169
6.4.7	Alcohol for CI Engines	170
6.5	Surface-Ignition Alcohol CI Engine	171
6.6	Spark-Assisted Diesel	172
6.7	Vegetable Oil	172
6.8	Biodiesel	173
6.8.1	Production	174
6.8.2	Properties	175
6.8.3	Environmental Effects	175
6.8.4	Current Research	175
6.9	Gaseous Fuels	176
6.9.1	Hydrogen	176
6.10	Hydrogen Engines	177
6.10.1	Natural Gas	178
6.10.2	Advantages of Natural Gas	179
6.10.3	Disadvantages of Natural Gas	179
6.10.4	Compressed Natural Gas (CNG)	180
6.10.5	Liquefied Petroleum Gas (LPG)	180

6.10.6 Advantages and Disadvantages of LPG	181
6.10.7 Future Scenario for LPG Vehicles	183
6.10.8 LPG (Propane) Fuel Feed System	183
6.11 Dual Fuel Operation	183
6.12 Other Possible Fuels	184
6.12.1 Biogas	184
6.12.2 Producer Gas	185
6.12.3 Blast Furnace Gas	185
6.12.4 Coke Oven Gas	185
6.12.5 Benzol	185
6.12.6 Acetone	186
6.12.7 Diethyl Ether	186
Review Questions	186
Multiple Choice Questions	187
7 Carburetion	189
7.1 Introduction	189
7.2 Definition of Carburetion	189
7.3 Factors Affecting Carburetion	189
7.4 Air–Fuel Mixtures	190
7.5 Mixture Requirements at Different Loads and Speeds	190
7.6 Automotive Engine Air–Fuel Mixture Requirements	192
7.6.1 Idling Range	192
7.6.2 Cruising Range	193
7.6.3 Power Range	194
7.7 Principle of Carburetion	195
7.8 The Simple Carburetor	196
7.9 Calculation of the Air–Fuel Ratio	197
7.9.1 Air–Fuel Ratio Neglecting Compressibility of Air	200
7.9.2 Air–Fuel Ratio Provided by a Simple Carburetor	200
7.9.3 Size of the Carburetor	201
7.10 Essential Parts of a Carburetor	201
7.10.1 The Fuel Strainer	201
7.10.2 The Float Chamber	201
7.10.3 The Main Metering and Idling System	202
7.10.4 The Choke and the Throttle	204
7.11 Compensating Devices	206
7.11.1 Air–bleed jet	206
7.11.2 Compensating Jet	207
7.11.3 Emulsion Tube	207
7.11.4 Back Suction Control Mechanism	208
7.11.5 Auxiliary Valve	210
7.11.6 Auxiliary Port	210

xvi Contents

7.12 Additional Systems in Modern Carburetors	210
7.12.1 Anti-dieseling System	211
7.12.2 Richer Coasting System	212
7.12.3 Acceleration Pump System	212
7.12.4 Economizer or Power Enrichment System	212
7.13 Types of Carburetors	213
7.13.1 Constant Choke Carburetor	214
7.13.2 Constant Vacuum Carburetor	214
7.13.3 Multiple Venturi Carburetor	214
7.13.4 Advantages of a Multiple Venturi System	216
7.13.5 Multijet Carburetors	216
7.13.6 Multi-barrel Venturi Carburetor	217
7.14 Automobile Carburetors	218
7.14.1 Solex Carburetors	218
7.14.2 Carter Carburetor	220
7.14.3 S.U. Carburetor	222
7.15 Altitude Compensation	223
7.15.1 Altitude Compensation Devices	224
Worked out Examples	225
Review Questions	234
Exercise	235
Multiple Choice Questions	238
8 Mechanical Injection Systems	241
8.1 Introduction	241
8.2 Functional Requirements of an Injection System	241
8.3 Classification of Injection Systems	242
8.3.1 Air Injection System	242
8.3.2 Solid Injection System	242
8.3.3 Individual Pump and Nozzle System	243
8.3.4 Unit Injector System	244
8.3.5 Common Rail System	244
8.3.6 Distributor System	245
8.4 Fuel Feed Pump	246
8.5 Injection Pump	246
8.5.1 Jerk Type Pump	246
8.5.2 Distributor Type Pump	248
8.6 Injection Pump Governor	248
8.7 Mechanical Governor	250
8.8 Pneumatic Governor	251
8.9 Fuel Injector	251

