

## INDEX

---

### A

Absolute pressure, 8  
Aggregatively fluidized beds,  
560, 566  
fluid flow in, 569  
particle flow in, 468  
pressure distribution in,  
567  
Analogies, between momen-  
tum and heat transfer,  
509  
Angular momentum, 81  
Angular velocity, 4, 39, 258,  
355  
Annular die, flow through,  
322  
Annular flow, 543, 552  
A.P.I., degrees, 11  
Archimedes, biographical  
sketch, 36  
Archimedes' law, 37  
Archimedes number, 200  
Axially symmetric irrotational  
flow, 378

### B

Balances, energy, 9, 55, 61  
mass, 9, 55, 57  
momentum, 9, 55, 78  
Basis or shape function, in  
finite-element methods,  
681  
Bearing, journal, 443

thrust, 443  
flow in, using COMSOL,  
448  
Bernoulli, Daniel, biographi-  
cal sketch, 68  
Bernoulli's equation, 67, 355,  
384, 533  
compressible flow, 161  
generalized, 64  
Bézier curves in COMSOL,  
720  
Bingham plastic fluids, 594,  
600  
in pipe flow 600  
Blake-Kozeny equation, 207  
Blasius equation, 129, 428,  
493, 495, 511  
Blasius solution for bound-  
ary layer flow, 425  
Blow molding, 313  
Blunt-nosed object, flow  
past, 358, 383  
Bob-and-cup viscometer, 627  
Body force, 56, 79  
Body-force potential, 321  
Boltzmann distribution, 649  
Boltzmann's constant, 131  
Boolean operations in  
COMSOL, 722  
Boundary, 9, 55  
Boundary conditions, 293  
Boundary layers, 414  
application to turbulent  
jets, 513  
dimensional analysis of,  
430  
laminar, 415  
simplification of equations  
of motion for, 422  
solution using COMSOL,  
435  
turbulent, 428  
Boundary settings in COM-  
SOL, 712, 724, 727  
Bourdon-tube pressure  
gauge, 89  
Brinkman equation with  
COMSOL, 729  
Brownian motion, 129  
Bubble caps, dynamics of, in  
distillation columns, 216  
Bubble flow in vertical pipes,  
543, 545  
Bubbles, in fluidized beds,  
560  
formation at an orifice, 563  
rise velocity of, 562, 572  
Bubbles, rise velocity of,  
531, 545  
Bubbles, terminal velocity,  
532  
Buckingham Pi theorem, 227  
Buffer region, 490  
Buoyancy, 36  
Burke-Plummer equation,  
207

### C

Cake, in a filter, 210  
Calendering, 313, 401, 450  
pressure distribution in,  
455

