

Index

- Ablative pyrolysis, 79, 86–87f, 89
 Above-ground outdoor storage, 274–275
 Acceleration, gravitational, 327
 Acetic acid, in pyrolysis, 66f
 Acid hydrolysis, 10
 Activation energy, 141–143t
 Aerobic digestion
 - in biomass conversion, 9
 - in waste degradation, 33
 Agricultural biomass sources, 28, 270
 Air
 - composition of, 331t
 - as gasification medium, 119t
 - physical properties of, 332t
 - tar and gasification in, 106
 Air-dry basis, 57
 Alkali, 108
 Alkali metal catalysts, 130
 Alkali remover, 115
 Alkyl tertiary product, 102
 Allocation, of feed points, 298
 Almond shell, kinetic rate constants of, 82t
 American Clean Energy and Security Act, 325–326
 Amin, Sanjay, 229
 Ammonia
 - formation heat of, 46t
 - syngas in production of, 305t, 313–314
 Ammonia synthesis, 24
 Anaerobic digestion, in waste degradation, 33
 Analysis
 - of biomass, 50t
 - proximate, 50–55, 54t, 69
 - thermogravimetric, 55–56
 - ultimate, 49–50, 51t
 Animal waste, ultimate analysis of, 51t
 Anthracite
 - C/H ratio of, 15t
 - ignition temperature of, 48t
 - ultimate analysis of, 51t
 Apparent density, 42–43
 Aquatic biomass, 29t
 Arching, 277
 Argon, in air, 331t
 Aromatics, condensed tertiary, 102
 Ash, 52
 - analysis, 50t
 - in biomass, 34
 - in bio-oil, 308t
 - fusibility of, 329t
 - ingredients, 52
 As-received basis, 56–57
 ASTM D 346 protocol, 52
 Atmospheric pressure, 327
 Atomic ratio, 39–40
 Auger, fuel, 294
 Autothermal, 84
 Avogadro's number, 327

 Bagasse, 93t
 Bales, 289
 Bark, 35
 Barrier filter, 113–114, 113f
 Barriers, corrosion-resistant, 264
 Bases
 - air-dry, 57
 - as-received, 56–57
 - of composition, 56–57
 - dry ash-free, 57
 - heating values, 58–59
 - moisture, 54–55
 - total-dry, 57
 Beech sawdust, kinetic rate constants of, 82t
 Beehive oven, 66f
 Belt feeder, 295
 Benzene, in pyrolysis, 66f
 Bergius process, 3
 Bins, biomass storage, 275
 Biochemical conversion of biomass, 9–10, 11f
 Biocrude, 306

- Biodiesel, 8, 319–320
- Biological sources of biomass, 28
- Biomass, 29–33
- above-ground outdoor storage, 274–275
 - agricultural sources of, 28
 - analysis, 50t
 - apparent density of, 42–43
 - aquatic, 29t
 - ash in, 34
 - bark in, 35
 - bases of composition of, 56–57
 - biological sources of, 28
 - cell constituents in, 36–38
 - cellulose in, 36–37
 - cell wall in, 33–34
 - char, 122
 - collection, 270
 - crops as, 31
 - definition of, 27–33, 325–326
 - acid hydrolysis of, 10
 - biochemical conversion of, 9–10, 11f
 - carbon dioxide and, 4–5, 17
 - C/H ratio of, 15t
 - chemical production from, 6
 - as clean, 6
 - combustion of, 10–13, 12t
 - conversion, 8–16, 9f
 - cooking with, 6–7, 7f
 - digestion in conversion of, 9
 - diversity of, 5
 - drawbacks of, 8
 - dust and, 18
 - electricity from, 12
 - energy from, 6–8
 - environmental benefits, 16–18
 - fermentation in conversion of, 9
 - formation of, 4
 - fossil fuels *vs.*, 4
 - gaseous fuels from, 5
 - gasification of, 12t, 14–15
 - heat from, 12
 - liquefaction of, 12t, 16
 - liquid fuels from, 5
 - motivation for use of, 16–19
 - nitrogen removal and, 18
 - products of, 5–8
 - pyrolysis of, 12t, 13–14
 - renewability of, 16–19
 - sociopolitical benefits of, 18–19
 - solid fuels from, 5
 - sources of, 5t
 - sulfur and, 18
 - thermochemical conversion of, 10–16, 12f, 12t
 - torrefaction of, 13–14
 - transport fuel from, 8
 - densities of, 42–44
 - entrained-flow gasification of, 190–191
 - extractives in, 33
 - feeders, 288–299
 - feed system in SCW gasifier, 261–262
 - flow, 274
 - forest sources of, 28
 - formation of, 27–29, 28f
 - as greenhouse neutral, 27
 - heating value estimations, 59
 - heat of formation in, 46
 - hemicellulose in, 37–38
 - ignition temperature in, 47–48, 48t
 - industrial sources of, 29t
 - lignin in, 38
 - ligno-cellulosic, 30–31
 - liquefaction of, 12t, 16, 90–91
 - mineral matter in, in char–oxygen reaction, 147
 - moisture in, 53–55, 229–230
 - municipal sources of, 28, 29t
 - oils as sources of, 28
 - photosynthesis and, 28–29
 - physical properties of, 42–48
 - preparation of, 284–288
 - proximate analysis of, 50–55
 - pyrolysis and composition of, 74–75
 - receiving, 272
 - retrieval from storage, 274
 - SCW and conversion of, 237–240
 - shelf-life, 274
 - sources of, 28, 269
 - specific heat in, 46, 335t
 - storage, 269, 272–284
 - structure of, 33–38
 - terrestrial, 29t
 - thermal conductivity in, 44–45, 45f
 - thermodynamic properties of, 44–48
 - transport fuels from, 315–323
 - true density of, 42
 - ultimate analysis of, 49–50
 - vegetables as, 31
 - virgin, 29t, 30
 - waste, 29t, 31–33
 - wood structure in, 34–36
- Bio-oil, 70, 305–306, 306f
- applications of, 309
 - ash in, 308t
 - carbon in, 308t