8.10 Nozzle	252
8.10.1 Types of Nozzle	253
8.10.2 Spray Formation	255
8.10.3 Quantity of Fuel and the Size of Nozzle Orifice	257
8.11 Injection in SI Engine	258
Worked out Examples	259
Review Questions	266
Exercise	267
Multiple Choice Questions	268
9 Electronic Injection Systems	271
9.1 Introduction	271
9.2 Why Gasoline Injection?	271
9.2.1 Types of Injection Systems	272
9.2.2 Components of Injection System	273
9.3 Electronic Fuel Injection System	275
9.3.1 Merits of EFI System	276
9.3.2 Demerits of EFI System	276
9.4 Multi-Point Fuel Injection (MPFI) System	277
9.4.1 Port Injection	277
9.4.2 Throttle Body Injection System	278
9.4.3 D-MPFI System	278
9.4.4 L-MPFI System	279
9.5 Functional Divisions of MPFI System	279
9.5.1 MPFI-Electronic Control System	279
9.5.2 MPFI-Fuel System	279
9.5.3 MPFI-Air Induction System	279
9.6 Electronic Control System	281
9.6.1 Electronic Control Unit (ECU)	281
9.6.2 Cold Start Injector	282
9.6.3 Air Valve	282
9.7 Injection Timing	283
9.8 Group Gasoline Injection System	284
9.9 Electronic Diesel Injection System	286
9.10 Electronic Diesel Injection Control	287
9.10.1 Electronically Controlled Unit Injectors	287
9.10.2 Electronically Controlled Injection Pumps (Inline and Distributor Type)	288
9.10.3 Common-Rail Fuel Injection System	290
Review Questions	292
Multiple Choice Questions	293

10 Ignition	295
10.1 Introduction	295
10.2 Energy Requirements for Ignition	295
10.3 The Spark Energy and Duration	296
10.4 Ignition System	296
10.5 Requirements of an Ignition System	297
10.6 Battery Ignition System	297
10.6.1 Battery	298
10.6.2 Ignition Switch	299
10.6.3 Ballast Resistor	299
10.6.4 Ignition Coil	299
10.6.5 Contact Breaker	300
10.6.6 Capacitor	301
10.6.7 Distributor	301
10.6.8 Spark Plug	302
10.7 Operation of a Battery Ignition System	304
10.8 Limitations	305
10.9 Dwell Angle	306
10.10 Advantage of a 12 V Ignition System	307
10.11 Magneto Ignition System	307
10.12 Modern Ignition Systems	309
10.12.1 Transistorized Coil Ignition (TCI) System	310
10.12.2 Capacitive Discharge Ignition (CDI) System	312
10.13 Firing Order	312
10.14 Ignition Timing and Engine Parameters	314
10.14.1 Engine Speed	314
10.14.2 Mixture Strength	315
10.14.3 Part Load Operation	315
10.14.4 Type of Fuel	315
10.15 Spark Advance Mechanism	315
10.15.1 Centrifugal Advance Mechanism	316
10.15.2 Vacuum Advance Mechanism	317
10.16 Ignition Timing and Exhaust Emissions	318
Review Questions	319
Multiple Choice Questions	320
11 Combustion and Combustion Chambers	323
11.1 Introduction	323
11.2 Homogeneous Mixture	323
11.3 Heterogeneous Mixture	324
11.4 Combustion in Spark-Ignition Engines	324
11.5 Stages of Combustion in SI Engines	324
11.6 Flame Front Propagation	326