- Capillary pressure, in porous medium, 393
- Capillary tube, for surface tension, 19
- Capillary viscometer, 623
- Caprock, 395
- Carreau model, 599, 607
- Cascade process in turbulence, 474
- Centrifugal filter, 214
- Centrifugal pump, 164, 189
- Characteristic time, 596
- Charge number, 644
- “Choking” of the throat, 163
- Churchill, S.W., Reynolds stress correlation, 496
  - interpolation between two asymptotic limits, 498
- Coating a moving substrate, 461
- Coating or spreading, 313
- Coaxial cylinder rheometer, 627
- Coefficient of contraction, 71
- Coefficient of discharge, 73
- Coefficient of thermal expansion, 12
- Coions, 649
- Colebrook and White equation, 136, 494
- Commercial pipe, sizes, 138
- Complex piping systems, 163
- Composite object, COMSOL, 712, 723
- Compressibility factor, 12
- Compressibility, isothermal, 12
- Compressible flow of gases,
  - in a nozzle, 159
  - in a pipeline, 156
  - with COMSOL, 729
- Compressive stress, 6
- Computational fluid dynamics (CFD), 473, 671
  - applications in chemical engineering, 672
- COMSOL, Inc., 703, 705
- COMSOL Multiphysics,
  - examples involving, boundary-layer flow, 435
  - die flow, non-Newtonian, 606
  - electroosmosis, 653, 657
  - jet flow and mixing, 505
  - lake flow, 373
  - lubricated bearing, 448
  - momentum diffusion, 307
  - multiphysics, 653, 657
  - orifice plate, 501
  - parallel-plate flow, 435
  - porous-medium flow, 705
  - screw extruder, 318
  - turbulent flow, 501, 505
- COMSOL Multiphysics,
  - capabilities of, 703
  - axes and grid settings, 710
  - Bézier curves, 720
  - Boolean operations, 722
  - boundary settings, 712, 724
  - composite object, 712, 723
  - documentation, 705
  - draw mode, 719
  - draw toolbar, 711
  - equations solvable by, 704
  - graphical user interface, 708
  - how to run, 705
  - interior boundaries
  - menus and toolbars, 709
  - mesh, 715, 716
  - model library
  - model navigator, 706
  - multiphysics, 653, 657
  - physics modes, 703
  - plot parameters, 718
  - postprocessing, 717
  - problems solvable by, 725
  - solving a problem, 717, 724
  - subdomain settings, 714, 724
  - surface plot, 716
- Cone-and-plate viscometer, 328, 626
- Connate water, 392
- Conservation laws, 9, 55
- Constitutive equations,
  - Bingham model, 594, 600
  - Carreau model, 599
  - generalized Newtonian fluids, 598
  - general viscoelastic fluids, 615
  - Maxwell model, 615
  - Newtonian fluids, 296, 595
  - power-law model, 599
  - White-Metzner model, 619
- Contact force, 56, 79
- Continuity equation, 59, 72, 267, 268
  - time-averaged, 477
- Control surface, 55
  - for momentum transfer, 81
- Convection of momentum, 81
- Convective derivative, 266, 619
- Converging/diverging nozzle, 159
- Conversion factors, table of, *inside front cover*, 25
- Coriolis mass-flow meter, 95
- Couette flow, 294, 312, 316, 328
  - in lubrication, 447
- Counterions, 649
- Critical pressure for compressible gas flow, 158, 163
- Cross product, 251
- Curl of a vector, 259
  - expressions for, 266
- Curvature, 458, 735
- Curved surface, change in pressure across, 18, 458
- Cyclone separation, 219
- Cylinder, flow past, computed by FlowLab, 195, 696
  - drag coefficient, 699
- Cylindrical coordinates, 263
  - mass balance in, 268
  - momentum balances in, 322
  - solution of problems in, 322

## D

- d'Arcy's law, 207, 388, 392, 706
- Dam, force on, 32
- Deborah number, 596
- Debye-Huckel limit, 650
- Debye length, 650
- Deformation of a fluid element, 275, 357
- Del (nabla) operator, in rectangular coordinates, 265
- Density, 10  
°A.P.I., 11
- Derivative, definition of, 27, 257
- Derivatives, 731
- Derived quantities, 225
- Diameter, hydraulic mean, 151
- Die swell, 614
- Dies, flow through, 313, 322  
non-Newtonian, 606
- Differential equations, solution of, separation of variables, 733  
spreadsheets, 466, 734
- Differential mass balance, 267
- Differential momentum balance, 271
- Diffuser, in a nozzle, 159
- Diffusion coefficient, 15
- Diffusion in microchannels, 642
- Diffusion of momentum, 307
- Dilatant fluids, 593, 599, 603
- Dimensional analysis, 224
- Dimensional analysis of boundary layer flow, 430
- Dimensionless groups, for drag force, 196  
filtration, 224  
flow through packed beds, 206  
laminar sublayer, 230  
pipe flow, 132, 134  
pumps, 192
- Dimensionless numbers, table of, 228
- Dimensionless shear stress, 132, 491
- Dimensions, 226  
mass, length, and time, 10
- Directional derivative, 252
- Discharge coefficient, 73
- Discretization, in numerical methods, 674
- Dissipation, *see* frictional dissipation
- Dissipation, turbulent, 499  
transport equation for, 500
- Distillation column, dynamics of bubble caps, 216
- Dittus-Boelter equation, 511
- Divergence of a vector, 254  
expressions for, 265
- Dot product, 250
- Double-dot product, 597
- Doublet, 384
- Drag coefficient, 196
- Drag coefficient on a flat plate, 415, 419, 428, 429, 432
- Drag force, 194
- Draw mode in COMSOL, 719
- Draw toolbar in COMSOL, 711
- Drawing or spinning, 312
- Droplet, excess pressure inside, 18
- Ducts, flow in noncircular, 150
- Dyadic product, 619, 740
- Dynamical similarity, 229
- E**
- Eddies, 131, 474, 480  
formation of, 475
- Eddy diffusivity, 483
- Eddy kinematic viscosity, 132, 482, 483, 484  
correlation for, 486  
determination of, 485  
in turbulent jets, 518
- Eddy thermal diffusivity, 483
- Eddy transport, 481
- Elastic modulus, 621
- Elastic recoil, 617
- Electrical double layer, 647, 648, 649
- Electric charge, 644  
flux of, 645
- Electric field, 644
- Electric potential, 646, 649, 650
- Electrokinetic flow, 639, 664
- Electrokinetic forces, 664
- Electroosmosis, 647, 651  
measurement of, 659
- Electroosmosis in a microchannel (COMSOL), 653, 657
- Electroosmotic flow around a particle, 653
- Electroosmotic mobility, 647
- Electrophoresis, 645, 664
- Electrophoretic mobility, 645
- Electrostatic precipitator, 202
- Electroviscosity, 661
- Energy balance, 55, 62, 598,  
pipe flow, 126, 128
- Energy, conservation of, 9, 55
- English units, 22
- Entrance region between flat plates, 440
- Eötvös number, in slug flow, 549
- Equations of motion, 268, 281, 294, 322, 327  
solutions of, 293
- Equipment, visual encyclopedia of, 185
- Equipotentials, 366  
in microfluidics, 656, 658
- Equivalent length of fittings, 154
- Ergun equation, 206
- Euler equation, 355, 397
- Euler's method, 733
- Eulerian viewpoint, 267
- Excel spreadsheets, 143, 145, 146, 150, 167, 454
- Extrusion of polymer, 312