- in chemical feedstock production, 309
- chemical properties of, 308t
- composition of, 307t
- in energy production, 309
- furfurals in, 307t
- heating value of, 71t
- hydrogen, nitrogen, oxygen, and sulfur in, 308t
- physical properties of, 307–308
- production of, 310
- terms associated with, 306
- in transport fuel production, 309
- water in, 307t
- Bituminous coal, C/H ratio of, 15t
- Boltzmann's constant, 327
- Boudouard reaction model, 123–124, 141–142, 142t
- Broido-Shafizadeh model, 78–80, 79f, 80t
- Bubbling fluidized bed, 7f, 86–87f, 87, 160–161, 177–179
- Bulk density, 43–44
- Calcium, true density of, 43t
- Calcium carbonate, formation heat of, 46t
- Candle filters, 113–114
- Canola oil, 8
- Carbon
 - analysis, 50t
 - in bio-oil, 308t
 - combustion, 23, 256–257
 - fixed, 55
 - reactions, 121t
- Carbon dioxide
 - in air, 331t
 - biomass and, 4–5
 - emission, biomass and, 17
 - formation heat of, 46t
 - tar and gasification in, 107
- Carbon gasification, 23
- Carbonization, characteristics of, 72t
- Carbon monoxide
 - formation heat of, 46t
 - specific heat of, 331t
 - in syngas, 303
- Carbon-to-hydrogen (C/H) ratio of fuels, 15t
- Catalyst selection, 129–130, 252
- Catalysts, in hydrothermal gasification, 243
- Catalytic cracking, 116
- Catalytic gasification, 128–130
- Cattle manure, moisture content of, 53t
- Cell, in wood, 35f
- Cell constituents, biomass, 36–38
- Cellulose, 36–37, 37f
 - kinetic rate constants in pyrolysis of, 82t
 - in pyrolysis, 66f, 75, 78–80
 - in torrefaction, 94f
- Cellulose analysis, 50t
- Cell wall, in biomass, 33–34
- Cereal, in ethanol production, 316–317
- CFD. *See* Computational fluid dynamics
- Char, 55, 70, 108
- Charcoal
 - in history, 2
 - pyrolysis in production of, 91
- Char combustion reactions, 126–128
- Char gasification, 122–126
- Char reactivity, 146–149
- Chemical equilibrium, in gasification, 136–146
- Chemical looping gasifier, 184–185
- Chemical moisture, 287
- Chemical production, from biomass, 6
- Chipper, 286
- Choren process, 190–191
- Chute, gravity, 290–291
- Chute design, 282–284
- Circulating fluidized-bed (CFB) gasifier, 179–185
- Circulating fluidized-bed pyrolyzer, 86–87f, 88
- Classification of fuels, 38–41
- Cleaning
 - gas, 98
 - syngas, 304–305
- Climate change, 4
- Coal
 - C/H ratio of, 15t
 - heating value of, 71t
 - ignition temperature of, 48t
 - spontaneous ignition of, 277–278
 - ultimate analysis of, 51t
- Coal-gas. *See* Town gas
- Coke, 2
- Cold gas efficiency, 219–221
- Collection, biomass, 270
- Combustion
 - of biomass, 10–13, 12t
 - of carbon, 23, 256–257
 - char, reactions, 126–128
 - gasification vs., 1, 20–22
 - heat of, 46–47, 139t
 - stoichiometric amount of air for, 59–60
- Commercial attraction of gasification, 19–22
- Composting, in biomass conversion, 9
- Computational fluid dynamics (CFD), 157–158

- Concentration, solid, 244–245
- Condensed tertiary aromatics, 102
- Conditioning, of syngas, 304–305
- Conductivity, thermal, 44–45, 45f
- Constant(s)
 - Boltzmann's, 327
 - equilibrium, 137t, 335t
 - physical, 327
 - Planck's, 327
 - reaction rate, 137
 - Stefan-Boltzmann, 327
 - universal gas, 327
- Contact avoidance, 264
- Conversion, biomass, 8–16, 9f
- Conveying, 288
- Cooking, with biomass, 6–7, 7f
- Corn, in ethanol production, 316–317
- Corn cob and stalks
 - fusibility of ash of, 329t
 - moisture content of, 53t
 - proximate analysis of, 54t
- Corrosion, 263–265
 - in hydrothermal gasification, 262–265
 - resistant barriers and materials, 264–265
- Cracking, 116
 - catalytic, 116
 - steam, 104
 - tar, 226
 - thermal, 104, 116
- Crops, as biomass, 31
- Crossdraft gasifier, 176–177
- Crude oil, carbon-to-hydrogen ratio of, 15t
- Cyclones, 113