11.7 Factors Influencing the Flame Speed	327
11.8 Rate of Pressure Rise	329
11.9 Abnormal Combustion	330
11.10 The Phenomenon of Knock in SI Engines	330
11.10.1 Knock Limited Parameters	332
11.11 Effect of Engine Variables on Knock	333
11.11.1 Density Factors	333
11.11.2 Time Factors	334
11.11.3 Composition Factors	335
11.12 Combustion Chambers for SI Engines	336
11.12.1 Smooth Engine Operation	337
11.12.2 High Power Output and Thermal Efficiency	337
11.13 Combustion in Compression-Ignition Engines	339
11.14 Stages of Combustion in CI Engines	342
11.14.1 Ignition Delay Period	342
11.14.2 Period of Rapid Combustion	344
11.14.3 Period of Controlled Combustion	344
11.14.4 Period of After-Burning	344
11.15 Factors Affecting the Delay Period	344
11.15.1 Compression Ratio	345
11.15.2 Engine Speed	346
11.15.3 Output	347
11.15.4 Atomization and Duration of Injection	347
11.15.5 Injection Timing	347
11.15.6 Quality of Fuel	347
11.15.7 Intake Temperature	347
11.15.8 Intake Pressure	348
11.16 The Phenomenon of Knock in CI Engines	348
11.17 Comparison of Knock in SI and CI Engines	350
11.18 Combustion Chambers for CI Engines	352
11.18.1 Direct-Injection Chambers	353
11.18.2 Indirect-Injection Chambers	355
Review Questions	357
Multiple Choice Questions	358
12 Engine Friction and Lubrication	361
12.1 Introduction	361
12.1.1 Direct Frictional Losses	361
12.1.2 Pumping Loss	361
12.1.3 Power Loss to Drive Components to Charge and Scavenge	362
12.1.4 Power Loss to Drive the Auxiliaries	362
12.2 Mechanical Efficiency	362

12.3	Mechanical Friction	363
12.3.1	Fluid-film or Hydrodynamic Friction	363
12.3.2	Partial-film Friction	363
12.3.3	Rolling Friction	363
12.3.4	Dry Friction	363
12.3.5	Journal Bearing Friction	364
12.3.6	Friction due to Piston Motion	364
12.4	Blowby Losses	364
12.5	Pumping Loss	365
12.5.1	Exhaust Blowdown Loss	365
12.5.2	Exhaust Stroke Loss	365
12.5.3	Intake Stroke Loss	365
12.6	Factors Affecting Mechanical Friction	366
12.6.1	Engine Design	366
12.6.2	Engine Speed	367
12.6.3	Engine Load	367
12.6.4	Cooling Water Temperature	367
12.6.5	Oil Viscosity	367
12.7	Lubrication	367
12.7.1	Function of Lubrication	368
12.7.2	Mechanism of Lubrication	368
12.7.3	Elastohydrodynamic Lubrication	371
12.7.4	Journal Bearing Lubrication	372
12.7.5	Stable Lubrication	374
12.8	Lubrication of Engine Components	375
12.8.1	Piston	375
12.8.2	Crankshaft Bearings	376
12.8.3	Crankpin Bearings	376
12.8.4	Wristpin Bearing	376
12.9	Lubrication System	377
12.9.1	Mist Lubrication System	377
12.9.2	Wet Sump Lubrication System	379
12.9.3	Dry Sump Lubrication System	382
12.10	Crankcase Ventilation	383
12.11	Properties of Lubricants	384
12.11.1	Viscosity	385
12.11.2	Flash and Fire Points	385
12.11.3	Cloud and Pour Points	385
12.11.4	Oiliness or Film Strength	386
12.11.5	Corrosiveness	386
12.11.6	Detergency	386
12.11.7	Stability	386
12.11.8	Foaming	386