## F

Falling-sphere viscometer, 202  
 Fanning friction factor, 132, 133, 135, 136, 137  
 Faraday's constant, 649  
 FEMLAB—see under its new name, COMSOL  
 Multiphysics  
 Fick's law, 644  
 Film flow, 456  
 Film, in lubrication, 443  
 Filtrate, 210  
 Filtration, 210  
 centrifugal, 213  
 plate-and-frame, 210  
 rotary-vacuum, 212  
 Finite-difference methods, 674  
 Finite-element methods, 680  
 Finite-volume methods, 676  
 Fittings, equivalent length, 154  
 Five-spot pattern, 391  
 Flooding, 555  
 Flow energy, 62  
 Flow, around sphere, 194  
 in noncircular ducts, 150  
 in open channels, 151  
 past a flat plate, 415, 428  
 through a porous medium, 207  
 through packed beds, 204  
 FlowLab, examples  
 involving,  
 flow in pipe entrance, 687  
 flow past a cylinder, 696  
 sudden expansion, 690  
 two-dimensional mixing, 692  
 FlowLab, CFD software, 682  
 geometry panel, 684  
 graphical user interface, 683  
 mesh and solve panels, 685  
 operation toolpad buttons, 683  
 physics, boundary condition, and materials

panels, 684  
 reports and postprocessing panels, 686  
 Flow rates, 9  
 Flow rate, measurement of, 94  
 by Coriolis meter, 95  
 by orifice plate, 71  
 by rotameter, 89  
 Flow regimes in two-phase flow,  
 horizontal pipes, 541  
 vertical pipes, 543  
 Fluent, Inc., 682  
 Fluid, definition of, 9  
 Fluid mechanics, laws of, 9  
 Fluidization, 215, 559  
 aggregative, 560, 566  
 particulate, 559  
 Fluidized bed, 559  
 reaction in, 572  
 Flux, 8, 254  
 Force, 22  
 as a rate of momentum transfer, 79  
 on arbitrary surfaces, 33  
 on dam, 32  
 power for displacement of, 64  
 units of, 21  
 Forced vortex, 39, 356  
 Form drag, 194  
 Fourier's law, 256, 260  
 Fox, T.R.C., xvii, 456 *footnote*  
 Free surface, 28, 33  
 of rotating fluid, 39  
 Free vortex, 40, 220, 356  
 Friction factor, 124  
 analogy with the Stanton number, 510  
 as a dimensionless group, 132, 210  
 in terms of  $Re$ , 135, 491  
 Friction-factor plot, 135  
 Friction velocity, 489  
 Frictional dissipation, 63, 598  
 noncircular ducts, 151  
 open channels, 152

packed beds, 207  
 pipe flow, 126, 134  
 Froude number, in slug flow, 549  
 Fundamental dimensions, 225