- Dairy cattle manure, moisture content of, 53t
- Degradation, waste, 33
- Dehydration, in ethanol production, 316, 323
- Density(ies)
 - apparent, 42–43
 - biomass, 42–44
 - bulk, 43–44
 - growth, 44
 - true, 42, 43t
- Depolymerization
 - in pyrolysis, 79–80
 - in tar formation, 100–101
 - in torrefaction, 92
- Design
 - chute, 282–284
 - gasifier, 167–169, 192–193
 - auxiliary items in, 216–218
 - efficiency in, 219–222
 - energy balance in, 200–204
 - entrained-flow, 214–218
 - equivalence ratio in, 195–196
 - fuel feed rate in, 194
 - gasification temperature in, 200–201
 - heat of reaction in, 201–204
 - height in, 210
 - mass balance in, 193–200
 - medium flow rate in, 194–200
 - operating issues in, 219–228
 - optimization, 218
 - oxygen in, 196–197
 - performance issues in, 219–228
 - process, 192–204, 218
 - product gas prediction and flow rate in, 193–194, 204–205
 - sizing in, 205–214
 - steam in, 197–200
 - tar and, 109–111
 - handling and, 269–270
 - handling system, 271–272
 - hopper, for mass flow, 279
 - hydrothermal gasification reactor, 251–262
 - modifications for tar removal, 112
 - pyrolyzer, 90–91
 - torrefaction, 95
- De-stoner, 284–285
- Devolatilization, 92–93
- Diagram
 - ternary, 40–41, 41f
 - van Krevelen, 39
- Diesel, 318–319
 - elemental analysis of, 308t
 - green, 8
 - methanol in production of, 319–320
- Differential thermogravimetry (DTG), 55–56
- Digestion
 - of biodegradable waste, 32f
 - in biomass conversion, 9
 - in waste degradation, 33
- Dioxin, 18
- Disposal, tar, 115
- Distillation, in ethanol production, 316, 323
- Distributor plate, 216
- Dolomite, 107
- Double-screw feeder, 292f
- Douglas fir, ultimate analysis of, 51t
- Downdraft gasifier, 100t, 109–111, 110f, 172–176, 207–208
- Dry ash-free basis, 57

- Dry-ash gasifier, 171–172
- Drying
 - in gasification, 120
 - handling and, 287–288
 - in pyrolysis, 77
- Dry tar reforming, 104
- DTG. *See* Differential thermogravimetry
- Dust, biomass and, 18
- Earth metal catalysts, 130
- Efficiency
 - cold gas, 219–221
 - energy conversion, in hydrothermal gasification, 265–266
 - gasification, 219–222
 - hot gas, 221–222
 - net gasification, 223–225
- E-gas gasifier, 189
- Electricity
 - from biomass, 12
 - emissions in generation of, 17t
- Electrostatic precipitators (ESP), 114
- Embargo, 1973 oil, 4
- Emissions
 - biomass and, 17
 - in electricity generation, 17t
- Energy
 - activation, 141–143t
 - balance in gasifier design, 200–204
 - from biomass, 6–8
 - bio-oil in production of, 309
 - Gibbs free, 138–140, 139t
- Enthalpy of formation, 46
- Entrained-flow gasifier, 3, 100t, 111, 134–136, 135f, 161–164, 168t, 185–191, 214–218, 226
- Environmental benefits of biomass, 16–18
- Enzymatic hydrolysis, 322–323
- Equilibrium constant, 137t, 335t
- Equilibrium moisture, 53–54
- Equivalence ratio (ER), 195–196
- ESP. *See* Electrostatic precipitators
- Ethanol
 - biochemical production of, 315–317
 - biochemical vs. thermochemical production of, 13t
 - from food sources, 316–317
 - ignition temperature of, 48t
 - nonfood sources in production of, 317
 - as transport fuel, 8
- Eucalyptus, ignition temperature of, 48t
- Extractives, in biomass, 33
- Fabric filters, 114
- Farm products, as biomass sources, 5t
- Fast pyrolysis, 72–74
- FC. *See* Fixed carbon
- Feeder(s), 288–299
 - belt, 295
 - in fluidized beds, 295–298
 - moving-hole, 294
 - pneumatic injection, 293–294
 - ram, 294–295
 - redundant, 298
 - screw, 291–293
- Feeding, 288–299
- Feed particle size, 245
- Feed points, 297t, 298
- Feed preparation, 284–288
- Fermentation
 - in biomass conversion, 9
 - in ethanol production, 316
 - in transport fuel production, 323
- Filters, 113–114, 113f
- Fischer-Tropsch reaction and synthesis, 3, 24, 305t, 313
- Fixed-bed pyrolyzer, 85–87
- Fixed carbon (FC), 55
- Flaming pyrolysis, 132
- Flash pyrolysis, 72t, 73
- Flow
 - funnel, 276
 - mass, 276–279
- Fluidization velocity, 210
- Fluidized-bed gasifier, 3, 100t, 111, 111f, 133–134, 159–161, 168t, 177–185, 208–214, 225–226, 295–298
- Flushing, 277
- Food, ethanol production from, 316–317
- Food waste, moisture content of, 53t
- Forestry, 270
- Forest sources of biomass, 28
- Formation, heat of, 46, 139t, 333–334t
- Fossil fuels, biomass vs., 4
- Freeboard height, 214
- Free energy, Gibbs, 138–140, 139t
- Free moisture, 53–54
- Fuel auger, 294
- Fuel classification, 38–41
- Fuel feed rate, 194
- Fuel heating value, 57–60
- Funnel flow, 276–277
- Furan, 18
- Furfurals, 307t
- Fusibility of biomass ash, 329t