12.12 SAE Rating of Lubricants	386
12.12.1 Single-grade	386
12.12.2 Multi-grade	387
12.13 Additives for Lubricants	388
12.13.1 Anti-oxidants and Anticorrosive Agents	388
12.13.2 Detergent-Dispersant	389
12.13.3 Extreme Pressure Additives	389
12.13.4 Pour Point Depressors	389
12.13.5 Viscosity Index Improvers	389
12.13.6 Oiliness and Film Strength Agents	389
12.13.7 Antifoam Agents	390
Review Questions	390
Multiple Choice Questions	390
13 Heat Rejection and Cooling	393
13.1 Introduction	393
13.2 Variation of Gas Temperature	393
13.3 Piston Temperature Distribution	394
13.4 Cylinder Temperature Distribution	395
13.5 Heat Transfer	395
13.6 Theory of Engine Heat Transfer	397
13.7 Parameters Affecting Engine Heat Transfer	399
13.7.1 Fuel-Air Ratio	399
13.7.2 Compression Ratio	399
13.7.3 Spark Advance	399
13.7.4 Preignition and Knocking	399
13.7.5 Engine Output	399
13.7.6 Cylinder Wall Temperature	400
13.8 Power Required to Cool the Engine	400
13.9 Need for Cooling System	400
13.10 Characteristics of an Efficient Cooling System	401
13.11 Types of Cooling Systems	401
13.12 Liquid Cooled Systems	401
13.12.1 Direct or Non-return System	402
13.12.2 Thermosyphon System	403
13.12.3 Forced Circulation Cooling System	403
13.12.4 Evaporative Cooling System	407
13.12.5 Pressure Cooling System	408
13.13 Air-Cooled System	409
13.13.1 Cooling Fins	409
13.13.2 Baffles	411

13.14 Comparison of Liquid and Air–Cooling Systems	411
13.14.1 Advantages of Liquid-Cooling System	411
13.14.2 Limitations	412
13.14.3 Advantages of Air-Cooling System	412
13.14.4 Limitations	412
Review Questions	413
Multiple Choice Questions	414
14 Engine Emissions and Their Control	417
14.1 Introduction	417
14.2 Air Pollution due to IC Engines	417
14.3 Emission Norms	418
14.3.1 Overview of the Emission Norms in India	419
14.4 Comparison between Bharat Stage and Euro norms	419
14.5 Engine Emissions	421
14.5.1 Exhaust Emissions	421
14.6 Hydrocarbons (HC)	422
14.7 Hydrocarbon Emission	423
14.7.1 Incomplete Combustion	423
14.7.2 Crevice Volumes and Flow in Crevices	424
14.7.3 Leakage Past the Exhaust Valve	425
14.7.4 Valve Overlap	425
14.7.5 Deposits on Walls	425
14.7.6 Oil on Combustion Chamber Walls	426
14.8 Hydrocarbon Emission from Two-Stroke Engines	426
14.9 Hydrocarbon Emission from CI Engines	427
14.10 Carbon Monoxide (CO) Emission	428
14.11 Oxides Of Nitrogen (NO _x)	429
14.11.1 Photochemical Smog	430
14.12 Particulates	430
14.13 Other Emissions	433
14.13.1 Aldehydes	433
14.13.2 Sulphur	433
14.13.3 Lead	434
14.13.4 Phosphorus	435
14.14 Emission Control Methods	435
14.14.1 Thermal Converters	435
14.15 Catalytic Converters	436
14.15.1 Sulphur	439
14.15.2 Cold Start-Ups	440
14.16 CI engines	441
14.16.1 Particulate Traps	441
14.16.2 Modern Diesel Engines	442