## G

Galerkin's method, 681  
 Gas constant, values of, 12  
 Gas law, 11  
 Gas-lift pump, 550  
 Gas, pressure variations in, 31  
 Gas, underground storage of, 395  
 Gases, 5  
 flow of compressible, 156, 159  
 viscosity of, 131  
 Gauge pressure, 8  
 Gate valve, 154  
 $g_c$ , conversion factor, 22  
 General linear viscoelastic fluids, 615, 618  
 Generalized Maxwell model, 618  
 Geometrical shapes, 731  
 Geometrical similarity, 229  
 Globe valve, 154  
 Gradient of a scalar, 252  
 expressions for, 265  
 Graphical interface, for COMSOL, 708

## H

Hagen-Poiseuille law, 125  
 Harrison, D., bubble formation in fluidized beds, 565  
 Head, of fluid, 68  
 Head/discharge curve for centrifugal pump, 192  
 Heat transfer, analogy with momentum transfer, 509

Hookean solid, 616  
 Hoop stress in pipe wall, 139  
 Hydraulic mean diameter, 151  
 Hydraulically smooth pipe, 136  
 Hydrostatics, 26  
   multiple fluids, 30

## I

Impeller, of pump, 91, 190  
 Incipient fluidization, 215, 559  
 Infinite-shear viscosity, 599  
 Injection molding, 312  
 Integrals, 731  
 Intensity of turbulence, 477  
 Internal energy, 61  
 Invariants of the strain-rate tensor, 597  
 Inviscid fluid, motion of, 321  
 Irrigation ditch, 152  
 Irrotational flow, 260, 356  
   axially symmetric, 378  
   in cylindrical coordinates, 363  
   in rectangular coordinates, 361  
   line source, 370  
   past a blunt-nosed object, 358, 383  
   past a cylinder, 367  
   past a sphere, 386  
   point source, 382  
   stagnation flow, 369, 383  
   uniform flow in, 366, 380  
 Irrotationality condition, for  
   axially symmetric flow, 379  
   for cylindrical flow, 364  
   for rectangular flow, 361  
 Isentropic expansion, 160  
 Isothermal compressibility, 12  
 Isothermal flow of gas in pipe, 156

## J

Jet mixing, COMSOL  
   computation of, 505  
   FlowLab computation of, 692  
 Journal bearing, 443

## K

Karamanev, D.G., method  
   for terminal velocities, 200  
 Kármán vortex street, 475, 697  
 $k/\varepsilon$  method for turbulent flows, 499  
   with COMSOL, 726  
   with FlowLab, 690  
 Kinematic viscosity, 15, 512  
 Kinetic energy, 61, 67  
   for pipe flow, 127  
 Kinetic energy, turbulent, 499  
   transport equation for, 500  
 Kolmogorov limit, 474, 476  
 Kronecker delta, 251

## L

Lagrangian viewpoint, 266  
 Lake flow, with COMSOL, 373  
 Lamb, Horace, feelings about turbulence, 473  
 Laminar flow, friction in, frictional dissipation, 126  
   friction factor for, 134  
   in a pipe, 122, 123  
 Laminar flow, unstable, 475, 700  
 Laminar sublayer, 155, 490  
   dimensional analysis of, 229  
   thickness of, 155, 493  
 Laminar velocity profile, 124, 155  
 Laplace, Pierre Simon, Mar-

quis de, biographical sketch, 362  
 Laplace's equation, 262  
   in irrotational flow, 362, 364, 379  
   for axially symmetric flow, 379  
   with COMSOL, 727  
 Laplacian operator, 262  
   expressions for, 266  
 Laws of fluid mechanics, 9  
 Leibnitz's rule, 618 *footnote*, 736  
 Leung, L.S., bubble formation in fluidized beds, 565  
 Linear viscoelasticity, 615  
 Line source, 370  
 Liquids, 5  
 Lockhart/Martinelli correlation, 539, 552  
 Logarithmic velocity profile, 487, 490  
 Lorentz force, 646  
 Loss angle, 621  
 Loss modulus, 621  
 Lubrication approximation, 444  
 Lubrication flow, with COMSOL, 448