- Gas
- applications of product, 98–99
 - cleaning, 98
 - composition of product, 60–61
 - in drying, 288
 - as pyrolysis product, 70–71
 - universal constant of, 327
- Gaseous fuels from biomass, 5
- Gas flow rate, 193–194
- Gasification, 1–4
- air as medium for, 119t
 - of biomass, 12t, 14–15
 - of carbon, 23
 - catalyst selection in, 129–130
 - catalytic, 128–130
 - char, 122–126
 - chemical equilibrium in, 136–146
 - combustion vs., 1, 20–22
 - commercial attraction of, 19–22
 - composition of product gas in, 60–61
 - drying in, 120
 - efficiency, 219–222
 - high-temperature, in syngas production, 303
 - high-temperature Winkler, 178
 - hydrothermal, 117–119, 229–230
 - application of, 247
 - biomass feed system in, 261–262
 - carbon combustion system, 256–257
 - catalysts in, 243, 252
 - challenges in, 266–267
 - chemical production with, 249–250
 - corrosion in, 262–265
 - energy conversion, 247–249, 265–266
 - feed particle size in, 245
 - gas–liquid separator system in, 257–261
 - heat exchange and transfer in, 253–256
 - heating rate in, 245
 - hydrolysis in, 237–238
 - operating parameters in, 241–247
 - pressure and, 247
 - reaction design and kinetics in, 250–262
 - reactor size, temperature, and type in, 247, 251–253
 - residence time in, 244
 - SCW in, 230–237
 - SCW oxidation in, 239
 - solid concentration in feedstock and, 244–245
 - subcritical steam in, 232
 - subcritical water in, 231–232
 - waste remediation with, 249
 - kinetics of, 136–149
 - low-temperature, in syngas production, 303
 - mass transfer control, 148–149
 - mediums, 118–119, 119t
 - milestones in, 2f
 - models, 149–158
 - oxygen as medium for, 118
 - plasma, 191–192
 - process, 119–136
 - pyrolysis, 117–118, 120–121
 - reactions, 117–119, 121t
 - simulation models, 150–158
 - steam as medium for, 119, 119t
 - in syngas production, 302–304
 - tar in, 121
 - temperature, in gasifier design, 200–201
- Gasifier(s), 168–169
- chemical looping, 184–185
 - circulating fluidized-bed, 179–185
 - crossdraft, 176–177
 - design, 167–169
 - auxiliary items in, 216–218
 - efficiency in, 219–222
 - energy balance in, 200–204
 - entrained-flow, 214–218
 - equivalence ratio in, 195–196
 - fuel feed rate in, 194
 - gasification temperature in, 200–201
 - heat of reaction in, 201–204
 - height in, 210
 - mass balance in, 193–200
 - medium flow rate in, 194–200
 - operating issues in, 219–228
 - operational considerations in, 225–226
 - optimization, 218
 - oxygen in, 196–197
 - performance issues in, 219–228
 - process, 192–204, 218
 - product gas, 193–194, 204–205
 - sizing in, 205–214
 - specifications in, 192–193
 - steam in, 197–200
 - tar and, 109–111
 - downdraft, 100t, 109–111, 110f, 172–176, 207–208
 - dry-ash, 171–172
 - E-gas, 189
 - entrained-flow, 3, 100t, 111, 134–136, 135f, 161–164, 168t, 185–191, 214–218, 226

- fluidized-bed, 3, 100t, 111, 111f, 133–134, 159–161, 168t, 177–185, 208–214, 225–226, 295–298
 - height, 210
 - Imbert type, 209t
 - Koppers-Totzek, 188
 - moving-bed, 15, 158–159, 169–177, 206–208
 - pressurized moving-bed, 3
 - side-fed, 187
 - sizing of, 205–214
 - slagging, 172
 - throated and throatless, 174–176
 - top-fed, 187
 - transport, 181
 - twin reactor, 181–184
 - updraft, 100t, 109, 110f, 130–133, 170–172, 207
- Gas light, 2–3
- Gas–liquid separator system, 257–261
- Gasoline
- C/H ratio of, 15t
 - elemental analysis of, 308t
 - hydrocarbons in, 317
 - methanol in production of, 317–318
- Gas-phase reactions, 144–146
- Gas–solid reactions, kinetics of, 140–144
- Gas velocity, superficial, 206
- Gesner, Abraham, 65–67, 67f
- Gibbs free energy, 138–140, 139t
- Global warming, 4
- Glycerol synthesis, 314
- Grape pruning, 329t
- Gravitational acceleration, 327
- Gravity chute, 290–291
- “Green diesel,” 8
- Grinder, 286
- Growth density, 44