14.17 Reducing Emissions by Chemical Methods	442
14.17.1 Ammonia Injection Systems	443
14.18 Exhaust Gas Recirculation (EGR)	443
14.19 Non-Exhaust Emissions	445
14.19.1 Evaporative Emissions	446
14.19.2 Evaporation Loss Control Device (ELCD)	447
14.20 Modern Evaporative Emission Control System	448
14.20.1 Charcoal Canister	449
14.21 Crankcase Blowby	450
14.21.1 Blowby Control	450
14.21.2 Intake Manifold Return PCV System (Open Type)	450
Review Questions	452
Multiple Choice Questions	453
15 Measurements and Testing	457
15.1 Introduction	457
15.2 Friction Power	457
15.2.1 Willan's Line Method	458
15.2.2 Morse Test	459
15.2.3 Motoring Test	461
15.2.4 From the Measurement of Indicated and Brake Power	461
15.2.5 Retardation Test	461
15.2.6 Comparison of Various Methods	463
15.3 Indicated Power	463
15.3.1 Method using the Indicator Diagram	464
15.3.2 Engine Indicators	465
15.3.3 Electronic Indicators	465
15.4 Brake Power	467
15.4.1 Prony Brake	469
15.4.2 Rope Brake	470
15.4.3 Hydraulic Dynamometer	471
15.4.4 Eddy Current Dynamometer	471
15.4.5 Swinging Field DC Dynamometer	473
15.4.6 Fan Dynamometer	473
15.4.7 Transmission Dynamometer	474
15.4.8 Chassis Dynamometer	474
15.5 Fuel Consumption	474
15.5.1 Volumetric Type Flowmeter	475
15.5.2 Gravimetric Fuel Flow Measurement	478
15.5.3 Fuel Consumption Measurement in Vehicles	479
15.6 Air Consumption	479
15.6.1 Air Box Method	480
15.6.2 Viscous-Flow Air Meter	480

15.7 Speed	481
15.8 Exhaust and Coolant Temperature	481
15.9 Emission	482
15.9.1 Oxides of Nitrogen	482
15.9.2 Carbon Monoxide	483
15.9.3 Unburned Hydrocarbons	484
15.9.4 Aldehydes	485
15.10 Visible Emissions	487
15.10.1 Smoke	487
15.11 Noise	490
15.12 Combustion Phenomenon	491
15.12.1 Flame Temperature Measurement	491
15.12.2 Flame Propagation	494
15.12.3 Combustion Process	495
Review Questions	496
Multiple Choice Questions	497
16 Performance Parameters and Characteristics	499
16.1 Introduction	499
16.2 Engine Power	500
16.2.1 Indicated Mean Effective Pressure (p_{im})	500
16.2.2 Indicated Power (ip)	501
16.2.3 Brake Power (bp)	502
16.2.4 Brake Mean Effective Pressure (p_{bm})	504
16.3 Engine Efficiencies	505
16.3.1 Air-Standard Efficiency	505
16.3.2 Indicated and Brake Thermal Efficiencies	505
16.3.3 Mechanical Efficiency	505
16.3.4 Relative Efficiency	506
16.3.5 Volumetric Efficiency	506
16.3.6 Scavenging Efficiency	507
16.3.7 Charge Efficiency	507
16.3.8 Combustion Efficiency	507
16.4 Engine Performance Characteristics	507
16.5 Variables Affecting Performance Characteristics	511
16.5.1 Combustion Rate and Spark Timing	511
16.5.2 Air-Fuel Ratio	512
16.5.3 Compression Ratio	512
16.5.4 Engine Speed	512
16.5.5 Mass of Inducted Charge	512
16.5.6 Heat Losses	512
16.6 Methods of Improving Engine Performance	512
16.7 Heat Balance	513

16.8 Performance Maps	516
16.8.1 SI Engines	516
16.8.2 CI Engines	516
16.9 Analytical Method of Performance Estimation	518
Worked out Examples	521
Review Questions	563
Exercise	564
Multiple Choice Questions	571
17 Engine Electronics	575
17.1 Introduction	575
17.2 Typical Engine Management Systems	576
17.3 Position Displacement and Speed Sensing	577
17.3.1 Inductive Transducers	578
17.3.2 Hall Effect Pickup	578
17.3.3 Potentiometers	579
17.3.4 Linear Variable Differential transformer (LVDT)	580
17.3.5 Electro Optical Sensors	581
17.4 Measurement of Pressure	582
17.4.1 Strain Gauge Sensors	582
17.4.2 Capacitance Transducers	584
17.4.3 Peizoelectric Sensors	584
17.5 Temperature Measurement	585
17.5.1 Thermistors	585
17.5.2 Thermocouples	587
17.5.3 Resistance Temperature Detector (RTD)	587
17.6 Intake air flow measurement	587
17.6.1 Hot Wire Sensor	589
17.6.2 Flap Type Sensor	590
17.6.3 Vortex Sensor	591
17.7 Exhaust Oxygen Sensor	592
17.7.1 Knock Sensor	592
Review Questions	594
Multiple Choice Questions	594
18 Supercharging	597
18.1 Introduction	597
18.2 Supercharging	597
18.3 Types Of Superchargers	598
18.3.1 Centrifugal Type Supercharger	599
18.3.2 Root's Supercharger	599
18.3.3 Vane Type Supercharger	599
18.3.4 Comparison between the Three Superchargers	600