## M

Macintosh computer for COMSOL, 706  
 Magnetic settling, 662  
 Manometer, 93  
 Mass, 21  
   conservation of, 9, 55  
 Mass balance, 55, 57  
   steady state, 57  
 Mass flow rate, 9  
 Mass velocity, 157  
 Material types, 591  
 MATLAB, xvi, 613, 703, 704, 706  
 Maxwell, James Clerk, biographical sketch, 616  
 Maxwell model, 615

Memory function, 618  
 Mesh refinement in  
   COMSOL, 715, 725  
 Microfluidics, 639  
   chips for, 640  
 Microscale fluid mechanics,  
   640  
 Mist flow, 475  
 Mixing length, correlation  
   for, 485  
   determination of, 484  
 Mixing-length theory, 481  
   for turbulent jets, 515  
 Model navigator, in  
   COMSOL, 706  
 Moment of inertia, 90  
 Momentum, 78  
   angular, 90  
   balance, 55, 78  
   conservation of, 55, 79  
   diffusion of, 307  
 Momentum balance, for  
   bubble formation at  
     an orifice, 564  
   in film flow, 405  
   shell, 301  
   time-averaged, 478  
 Momentum transfer,  
   by convection, 9, 81  
   by force, 79  
   in laminar flow, 129  
   in turbulent flow, 131  
 Momentum transfer, analogy  
   with heat transfer, 509  
 Moody friction factor, 132

## N

Natural gas, underground  
 storage of, 395  
 Navier, Claude-Louis-Marie-  
 Henri, biographical  
 sketch, 281  
 Navier-Stokes equations,  
   278, 281  
   in microfluidics, 646  
   with COMSOL, 725  
 Needle valve, 154  
 Newton, Sir Isaac, bio-  
   graphical sketch, 131  
   law of viscosity, 124, 130  
   second law of motion,  
     21, 27  
 Newtonian fluid, 4, 14, 124,  
   130, 275, 276, 279,  
   591, 598  
 Nicklin, D.J., correlation for  
   two-phase slug flow, 548  
 Nikuradse, pipe friction  
   experiments, 136  
 Nonlinear simultaneous  
   equations, 149, 166  
 Non-Newtonian flow in a die,  
   with COMSOL, 606  
   viscosity profiles, 611  
 Non-Newtonian flows using  
   COMSOL, 728  
 Non-Newtonian fluid, 4, 592  
 Normal stresses, 271, 276,  
   viscoelastic, 613  
 Normal-stress difference, 613  
 No-slip boundary condition,  
   273  
 Nozzle, gas flow in, 159  
 Numerical methods for  
   solving fluid mechanics  
   problems, 673

## O

Oldroyd derivative, 620  
 One-seventh power law,  
   493, 495  
 Open-channel flow, 151  
 Order-of-magnitude  
   analysis,  
   for boundary-layer flow,  
     423  
   for turbulent jets, 513  
 Ordinary differential equa-  
   tions, solution of, 733  
 Orifice, flow through,  
   compressible, 159  
   incompressible, 70  
 Orifice-plate “meter,” 71  
 Orifice plate, COMSOL  
   solution, 88, 501  
   pressure recovery, 504  
 Oscillatory shear, with  
   COMSOL, 309  
 Ostwald-de-Waele model,  
   599

## P

Packed beds, 204  
 Packed-bed reactor, pressure  
   drop in, 208  
 Packed column, flooding of,  
   556  
 Paint films, leveling of, 463  
 Parabolic velocity profile,  
   124, 155  
 Parallel-plate rheometer, 627  
 Particle motion in micro-  
   fluidic channels, 661  
 Particles, settling of, 199,  
   201, 222  
 Particulate phase (“emul-  
   sion”), in fluidization,  
   560  
 PC for COMSOL, 706  
 Péclet number, 643  
 Permeability, 208, 387,  
   391, 396  
 Permittivity, 646, 654  
 Physical properties, 10  
 Piezoelectric and piezoresis-  
   tive effects in pressure  
   transducer, 93  
 Piezometer, 93  
 Piezometric tube, 69, 93  
 Pipe fittings, pressure drop,  
   154  
 Pipe flow, Bingham plastic,  
   604  
   power-law fluid, 600  
 Pipe flow, pressure drop in,  
   123, 133, 139  
 Pipe roughness, 136  
 Pipeline, for gas, 156  
 Pipes, flow through, 120  
 Piping systems, 149, 163  
 Pitot tube, 74  
 Pitot-static tube, 74  
 Plate-and-frame filter, 210  
 Plot parameters in  
   COMSOL, 718  
 Point source, 381  
 Poiseuille flow, 294, 312, 316  
   in lubrication, 447  
 Poisson’s equation, in  
   lubrication, 445