Handling, biomass, 269

- chute design and, 282–284
- components in, 271
- conveying and, 288
- design of system, 269–272
- drying and, 287–288
- feeding and, 288–299
- feed preparation in, 284–288
- flow and, 274
- gravity chute in, 290–291
- hoppers for, 276–278
- mass flow and, 278
- receiving and, 272
- size reducers in, 285–286

- storage and, 272–284
 - underground storage and, 273–274
- H/C ratio. *See* Hydrogen-to-carbon (H/C) ratio

Heat

- from biomass, 12
 - of combustion, 46–47, 139t
 - of formation, 46, 139t, 333–334t
 - of reaction, 46–47, 201–204
 - specific, 46, 335t
 - transfer in SCW, 255–256
- Heating oil, elemental analysis of, 308t
- Heating rate, 72t, 76–77, 245
- Heating value, 57–60, 71t, 330t
- Heat transfer in pyrolyzer, 83–84

Height

- freeboard, 214
 - gasifier, 210
- Hemicellulose, 37–38, 37f, 80
- in torrefaction, 94–95
- Hemicellulose analysis, 50t
- Herbaceous plants, as biomass, 30
- Higher heating value (HHV), 39, 58
- High-temperature gasification, in syngas production, 303
- High-temperature Winkler (HTW) gasification, 178
- Hoppers, 276–279
- Hot gas efficiency, 221–222
- Hyacinth, moisture content of, 53t
- Hydrocarbon, steam reforming of, 143–144
- Hydrogasification reaction, 126, 143

Hydrogen

- in bio-oil, 308t
 - in pyrolysis, 66f
 - specific heat of, 331t
 - in syngas, 303
- Hydrogen analysis, 50t
- Hydrogen sulfide, specific heat of, 331t
- Hydrogen-to-carbon (H/C) ratio, 39
- Hydrolysis
- acid, 10
 - enzymatic, 322–323
 - in ethanol production, 316
 - in hydrothermal gasification, 237–238
 - in transport fuel production, 322–323
- Hydropyrolysis, 72t, 73
- Hydrothermal gasification, 229–230
- application of, 247
 - biomass feed system in, 261–262
 - carbon combustion system, 256–257
 - catalysts in, 243, 252
 - challenges in, 266–267

- Hydrothermal gasification (*cont'd*)
 chemical production with, 249–250
 corrosion in, 262–265
 energy conversion, 247–249, 265–266
 feed particle size in, 245
 gas–liquid separator system in, 257–261
 heat exchange in, 253–256
 heating rate in, 245
 hydrolysis in, 237–238
 operating parameters in, 241–247
 pressure and, 247
 reaction kinetics in, 250–251
 reactor design, size, and temperature, 251–262
 reactor type in, 247
 residence time in, 244
 SCW water in, 230–237
 SCW oxidation in, 239
 solid concentration in feedstock and, 244–245
 subcritical steam and water in, 231–232
 waste remediation with, 249
- Hydrous pyrolysis, 74
- Ignition temperature, 47–48, 48t
- Imbert type gasifiers, 209t
- Industrial waste, as biomass source, 29t
- Industry, gasification as attractive to, 19–22
- Inherent moisture, 53–54
- Injection feeder, pneumatic, 293–294
- In-situ tar reduction, 104–112
- Integrated gasification combined cycle (IGCC) power plants, 4, 17
- Internal combustion, tar and, 99
- Intrinsic reaction rate, 147–149
- Iron, true density of, 43t
- Janssen equation, 281
- Jenike equation, 281–282
- Kerosene production, 65–67
- Kinetic models, of pyrolysis, 81–83
- Kinetics
 gasification, 136–149
 gas-phase reactions, 144–146
 gas–solid reactions, 140–144
 hydrothermal gasification reaction, 250–251
 pyrolysis, 77–83
- Koppers-Totzek gasifier, 188
- Lamella, middle, 35–36
- Landfills, 32
- LHV. *See* Lower heating value
- Light
 from gas, 2–3
 speed of, 327
- Lignin, 38
 analysis, 50t
 kinetic rate constants, 82t
 macromolecules, 70
 pyrolysis, 81
 in torrefaction, 94f
- Lignite
 carbon-to-hydrogen ratio of, 15t
 ultimate analysis of, 51t
- Ligno-cellulosic materials, as biomass sources, 5t, 30–31
- Ligno-cellulosic proportions, 40
- Limits
 particulate, 99, 99t
 tar, 98–100, 99t
- Liquefaction, of biomass, 12t, 16, 90–91
- Liquid fuels from biomass, 5
- Liquid smoke and wood, 306
- Liquid yield of pyrolysis, 70
- Logging, 270
- Lower heating value (LHV), 58
- Low-temperature gasification, in syngas production, 303
- Macrofibrils, 35–36
- Macromolecules, lignin, 70
- Magnesium, true density of, 43t
- Magnetic metal separation, 285
- Manure, moisture content of, 53t
- Maple, ultimate analysis of, 51t
- Mass balance, 193–200
- Mass flow, 276–279
- Mass transfer control, 148–149
- Mass transfer effect, 83–84
- Matter, volatile, 51–52
- Medium(s)
 flow rate, 194–200
 gasification, 118–119, 119t
 tar and gasification, 105–107
- Metal separation, 285
- Methanation reaction, 24–25, 121t
- Methane
 formation heat of, 46t
 in landfills, 33
 in pyrolysis, 66f
 specific heat of, 331t
- Methanol, production, 24, 305t, 310–313, 315t
 in diesel, 319–320
 in gasoline, 317–318