18.4 Methods of Supercharging	600
18.4.1 Electric Motor Driven Supercharging	601
18.4.2 Ram Effect of Supercharging	601
18.4.3 Under Piston Supercharging	601
18.4.4 Kadenacy System of Supercharging	601
18.5 Effects of Supercharging	602
18.6 Limitations to Supercharging	603
18.7 Thermodynamic Analysis of Supercharged Engine Cycle	603
18.8 Power Input for Mechanical Driven Supercharger	604
18.9 Gear Driven and Exhaust Driven Supercharging Arrangements	606
18.10 Turbocharging	607
18.10.1 Charge Cooling	610
Worked out Examples	610
Review Questions	620
Exercise	621
Multiple Choice Questions	623
19 Two-Stroke Engines	625
19.1 Introduction	625
19.2 Types of Two-Stroke Engines	625
19.2.1 Crankcase Scavenged Engine	625
19.2.2 Separately Scavenged Engine	626
19.3 Terminologies and Definitions	628
19.3.1 Delivery Ratio (R_{del})	629
19.3.2 Trapping Efficiency	629
19.3.3 Relative Cylinder Charge	629
19.3.4 Scavenging Efficiency	630
19.3.5 Charging Efficiency	631
19.3.6 Pressure Loss Coefficient (P_l)	631
19.3.7 Index for Compressing the Scavenge Air (n)	632
19.3.8 Excess Air Factor (λ)	632
19.4 Two-stroke Air Capacity	632
19.5 Theoretical Scavenging Processes	632
19.5.1 Perfect Scavenging	633
19.5.2 Perfect Mixing	633
19.5.3 Short Circuiting	633
19.6 Actual Scavenging Process	633
19.7 Classification Based on Scavenging Process	634
19.8 Comparison of Scavenging Methods	636
19.9 Scavenging Pumps	636
19.10 Advantages and Disadvantages of Two-stroke Engines	637
19.10.1 Advantages of Two-stroke Engines	637
19.10.2 Disadvantages of Two-Stroke Engines	638

19.11 Comparison of Two-stroke SI and CI Engines	639
Worked out Examples	639
Review Questions	645
Exercise	645
Multiple Choice Questions	647
20 Nonconventional Engines	649
20.1 Introduction	649
20.2 Common Rail Direct Injection Engine	649
20.2.1 The Working Principle	650
20.2.2 The Injector	650
20.2.3 Sensors	652
20.2.4 Electronic Control Unit (ECU)	652
20.2.5 Microcomputer	653
20.2.6 Status of CRDI Engines	653
20.2.7 Principle of CRDI in Gasoline Engines	654
20.2.8 Advantages of CRDI Systems	654
20.3 Dual Fuel and Multi-Fuel Engine	654
20.3.1 The Working Principle	655
20.3.2 Combustion in Dual-Fuel Engines	655
20.3.3 Nature of Knock in a Dual-Fuel Engine	656
20.3.4 Weak and Rich Combustion Limits	657
20.3.5 Factors Affecting Combustion in a Dual-Fuel Engine	657
20.3.6 Advantages of Dual Fuel Engines	658
20.4 Multifuel Engines	658
20.4.1 Characteristics of a Multi-Fuel Engine	659
20.5 Free Piston Engine	660
20.5.1 Free-Piston Engine Basics	661
20.5.2 Categories of Free Piston Engine	661
20.5.3 Single Piston	661
20.5.4 Dual Piston	661
20.5.5 Opposed Piston	662
20.5.6 Free Piston Gas Generators	663
20.5.7 Loading Requirements	664
20.5.8 Design Features	664
20.5.9 The Combustion Process	664
20.5.10 Combustion Optimization	665
20.5.11 Advantages and Disadvantages of Free Piston Engine	665
20.5.12 Applications of Free Piston Engine	666
20.6 Gasoline Direct Injection Engine	667
20.6.1 Modes of Operation	668