- Poisson's equation,  
 solution of,  
 by COMSOL, 373, 727  
 by finite-element methods,  
 674  
 by finite-difference  
 methods, 674  
 microfluidics, 646
- Polymath, 150, 164
- Polymer processing, 312, 450
- Pores, flow through, 205
- Porosity, 391, 396
- Porous medium, flow  
 through, 207, 566  
 single-phase, 364, 388, 390  
 two-phase, 390  
 with COMSOL, 728
- Potential, for porous-  
 medium flow, 392
- Potential energy, 61
- Potential flow, 261, 361
- Power,  
 for flowing stream, 64  
 for force displacement, 64  
 for pump, 64  
 for rotating shaft, 64
- Power-law fluids, 599, 600
- Power-law velocity profile,  
 495, 603
- Prandtl hypothesis, 486
- Prandtl, Ludwig, bio-  
 graphical sketch, 434
- Prandtl mixing length, 483
- Prandtl-Taylor analogy, 510
- Pressure, 6  
 absolute, 8  
 gauge, 8
- Pressure as a function of  
 height, 26
- Pressure change caused by  
 rotation, 39
- Pressure distribution, in  
 calendering, 454  
 in fluidized beds, 567
- Pressure drop, across pipe  
 fittings, 154  
 in pipe flow, 123, 133, 139
- Pressure drop in two-phase  
 flow  
 horizontal pipes, 536  
 vertical pipes, 549, 552
- Pressure forces on sub-  
 merged objects, 36
- Pressure head, 68
- Pressure measurement, 92
- Pressure transducer, 93
- Primary recovery of oil, 390
- Projected area, 196
- Pseudoplastic fluids, 593,  
 599, 603
- Pump impeller, 91, 190
- Pumps, centrifugal, 164, 189  
 positive displacement,  
 188, 189
- Pumps in series and  
 parallel, 193
- ## R
- Rabinowitsch equation, 624
- Radius of curvature, 735
- Rate laws, 57
- Rate-of-deformation tensor,  
 279
- Rate-of-strain tensor,  
 279, 596  
 invariants of, 597
- Reaction in fluidized bed,  
 572
- Reciprocating pumps, 188
- Recirculation in sudden  
 expansion,  
 in jet mixing, with  
 FlowLab, 694  
 using FlowLab, 691
- Rectangular coordinates,  
 249  
 mass balance in, 268  
 momentum balances in,  
 272, 281  
 problems in, 294
- Rectangular duct, flow  
 through, 150, 294
- Reference quantities, 430
- Relaxation modulus, 618
- Relaxation time, 616
- Residual oil, 392
- Reynolds analogy, 509
- Reynolds experiment, 121
- Reynolds number, 73,  
 122, 228  
 for boundary-layer flow,  
 415, 428  
 for drag force, 196  
 in microfluidics, 641  
 in pipe flow, 134, 135,  
 137, 149
- Reynolds, Osborne, bio-  
 graphical sketch, 121
- Reynolds stresses, 479  
 correlation for, 496
- Rheometers, 625
- Rheopectic fluids, 594
- Richardson-Zaki correlation,  
 222, 560
- Rod-climbing effect, 614
- Rotameter, 89
- Rotary pumps, 189
- Rotary-vacuum filter, 212
- Rotating fluid, 39
- Rotational flow, 356
- Rotational rheometers, 625
- Roughness, pipe, 136
- Rough pipe, flow in, 136, 494
- ## S
- Saturation, in porous  
 medium, 391
- Scalars, 249
- Schedule number for pipe,  
 137
- Screw extruder, 313  
 with COMSOL, 318
- Secondary recovery of oil,  
 390
- Sedimentation, 222
- Separation of variables, 733
- Settling of particles, 199,  
 201, 222
- Shacham equation, for  
 turbulent friction  
 factor, 137, 150
- Shear stress, 3, 6, 14,  
 271, 274  
 dimensionless groups for  
 pipe flow, 225  
 distribution, 124, 300, 605