- Methanopyrolysis, 72t
- Middle lamella, 35–36
- Moisture, 50t, 53–55, 229–230, 287–288
- Moving-bed gasifier, 15, 158–159, 169–177, 206–208
- Moving-bed reactor, 130–133
- Moving-hole feeder, 294
- Municipal solid waste (MSW), 30–32, 51t
- Municipal sources of biomass, 28, 29t
- Murdoch, William, 2

- Natural gas, C/H ratio of, 15t
- Net gasification efficiency, 223–225
- Neural network models, 155–157
- Nickel, 108
- Nickel-based catalyst, 130
- Nickel corrosion, 263
- Nitrogen
 - in air, 331t
 - in bio-oil, 308t
 - specific heat of, 331t
- Nitrogen analysis, 50t
- Nitrogen removal, biomass and, 18
- Nonferrous metal separators, 285

- O/C ratio. *See* Oxygen-to-carbon ratio
- Oil, 305–306
 - bio-, 70, 306f
 - applications of, 309
 - ash and carbon in, 308t
 - in chemical feedstock production, 309
 - chemical properties of, 308t
 - composition of, 307t
 - in energy production, 309
 - furfurals in, 307t
 - heating value of, 71t
 - hydrogen in, 308t
 - nitrogen, oxygen, and sulfur in, 308t
 - physical properties of, 307–308
 - production of, 310
 - terms associated with, 306
 - in transport fuel production, 309
 - water in, 307t
 - C/H ratio of, 15t
 - pyrolysis, 306
 - wood, 100–101
- Oil embargo (1973), 4
- Olivine, 108
- One-stage global single-reaction model, 81–83, 82t
- Ontario Corporations Tax Act, 326

- Organization of Petroleum Exporting Countries (OPEC), 4
- Outdoor storage, above-ground, 274–275
- Outlet, 283–284, 291
- Oven, beehive, 66f
- Over-bed system, 295–296
- Oxidation, supercritical water, 239
- Oxidation reactions, 121t
- Oxygen
 - in air, 331t
 - analysis, 50t
 - in bio-oil, 308t
 - formation heat of, 46t
 - as gasification medium, 118, 119t
- Oxygen-to-carbon (O/C) ratio, 39

- Paper, ultimate analysis of, 51t
- Particle size, 245
- Particulate limits, 99, 99t
- Peat
 - C/H ratio of, 15t
 - ultimate analysis of, 51t
- Pelletization, 95–96
- PET. *See* Polyethylene terephthalate
- Petcoke
 - heating value of, 71t
 - ultimate analysis of, 51t
- Phenol, in pyrolysis, 66f
- Photosynthesis, in biomass formation, 28–29
- Physical constants, 327
- Physical properties of biomass, 42–44
- Planck's constant, 327
- Plant, pyrolysis, 69f
- Plasma gasification, 191–192
- Plate, distributor, 216
- Plugging, of screw feeder, 291
- Pneumatic injection feeder, 293–294
- Points, feed, 297t, 298
- Political benefits of biomass, 18–19
- Polyethylene terephthalate (PET), 238f
- Poplar, ignition temperature of, 48t
- Pore diffusion, 127t
- Potassium, true density of, 43t
- Power plants, integrated gasification combined cycle, 4, 17
- Precipitation, 287
- Pressure
 - atmospheric, 327
 - tar and, 105
- Pressurized moving-bed gasifier, 3
- Primary tar, 100–101
- Process design, gasifier, 192–204