xxviii *Contents*

20.7	Homogeneous Charge Compression Ignition Engine	670
20.7.1	Control	671
20.7.2	Variable Compression Ratio	671
20.7.3	Variable Induction Temperature	671
20.7.4	Variable Exhaust Gas Percentage	672
20.7.5	Variable Valve Actuation	672
20.7.6	Variable Fuel Ignition Quality	672
20.7.7	Power	673
20.7.8	Emissions	673
20.7.9	Difference in Engine Knock	673
20.7.10	Advantages and Disadvantages of HCCI Engine	674
20.8	Lean Burn Engine	674
20.8.1	Basics of Lean Burn Technology	676
20.8.2	Lean Burn Combustion	676
20.8.3	Combustion Monitoring	677
20.8.4	Lean Burn Emissions	677
20.8.5	Fuel Flexibility	677
20.8.6	Toyota Lean Burn Engine	678
20.8.7	Honda Lean Burn Systems	678
20.8.8	Mitsubishi Ultra Lean Burn Combustion Engines	679
20.9	Stirling Engine	680
20.9.1	Principle of Operation	681
20.9.2	Types of Stirling Engines	683
20.9.3	Alpha Stirling Engine	683
20.9.4	Working Principle of Alpha Stirling Engine	684
20.9.5	Beta Stirling Engine	685
20.9.6	Working Principle of Beta Stirling Engine	685
20.9.7	The Stirling Cycle	686
20.9.8	Displacer Type Stirling Engine	687
20.9.9	Pressurization	687
20.9.10	Lubricants and Friction	688
20.9.11	Comparison with Internal Combustion Engines	688
20.9.12	Advantages and Disadvantages of Stirling Engine	688
20.9.13	Applications	691
20.9.14	Future of Stirling Engines	691
20.10	Stratified Charge Engine	692
20.10.1	Advantages of Burning Leaner Overall Fuel-Air Mixtures	692
20.10.2	Methods of Charge Stratification	695
20.10.3	Stratification by Fuel Injection and Positive Ignition	695
20.10.4	Volkswagen PCI stratified charge engine	696
20.10.5	Broderson Method of Stratification	697
20.10.6	Charge Stratification by Swirl	698

20.10.7 Ford Combustion Process (FCP)	698
20.10.8 Ford PROCO	700
20.10.9 Texaco Combustion Process (TCP)	700
20.10.10 Witzky Swirl Stratification Process	702
20.10.11 Honda CVCC Engine	702
20.10.12 Advantages and Disadvantages of Stratified Charge Engines	703
20.11 Variable Compression Ratio Engine	704
20.11.1 Cortina Variable Compression Engine	705
20.11.2 Cycle Analysis	706
20.11.3 The CFR Engine	707
20.11.4 Performance of Variable Compression Ratio Engines	707
20.11.5 Variable Compression Ratio Applications	709
20.12 Wankel Engine	709
20.12.1 Basic Design	710
20.12.2 Comparison of Reciprocating and Wankel Rotary Engine	712
20.12.3 Materials	712
20.12.4 Sealing	712
20.12.5 Fuel consumption and emissions	712
20.12.6 Advantages and Disadvantages of Wankel Engines	713
Review Questions	714
Multiple Choice Questions	716
Index	719