- in pipe flow, 80, 123
  - models for, 129
  - Shear-thickening fluids, 593, 604
  - Shear-thinning fluids, 593, 599, 604
  - Shell momentum balance, 301
  - Shock, in gas flow, 159, 163
  - SI units, 21, 23
  - Sign convention for stresses, 271
  - Similar velocity profiles, 417
  - Simple shear, 592, 597, 615
  - Simpson's rule, 733
  - Simultaneous nonlinear equations, 149, 166
  - Slug flow in vertical pipes, 543, 547
  - Slurry, 210
  - Smooth pipe, flow in, 490
  - Solenoidal flow, 256
  - Solids, 591, 616
  - Solution procedure, for viscous-flow problems, 293
  - Sound, speed of, 159, 163
  - Source in a uniform stream, 382
  - Specific gravity, 13
  - Sphere, drag force on, 194, 434
  - Sphere, flow past, 194, 386, 434
  - Spherical coordinates, 263
    - mass balance in, 268
    - momentum balances in, 283
    - solution of problems in, 327
  - Spherical-cap bubbles, 533
  - Sphericity, particle, 197, 198
  - Spinning of fibers, 325
  - Spray drier, 201
  - Spreadsheets, 143, 145, 146, 150, 167, 454, 734
  - Spreadsheet solution of differential equations, 734
  - Spring/dashpot model, 617
  - Stagnation flow, 369, 383
  - Stagnation point, 369, 383, 533
  - Static head, 68
  - Steady in the mean, 87, 421
  - Steady-state energy balance, 62
  - Steady-state mass balance, 59
  - Steady-state problems, 57
  - Stokes, Sir George Gabriel, biographical sketch, 198
  - Stokes' law, 198
  - Storage modulus, 621
  - Strain rate, 592, 595, 598
    - for non-Newtonian flow in a die, 613
  - Strain-rate tensor, 279, 596
  - Stream function, 362, 364, 378
    - for boundary layers, 426
    - for turbulent jets, 516, 518
    - physical interpretation of, 364, 378
  - Streaming potential, 659
  - Streamlines, 57, 355, 366
    - in microfluidics, 656, 658
  - Stream tube, 62
  - Strength, of a doublet, 384
    - of a line source, 370
    - of a point source, 381
  - Stress and strain, for visco-elastic fluid, 622
  - Stress, compressive, 6
  - tensile, 5
  - Stress, sign convention for, 271
  - Stress relaxation, 617
  - Stress tensor, 274, 279, 595
  - Strong conservation form, 673, 676
  - Strouhal number, 699
  - Subdomain settings in COMSOL, 714, 724
  - Substantial derivative, 266
  - Sudden expansion, after orifice plate, 86
    - in a pipe, 88
    - solved by FlowLab, 690
  - Superficial velocity, 205
  - Supersonic velocity, 159, 162
  - Surface energy, 17
  - Surface plot in COMSOL, 716
  - Surface roughnesses, 136
  - Surface tension, 16
    - in thin-film flow, 456
    - methods for measuring, 19
  - Surface waves, 396
  - Surroundings, 9, 55
  - System, 9, 55
- T**
- Tangential stresses, 6, 272, 274
  - Tank draining, 70
    - evacuation, 58
    - filling, 76
  - Taylor dispersion, 642
  - Taylor, Geoffrey Ingram, biographical sketch, 534
  - Taylor's expansion, 31, 733
  - Tensile stress, 5
  - Tensors, 274, 279, 595, 740
    - "divergence" of, 741
    - "Laplacian" of, 741
  - Terminal velocities of spheres, 199
    - Karamanev method, 200
  - Tertiary recovery of oil, 390
  - Thermal diffusivity, 512
  - Thermal expansion, coefficient of, 12
  - Thin films, 456
  - Thixotropic fluids, 594
  - Thrust bearing, 443
  - Time-averaged continuity equation, 477
    - momentum balance, 478
  - Time-averaging, 476
  - Torque, 91, 191
    - power for rotation of, 64
  - Total head, 69
  - Transducer, for measuring pressure, 93
  - Transient problems, 57
  - Transient viscous diffusion of momentum