- Product gas
 applications, 98–99
 composition, 60–61
 prediction, 204–205
- Product yield, pyrolysis, 74–77
- Proximate analysis, 50–55, 54t, 69
- Pruning, grape, 329t
- Pyroligneous tar, 306
- Pyrolysis, 23, 65, 71–74. *See also*
 Torrefaction
 ablative, 79, 86–87f, 89
 as autothermal, 84
 of biomass, 12t, 13–14
 biomass composition and, 74–75
 in biomass particle, 68f
 bio-oil from, 70
 Broido-Shafizadeh model and, 78–80,
 79f, 80t
 cellulose in, 78–80
 charcoal production through, 91
 char from, 70
 chemical aspects of, 78–81
 depolymerization in, 79–80
 drying in, 77
 fast, 72–74, 72t
 final stage of, 78
 final temperature in various processes
 of, 72t
 flaming, 132
 flash, 72t, 73
 gaseous products of, 70–71
 in gasification, 117–118, 120–121
 heating rate, 65–67, 72t, 76–77
 hemicellulose in, 80
 hydro-, 72t, 73
 hydrocarbon decomposition in, 66f
 hydrous, 74
 initial product of, 68
 initial stage of, 77
 intermediate stage of, 77
 kerosene production with, 65–67
 kinetic models of, 77–83
 lignin in, 81
 liquid production through, 90–91
 liquid yield of, 70
 mass transfer effect in, 83–84
 methanopyrolysis, 72t
 oil, 306
 one-stage global single-reaction model
 of, 81–83
 operating variables and yield in, 85t
 particle size and, 75
 physical aspects of, 77–78
 plant, 69f
 in presence of medium, 73–74
 process of, 67–74
 products, 69–71, 72t, 74–77
 rapid thermal, 88
 residence time in various processes
 of, 72t
 slow, 72
 solid product of, 70
 temperature, 67, 75
 ultra-rapid, 73, 88
 vacuum, 72t, 86–87f, 89
 vapor products of, 70–71
- Pyrolyzer, 85–89
 ablative, 86–87f, 89
 bubbling fluidized-bed, 86–87f, 87
 circulating fluidized-bed, 86–87f, 88
 design considerations, 90–91
 fixed-bed, 85–87
 heat transfer in, 83–84
 rotating-cone, 89
 ultra-rapid, 88
 vacuum, 86–87f, 89
- Rain, 287
- Ram feeder, 294–295
- Rape seed, 8
- Rapid thermal pyrolysis (RTP), 88
- Rate, heating, 72t, 76–77, 245
- Rate constant, reaction, 137
- Rat holing, 277
- RDF. *See* Refuse-derived fuel
- Reaction(s)
 Boudouard, 123–124, 141–142, 142t
 carbon, 121t
 char, 123, 126–128
 in gasification, 121t
 gas-phase, 144–146
 gas–solid, kinetics of, 140–144
 heat of, 46–47, 201–204
 hydrogasification, 126, 143
 kinetics in hydrothermal gasification,
 250–251
 oxidation, 121t
 rate constant, 137
 shift, 121t, 124–126, 304
 water–gas, 124, 142
- Reactor pressure, tar and, 105
- Receiving, biomass, 272
- Reducers, size, 285–286
- Reduction, tar, 103–116
- Redundant, feeder, 298
- Redwood, ultimate analysis of, 51t

- Reforming
 of hydrocarbon, steam, 143–144
 tar, 104
- Refuse-derived fuel (RDF), 294–295, 329t
- Remediation, waste, 249
- Renewability of biomass, 16–19
- Rentech-Silvagas process, 183–184
- Residence time, 72t, 76, 107, 244
- Rice hulls, 329t
- Rice husk, proximate and ultimate analysis
 of, 51t, 54t
- Rice straw
 fusibility of ash of, 329t
 moisture content of, 53t
 ultimate analysis of, 51t
- Rotary spreader, 296
- Rotating-cone pyrolyzer, 89
- SASOL. *See* South African Synthetic Oil Limited
- Sawdust
 heating value of, 71t
 kinetic rate constants of, 82t
 moisture content of, 53t
 ultimate analysis of, 51t
- Screw feeder, 291–293
- Scrubbers, wet, 114–115
- SCW. *See* Supercritical water
- Secondary tar, 102
- Separator system, gas-liquid, 257–261
- Sewage sludge, ultimate analysis of, 51t
- Shelf life, biomass, 274
- Shift reaction, 121t, 124–126, 304
- Shirley, Thomas, 2
- Side-fed gasifier, 187
- Silicon, true density of, 43t
- Silos, 275
- Simulation, gasification, 150–158
- Size, feed particle, 245
- Size reducers, 285–286
- Sizing, gasifier, 205–214
- Slagging gasifier, 172
- Slow pyrolysis, 72
- Snow, 287
- Sociopolitical benefits, of biomass,
 18–19
- Sodium, true density of, 43t
- Solid concentration, 244–245
- Solid fuels from biomass, 5
- South African Synthetic Oil Limited
 (SASOL), 302
- Space velocity, 206
- Specific heat, 46, 331t, 335t
- Spiral chunker, 286
- Spreader, 293
- Standards D-1102, E-1755-01, and D-3174-04,
 52
- Standard D-3175-07, 52
- Standards E-871-82 and E-1358-06, 53–54
- Steam
 cracking, 104
 as gasification medium, 119, 119t
 in gasifier design, 197–200
 reforming, of hydrocarbon, 143–144
 subcritical, 232
- Steam-reforming reaction, 121t
- Steven-Boltzmann's constant, 327
- Stoichiometric air requirement, 195
- Stoichiometry, 59–60, 152–153
- Storage, biomass, 269, 272–284
 above-ground outdoor, 274–275
 bins and silos for, 275
 underground, 273–274
 ventilation and, 274–275
- Subcritical steam, 232
- Subcritical water, 231–232
- Sulfur
 biomass and, 18
 in bio-oil, 308t
 true density of, 43t
- Supercritical water (SCW), 230–237. *See also*
 Hydrothermal gasification
 oxidation, 239
- Superficial gas velocity, 206
- Surface moisture, 287–288
- Syngas, 1, 302
 ammonia production with, 305t, 313–314
 applications of, 302
 from biomass, 6
 C/H ratio of, 15t
 cleaning of, 303–305
 conditioning of, 304–305
 conversion of, into chemicals, 310–314
 in Fischer-Tropsch synthesis, 305t, 313
 gasification and, 302–304
 in glycerol synthesis, 314
 hydrogen/carbon monoxide ratio in,
 303
 low- and high-temperature gasification
 and, 303
 in methanol synthesis, 305t, 310–313
 production, 24, 302–303, 305t
 shift reaction and, 304
 tar and, 303–304
 uses of, 301
- Syrup, wood, 100–101

- Tar, 97–102
 acceptable limits for, 98–100
 air gasification and, 106
 alkali and, 108
 alkali remover and, 115
 barrier filters and, 113–114
 carbon dioxide gasification and, 107
 char and, 108
 composition of, 101–102
 cracking, 226
 cyclones and, 113
 design modifications, for removal of, 112
 in direct-combustion systems, 98
 disposal of, 115
 dolomite and, 107
 in downdraft gasifier, 100t, 109–111, 110f
 electrostatic precipitators and, 114
 in entrained flow gasifier, 100t, 111
 in fluidized-bed gasifier, 100t, 111, 111f
 formation, 100–101
 gas cleaning and, 98
 in gasification, 121
 gasification factors and, 99–100
 gasifier design and, 109–111
 by gasifier type, 100t
 in-situ reduction of, 104–112
 internal combustion and, 99
 medium of gasification and, 105–107
 nickel and, 108
 olivine and, 108
 operating conditions and, 105–107
 physical removal of, 112–115
 post-gasification reduction of, 112–116
 primary, 100–101
 problems of, 97
 pyrolygineous, 306
 reduction, 103–116
 reforming, 104
 residence time and, 107
 scrubbers and, 114–115
 secondary, 102, 112–116
 steam gasification and, 106
 steam–oxygen gasification and, 106–107
 syngas and, 303–304
 temperature and, 105
 tertiary products, 102
 in updraft gasifier, 100t, 109, 110f
 upper limits of, 99t
- Temperature
 of drying gas, 288
 effects on pyrolysis, 75
 gasification, in gasifier design, 200–201
 ignition, 47–48, 48t
 pyrolysis, 67
 tar and, 105
- Ternary diagram, 40–41, 41f
- Terrestrial biomass, 29t
- Tertiary tar products, 102
- Thermal conductivity, 44–45, 45f
- Thermal cracking, 104, 116
- Thermochemical conversion, of biomass,
 10–16, 12f, 12t
- Thermodynamic equilibrium models,
 151–154
- Thermodynamics, of biomass, 44–48
- Thermogravimetric analysis, 55–56
- Throated and throatless gasifiers,
 174–176
- Time, residence, 72t, 76, 107, 244
- Top-fed gasifier, 187
- Torque, in screw feeder, 292–293
- Torrefaction, 13–14. *See also* Pyrolysis
 advantages of, 93–94
 depolymerization in, 92
 design considerations, 95
 devolatilization in, 92–93
 hemicellulose in, 94–95
 mechanism of, 94–95
 moisture absorption and, 93
 thermodynamic loss and, 92
- Torrefied pellet, 95–96
- Total-dry basis, 57
- Town gas, 2
- Tracheids, 35
- Transfer of heat, in pyrolyzer, 83–84
- Transfer of heat, in SCW, 255–256
- Transportation fuels. *See also* Ethanol
 biochemical process for, 320
 biomass in, 8, 315–323
 bio-oil in, 309
 feed preparation, in production of, 322
 fermentation, in production of, 323
 gasification in, 3, 3f
 hydrolysis in production of, 322–323
 thermal process for, 320
- Transport gasifier, 181
- True density, 42, 43t
- Twin reactor system, 181–184
- Ultimate analysis, 49–50, 51t
- Ultra-rapid pyrolysis, 73, 88
- Under-bed system, 296–298
- Underground storage, 273–274
- Universal gas constant, 327
- Updraft gasifier, 100t, 109, 110f, 130–133,
 170–172, 207

- Vacuum pyrolysis, 72t, 86–87f, 89
- Value, heating, 57–60, 330t
- Van Krevelen diagram, 39
- Vapor pyrolysis products, 70–71
- Vegetable oil, 8
- Vegetables, as biomass, 31
- Velocity
 - fluidization, 210
 - space, 206
- Ventilation, biomass storage and, 274–275
- Virgin biomass, 29t, 30
- Volatile matter, 51–52
- Walnut shell, 329t
- Waste biomass, 29t, 31–33, 32t
- Waste degradation, 33
- Waste remediation, 249
- Water
 - in bio-oil, 307t
 - formation heat of, 46t
 - specific heat of, 331t
 - subcritical, 231–232
 - supercritical, 230–237
- Water–gas reaction model, 124, 142
- Water hyacinth, moisture content of, 53t
- Wet electrostatic precipitators, 114
- Wet scrubbers, 114–115
- Wheat straw
 - ignition temperature of, 48t
 - moisture content of, 53t
- Winkler, Fritz, 177
- Winzer, Friedrich, 2
- Wood, structure of, 34–36
- Wood bark, moisture content of, 53t
- Wood cell, 35f
- Wood liquid and distillates, 306
- Wood oil, 100–101
- Wood syrup, 100–101
- Woody plants, as biomass, 30
- Xylan, 37f
- Yield
 - operating variables and, 85t
 - pyrolysis product, 74–77
- Yom Kippur War, 4
- Zinc, true density of, 43t