(COMSOL), 307  
 Transition flow, 121  
 Turbulence, 122, 124, 473  
   computation by the  $k/\varepsilon$  method, 499  
   intensity of, 477  
    $k/\varepsilon$  method for, 499  
   mixing-length theory, 481  
   momentum transport in, 131, 480, 509  
   orifice-plate flow, 501  
   solved by COMSOL, 726  
   solved by FlowLab, 690, 692  
   velocity profiles, 155, 487, 490, 492  
 Turbulent boundary layers, 428  
 Turbulent core, 155, 229, 490, 492  
 Turbulent energy, 474, 499  
   dissipation rate  $\varepsilon$ , 499  
   fluctuations, 475, 476, 479  
 Turbulent jets, 513  
   axisymmetric, 519  
   plane, 514  
 Turbulent properties computed by COMSOL, 503, 508  
   kinematic viscosity, 503, 507  
   kinetic energy, 503, 508  
 Turbulent transport, summary of, 483  
 Two-phase flow in porous media, 390  
 Two-phase flow in pipes, horizontal pipes, 536  
   vertical pipes, 543

## U

Underground flow of water, 364, 388  
 Underground storage of natural gas, 395  
 Unit vectors, 250  
 Universal velocity profile, 488

Unstable laminar flow, 475, 700  
 Unsteady-state problems, 57  
 Usagi, R., interpolation between two asymptotic limits, 498

## V

Valve, for pipeline, 154  
 Vanes, of centrifugal pump, 190  
 Variable-viscosity momentum balance, 284  
 Vector components, 250  
 Vector differentiation, 251  
 Vectors, 249  
   addition and subtraction, 250  
   dyadic product, 740  
   multiplication, 250  
 Velocity, 8  
 Velocity head, 68  
 Velocity, no-slip boundary condition, 293  
 Velocity of sound, 159, 162  
 Velocity potential, 260, 361, 364, 379  
 Velocity profiles, boundary-layer flow, 417, 418, 426, 428  
   calendering, 453, 463  
   concentric cylinders, 4  
   development in entrance region, 440  
   lubrication, 444  
   parallel plates, 14  
   pipe flow, 124, 155, 487, 490  
   turbulent flow, 487, 490, 492  
   turbulent jets, 517, 520  
   viscous flow, 124, 297, 305, 316, 324, 331  
*Vena contracta*, 71  
 Viscoelastic fluids, 613, 618  
   constitutive equations, 613  
   phase relations, 622, 623  
 Viscometers, 625

Viscosity, 3, 13  
   eddy kinematic, 131, 483  
   kinematic, 15, 512  
   of gases, 131  
 Viscous dissipation function, 598  
 Viscous drag, 194  
 Viscous-flow problems, 292  
 Viscous modulus, 621  
 Visual encyclopedia of chemical engineering equipment, 185  
 Void fraction, 205  
   in two-phase flow, 536, 544, 549  
 Volumetric flow rate, 9  
 Volute chamber, 190  
 Von Kármán hypothesis, 487  
 Vortex, forced, 39, 356  
   free, 40, 356  
 Vortex formation during jet mixing, 506  
 Vortex lines, 355  
 Vortex shedding past a cylinder, 698  
 Vorticity, 260, 355, 358  
   for non-Newtonian flow in a die, 612  
   source term for, 373

## W

Waterflooding, 391  
 Wave motion in deep water, 396  
   paths followed by particles, 399  
 Weight, 21  
 Weir, in distillation column, 217  
 Weissenberg effect, 614  
 Weissenberg, lectures of, 592  
 Weissenberg rheogoniometer, 328, 626  
 Wetted perimeter, 150  
 Weymouth equation, 157  
 White-Metzner model, 619  
 Work, 56, 61

**Y**

Yield stress, 594, 600

**Z**

Zajic, S.C., Reynolds stress  
correlation, 496

Zero-shear boundary  
condition, 294

Zero-shear viscosity, 599

Zeta potential, 647, 649, 651

Zoom extents, 375, 501, 506